Development of Surge Protection Device/Controller at JMICC Power Distribution Box

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Certificate

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of BS(EE).

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Dedication

This piece of writing is gratefully acknowledged by us to our parents for their love, sacrifices, faith, and prayers that have enabled us to be able to reach this stage in life. It goes out to Dr. Syed Umaid Ali, who served as our mentor throughout this project. The knowledge and experience that you imparted to us has made this project possible and also gave us a perspective on how one should do his/her engineering. We are indeed very thankful to our project partner and colleague who joined hands with us to complete this task successfully. This thesis is a manifestation of support, trust, and encouragement of everyone that we acknowledged above and we thank all of you.

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We would like to thank the faculty and staff of the Electrical Engineering Department of Bahria University, Islamabad, for providing us the opportunity to conduct this project within an educational environment. The four years that we have been associated with this department have provided us the foundation of all the aspects that we will incorporate into this project. We owe the most profound gratitude to our parents, who have been our constant source of motivation, encouragement, and patience throughout this project as well as all the other projects we had to undertake.

Lastly, it must be mentioned that we need to recognize the importance of our involvement in the project. In fact, the cooperation and dedication of both sides made this project a success.

Abstract

With the growing use of sensitive electrical and electronic devices in homes, businesses, and industries, surge protection has become essential. The first objective of this project is to construct an Intelligent Surge Protection Device (ISPD), which safeguards electrical installations against any adverse effects that could arise from transient overvoltages that result from lightning, switching surges, or any other form of electrical disturbance. The ISPD designed in this project utilizes voltage monitoring, quick response, and isolation techniques to reduce any possible negative effects on the connected devices. The design and implementation of the ISPD depend on the application of several components, whose efficiency has been verified through testing results, indicating that there are no voltage spikes within the acceptable range. As a result, the system is reliable and durable. The proposed system focuses on three-phase power systems, where the continuous monitoring and quick reaction are necessary for its efficient working. The system is capable of taking prompt action by disconnecting the loads because of its intelligent decision-making capability and sensing. This can be verified through simulation and hardware approaches because of its easy installation process and affordability, making it appropriate for the implementation of intelligent electrical protection systems. The availability of real-time system status and alerts becomes extremely important in the proposed model because it assists the users in comprehending the functioning of the system, and hence, it is suitable for implementing intelligent electrical protection systems.

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Chapter 1

Introduction

1.1 Project Background/Overview

Since most of the equipment and devices are either being electrified or made electronic, these types of devices have become the main target for the occurrence of transient overvoltage phenomenon known as power surge. Power surge may happen due to many reasons such as lightning, switching, and even any malfunctions which are likely to result in destruction of the apparatus due to high voltage. In this case, a viable solution is the adoption of surge protection methods in order to shield the equipment from high voltage surges which have become very essential in electrical engineering.

A Surge Protective Device (SPD) will be developed and tested in order to shield electrical equipment from transient overvoltage phenomena. In this particular design, the SPD operates in the sense that it senses any abnormal situation and then diverts the excess energy to safer zones within the circuits. Some key components employed in this design include Metal Oxide Varistors (MOVS) and Gas Discharge Tubes.

1.2 Problem Description

The design of a Surge Protection Device (SPD) and its controller forms the basis of this project, which seeks to ensure the proper protection of electrical circuits against overvoltages in any electrical network. This particular SPD is tailored towards a 2 kVA single phase electrical power distribution system. These power distribution systems are usually used in various small commercial institutions, offices, and laboratories where numerous electrical loads are supplied from the same source. This power distribution system is usually characterized by the sensitivity of the loads attached to it as well as the moderate capacity of the system. In addition, the loads attached to this power distribution system are usually directly connected to the source. The power rating of the system and its load characteristics make this distribution system particularly vulnerable to voltage transients and fault conditions, thus posing a potential danger to the equipment.

The device will ensure that any abnormality in voltage levels is detected in real-time and protects any attached loads via either limiting or diverting any excess energy. The design of the device requires choosing the right components that protect any overvoltage in the distribution box by ensuring that they have ratings and reaction times compatible with voltage and current levels in the distribution box. Apart from using passive protection techniques, the design incorporates a monitoring and control unit which will constantly monitor voltage levels and make decisions based on its findings. If overvoltage is found to occur frequently or a fault condition is detected, the control system will isolate the load by controlling a switch so that no damage is done to the load. The implementation of this design will involve hardware designing of the circuits, programming of an embedded microcontroller and experimental analysis to ensure that the designed device can limit overvoltage. Experimental analysis will take place under simulated fault and surge conditions. These conditions will be similar to those of a 2kVA load and help to test the efficiency and reliability of the implemented system.

1.3 Project Objectives

This project seeks to create a Surge Protection Device (SPD) and its controller to protect electrical circuits from any transient overvoltages. The project seeks to accomplish the following objectives:

- It establishes the characteristics of electrical surges and identify their causes and effects. It also seeks to identify the technical specifications required to ensure effective surge protection.
- Creating a highly effective surge protection circuit with suitable components like metal oxide varistors (MOVs), gas discharge tubes, and transient suppression devices that can withstand different levels of surges.
- The project aims to design a smart control circuitry that will be able to monitor and control the voltage, take quick action during unusual conditions, and switch the connected load during the protection process.
- The process of integrating the circuit protector and controller into one SPD device with the intention of increasing reliability and efficiency as well as ensuring safety.
- Conducting the tests using set surge conditions to verify the effectiveness of the SPD, its compliance with the protection limits, and its robustness during different modes of operation.
- Proposing an implementable solution for the electrical distribution system considering the financial feasibility, installation process, and maintenance requirements.

1.4 Project Scope

In this project, the design and manufacture of the SPD and its control system are considered. It is necessary to find out what kind of electrical surges are and what consequences they entail, and thus, appropriate protective elements (Metal Oxide Varistors and Gas Discharge Tubes) should be selected and included in a reliable and stable protection circuit. The goal of the controller is to maintain stability by continuously observing the voltage, reacting quickly to any anomalies, and ensuring the security of the vital electrical load.

Another important aspect of this research project is testing the performance and operation of the SPD prototype, created based on all previously accumulated knowledge about them. The main objective here is to identify the effectiveness and operational capabilities of the developed protector. Although the work is devoted mainly to research, it lays a basis for further application in the future.

Chapter 2

Literature Review

2.1 Introduction

Surge protective devices are necessary to keep electrical equipment safe from the damage that electrical surges can cause. Power systems have these surges happen a lot, especially in developing countries like Nigeria. SPDs work by sending surge currents to the ground or back to their source. This action stops damage to delicate electronic devices. But SPDs can run into different problems that can make them less reliable and less effective over time [1].

2.2 Challenges in SPD Reliability and Failure Detection

One of the biggest problems with SPDs is that they break down after being used for a long time in very harsh conditions. If something breaks down, it may lose its ability to protect against surges, making the connected equipment more likely to be damaged by surges. Also, not fixing the broken SPD makes it more likely that systems and equipment will fail because of surges. Choosing the wrong environment for the SPDs to work in can also make them less useful, which puts the system at risk [2].

To address these challenges, several researchers have developed condition monitoring systems that can detect SPD failures before they occur remotely. These systems use sensors that continuously monitor key electrical parameters like voltage, current, and power quality; they analyze such data for any anomalies that could indicate an imminent SPD failure [3].

2.3 Monitoring of Electrical Power Systems

Designed system makes use of ESP8266 Wi-Fi module and Arduino UNO microcontroller for constantly monitoring performance of the surge safety equipment in electrical distribution systems. In this regard, voltage, current, and temperature sensors are used for gathering information regarding performance of SPDs. Gathered data is uploaded to the cloud platform using Wi-Fi module, which enables one to monitor and manage SPD remotely using Firebase [4].

System controls the SPD, whereupon different people have access to the software and monitor database that belongs to them. Thus, users can conveniently check whether the SPD is operating properly and replace it in case of failure. After logging into the system, users can observe how the system works, and system facilitates the grouping of different products so as to maximize number of devices under control. The application is created using Flutter and Firebase [5]

The proposed system was able to achieve real-time monitoring, remote control, high accuracy of data, satisfaction of users, and enhanced reliability in managing SPDs. In this case, the proposed system will be able to provide a robust solution in safeguarding and controlling the operation of electrical devices from surge events by employing IoT and automation techniques to develop an efficient surge protection system in Nigeria and other countries.

2.4 Intelligent Lightning Detection and Surge Detection

The increasing occurrence of lighting cases around the world highlights the critical need to have effective safety measures at home. These types of natural disasters pose a major threat not only to individuals but also to their belongings, especially due to electrical overload that could possibly affect electronic items. Although the traditional use of lightning detectors and surge protectors proves to be useful, these systems have shown weaknesses in various areas, including automation, flexibility, comprehensiveness, and cost effectiveness. This situation has made the disruption of power supply more common than ever among households.

2.5 Methodology

This system's architecture is well-suited for ensuring that lightning is detected, protected against, analyzed, and communicated in order to increase the level of safety at home due to electrical surges caused by lightning. The operation of this system is done through the use of four main modules, namely lightning detection module, surge protection PCB module, data processing and control module, and monitoring interface. In the case of lightning detection module, it detects and describes a strike in up to 40 kilometers using the AMS AS3935 Franklin lightning sensor IC and Coilcraft MA5532-AE antenna [6]. The processing unit that is made up of an Arduino Uno has the role of ensuring proper process control, processing all information gathered by the sensors, and issuing control signals as required. The processing unit has the relay component that enables the device to switch off a double-pole mini circuit breaker when it is detected

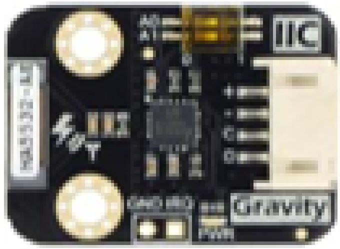

Figure 2.1: DFRobot gravity lightning sensor

that there are thunderstorms occurring, resulting in immediate isolation of the power supply from the electrical circuit. To offer additional protection against lightning strike, one can utilize the surge protection printed circuit board together with the mini circuit breaker [7].

The lightning detector worked well by being able to detect the lightning and determine its intensity and distance. This is proven by the first experiment conducted since it proved the presence of some inaccuracies in measuring the distances. In addition, the signals generated by the device are either, "lightning detected!" which depends on the distance and intensity, and "disturber detected!" or "noise level is too high!" concerning EMIs. In this respect, it should be noted that a high noise level occurs when the frequency of lightning is high because of the sensitivity of the sensor. [8].

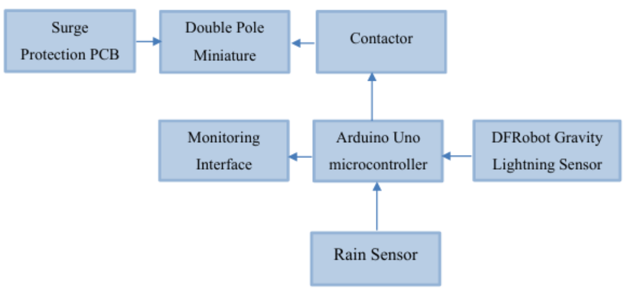

Figure 2.2: System Block Diagram

Intelligent lightning detector with surge protection works as an integrated system that integrates control, protection, and sensing functionality into one. The device features a lightning detection unit that comprises a sensitive sensor able to detect individual lightning strikes in the entire region, indicating frequency, energy level, and distance. This device operates in fewer disturbances from electromagnetic noise generated by other appliances since it possesses noise filtration capabilities. On the other hand, surge protection consists of specifically developed circuit boards that integrate components such as fuses, gas discharge tubes, and metal oxide varistors. Moreover, additional LED indicators were incorporated to make it possible to monitor the operational status of the appliance. These operations are performed by the microcontroller unit by analyzing input signals received from sensors and evaluating the environment. It performs all necessary preventive actions after relaying turns off the circuit breaker through the double-pole Miniature Circuit Breaker when predefined thresholds have been surpassed. Users can access various information such as detected lightning strikes and the performance condition of the device without any technical skill, thanks to an intuitive user display interface.

Figure 2.3: Lightning detection system with surge protection system

When tested with an AC single phase supply to simulate overvoltages, the surge protection module works perfectly. It's clear that the system can accurately show its condition and always find grounding problems. The protection mechanism also makes sure that all connected devices are safe by effectively stopping overvoltages. Using modules in the protection system is another benefit because it makes it easier to keep up with.

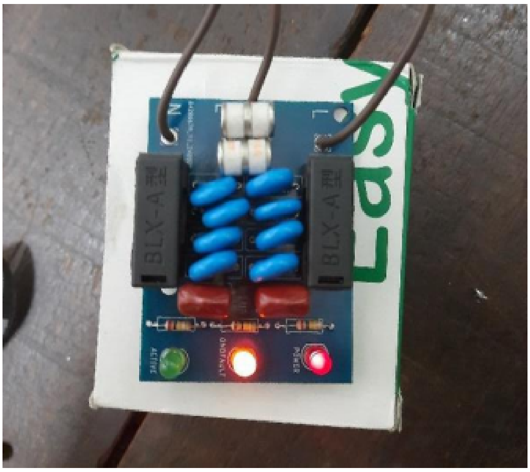

Figure 2.4: Surge Protection Module

2.6 Advanced System Architecture for Real-time SPD Lifetime Monitoring and Analysis

Because of the increasing number of extreme weather conditions like lightning in various regions across the globe, the electrical/electronic systems are now subjected to more risks than ever before. Lightning is an act of nature that can cause massive destruction not just to people but to the equipment as well. Therefore, it is necessary that proper precautions are taken by installing a reliable protection system. SPD plays an essential role in controlling voltage surges and ensuring proper functionality of components in a system. However, an SPD has a limited lifespan depending on the number of times surge occurs. [9].

In this system, an architectural approach that involves various elements performing different functions in the measurement and estimation process of the lifespan of the SPD is used. The Smart Lightning Counter installed in each SPD is the main device used to gather data. As opposed to normal SPDs, the Smart Lightning Counter has the capability to measure not only the number but also the amplitude of lightning surge impacting the SPD. On its part, the CT monitors the magnitude of lightning current flowing through the SPD, providing real-time figures. Such information is valuable when analyzing the pressure imposed on the SPD.

The gathered raw data first goes to the microcontroller through RS485. The reason for doing so is that this type of protocol is very efficient and reliable in transferring data over long distances in a factory setting. Afterwards, the processed data is sent to the Raspberry Pi [10], acting as the main processing unit of our suggested system to perform further calculations in estimating the lifespan of the SPD. Moreover, Node-RED, a flow-based software, can be employed for data stream development, receiving the data, and passing it along the line to the next processing phase. The data storage mechanism will employ the online MySQL database [11]. The benefit of using MySQL is the possibility of saving large amounts of information. This database is capable of storing information such as the value of a surge, its estimated lifespan, and more. All of this information can be accessed easily because it is structured. Finally, the obtained information would be presented to the user through a monitoring system. This monitoring system may take many forms, either stand-alone or connected to the SCADA system [12].

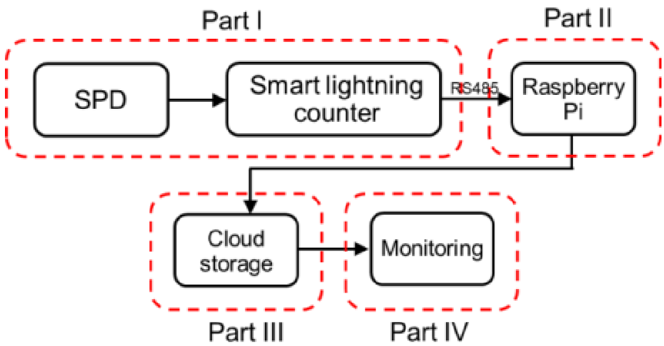

Figure 2.5: Block Diagram of SPD Lifetime Analysis

2.7 Methodology for Service Life Estimation

The effectiveness of the lifespan analysis system of the SPD under investigation depends on a proper estimation of the remaining lifespan of the components in question. Montha et al. managed to design an efficient procedure for correlating the number of impulses and decreased lifespan of the investigated devices. It should be noted that the validation of the suggested procedure was performed using industrial criteria and proved effective. One of the essential parts of the procedure mentioned above is related to evaluating the lifespan of different models of the SPDs through experiments. Specifically, the investigation covered two types of SPDs, namely, AC Class II and DC Class II, that are currently widely used in modern power system networks. Impulses used during testing included simulated electrical impulses in the form of successive current injections that were conducted in order to estimate longevity. One of the main aspects concerning impulses is the waveform 8/20 µs for lightning current injections. Various SPDs underwent injection of a particular amount of current, e.g., 10 kA, 20 kA, 30 kA, 40 kA, and 50 kA for AC Class II; the same applied to DC Class II. Such findings led to the formulation of lifetime analysis. Lightning impulse

TABLE I. SPD TEST

No.	Type of SPD	Current (kA), 8/20 us
1	SPD AC Class II	10
2	SPD AC Class II	20
3	SPD AC Class II	30
4	SPD AC Class II	50
5	SPD DC Class II	10
6	SPD DC Class II	20
7	SPD DC Class II	30
8	SPD DC Class II	40

Figure 2.6: SPD Test Table

events do not take place one after the other while an SPD is in operation. What happens is that an SPD comes across many lightning impulse events at various amplitudes throughout its whole period of operation. Thus, the program analyzes the amount of remaining time left for each SPD to last based on the amount of the total surge resistance used up by each impulse. Take the case of the AC class II SPD tested and found to withstand 120 strikes at 10kA before failure, which means each impulse at 10KA consumes 1/120 of the total operating time [13].

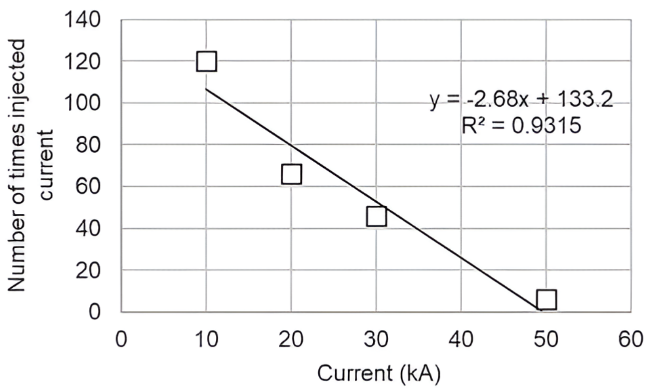

Figure 2.7: Injected current results of SPD AC Class II

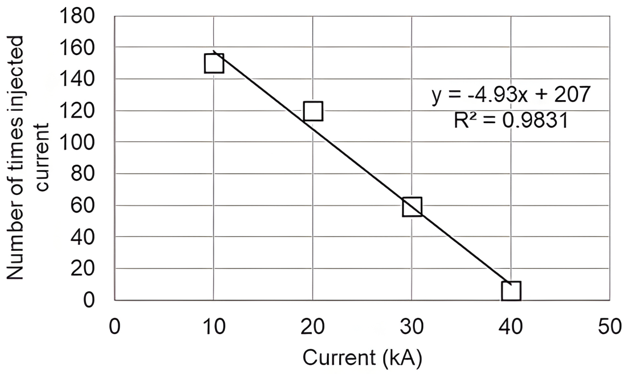

Figure 2.8: Injected current results of SPD DC Class II

2.8 Monitoring Deficiencies in SPDs

According to several recent studies, passive protection devices such as fuses, micro circuit breakers, and surge protectors are used extensively in conventional surge protection systems to help deflect or consume excess voltage and shut off the circuit in the event of an abnormal current flow. These techniques lack real-time system monitoring capabilities and are mainly reactive in nature [14]. Conventional surge protection systems do not provide any information regarding the device's operating state, level of degradation, or even its fault record, according to Davis et al. Therefore, such typical devices are completely ineffective in electrical systems that require continuous monitoring and instantaneous reaction capacity. The truth is that protection devices may gradually deteriorate but appear to be functioning until a catastrophic crisis occurs if there is no means to monitor and assess their state [15].

Manual inspection has always considered a supplemental method of monitoring. It entails routinely inspecting electrical components and cables for obvious indications of damage caused by surges. However, this approach is intrinsically limited by its inability to identify surge events in real time. By the time an inspection finds evidence of damage, the protective components may have already lost their effectiveness, leaving the connected equipment exposed to unreduced risk. The study also highlighted the significant time and resource costs associated with manual fault diagnosis in industrial settings, which requires maintenance teams to physically inspect the system in order to identify fault sources [16]. This process is labor-intensive and frequently yields inconclusive results when faults occur infrequently. Together, these documented limitations make a compelling case for automated continuous real-time monitoring systems that can identify anomalous electrical conditions as they arise and notify operators of them without human assistance.

2.9 IoT-Enabled Surge Monitoring Systems

Recent studies on the application of IoT for monitoring and detecting electricity surges have been conducted. According to Tiwari and Kashyap [17], IoT-based devices can be applied in monitoring and detecting power surges in the form of wireless transmission of electricity information to a monitoring unit. From this study, it becomes evident that it is possible to monitor electricity through IoT, hence enabling one to respond appropriately whenever there is an electricity problem since passive approaches may not achieve this. Another study regarding the application of IoT for monitoring electricity parameters showed that microcontrollers in embedded systems capable of wireless transmission can be used in collecting, processing, and delivering voltage and current data [18].

From this, Yunus et al. created a power surge warning system utilizing the ESP32 WiFi microcontroller, ZMPT101B voltage sensor, and SCT013 current sensor to detect any power surges occurring in the electrical circuits through constant surveillance and immediately alert about them via the Telegram mobile application. Data collected from this process was uploaded to the cloud server of Favoriot. This model by the authors rightly represents the IoT-based monitoring system discussed in previous researches [19].

2.10 Multi-Parameter Sensing

It should be stated that electrical protection systems were designed to utilize more than one sensor all along. This statement can be confirmed based on the utilization of two sensors within the design of the proposed protection system: voltage and current sensors. The former one is called ZMPT101B and the latter one is an SCT013 current transformer [18]. Authors underline the significance of the voltage sensor in preventing false alarms. In other words, without reference voltage, the absence of the current may lead to a wrong conclusion about a fault since there will be no loads functioning.

Many experiments have been conducted. Their results show that the ZMPT101B voltage sensor module, which uses a small voltage transformer and an op amp conditioning circuit, is a reliable way to measure voltage with embedded microcontrollers. This method is also suitable for voltage measurement because it can produce an isolated and scaled sinusoidal output voltage signal [20].

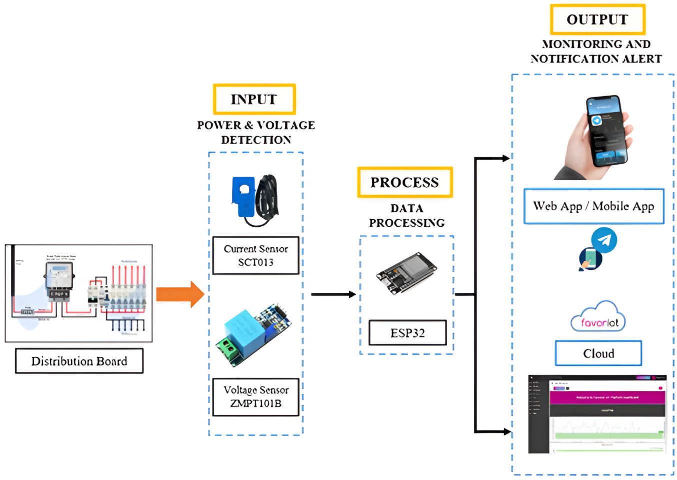

Figure 2.9: Block Diagram of the Power Surge Detection System

2.11 Overcurrent Detection Mechanisms

The experimental study conducted yielded significant quantitative data that can be helpful in understanding the influence of overcurrent intensity on the operating time of Miniature Circuit Breakers (MCB). In their work, they examined three different combinations of loads in form of domestic appliances, including a hair dryer and an air fryer, an air fryer and a kettle, and lastly a hair dryer and a kettle. Each pair of the load was analyzed in conjunction with a miniature circuit breaker with a maximum 6A current. As per the thermal-magnetic theory of circuit breakers, there was an evident inverse relationship between the level of overcurrent and the operating time.

For example, the circuit breaker was triggered in 23 seconds, whereas the load was 10.49A, which was equal to 175 percent of the MCB rated load. Moreover, in other scenarios, it took 6 seconds for the MCB to trip, when the load on the circuit was 13.47A and 15.34A (224 percent and 256 percent of the rated load). This particular performance of the circuit breaker could have been due to the purposeful time delay introduced in its mechanism to help it bear overloads for a short while without tripping the circuit. It was done to avoid unnecessary trips that may occur because of the motor starting inrush current and other overcurrent conditions. Nonetheless, for overcurrent exposure for up to 23 seconds, it was quite risky.

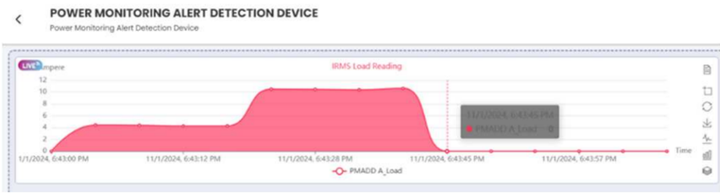

Figure 2.10: The MCB limit of 6A takes 23 seconds to trip with the load of 10.49A

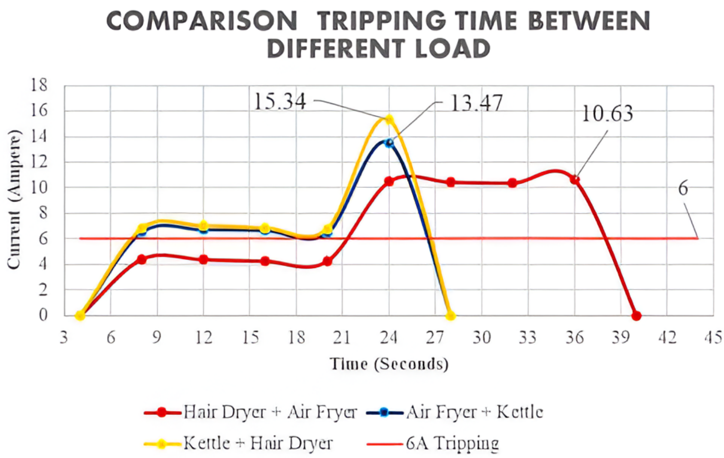

Figure 2.11: The comparison of tripping time for different loads

This experimental outcome not only has practical implications but also is relevant to the logic of the present project. Indeed, the disadvantage that exists in using mechanical devices to protect an electric circuit is clear to see in the case of a 23 seconds delay that occurred in operation of the MCB when there was a moderate overload. The smart way through which faults can be detected and relays switched in this project is the solution to this problem. Whenever there is an overcurrent during the cycle time, the relay will be turned off due to the STM32F106TA microcontroller.

2.12 Cloud-Based Data Logging and Predictive Maintenance

Electrical monitoring systems that utilize cloud-based data logging represent a significant development in the field of intelligent protection systems. By incorporating cloud-based data logging into a protection system, one can perform detailed analysis through detecting trends and predicting failures rather than just spotting a failure in the monitored system. Rather than depending on alarm limits, continuous data logging enables identification of issues which would otherwise remain undetected. Therefore, data logging makes an electrical monitoring system effective when it spots an issue.

The research carried out on IoT-enabled power monitoring [17, 18] has proven conclusively that when warnings are combined with data logging, the resultant power monitoring system becomes highly efficient compared to what it would be if either warning or logging was done on its own. Warnings allow operators to know about any defects happening in real time, and hence take measures that can help prevent them. With the help of data logging, operators are able to identify the factors that cause defects, frequency of anomalies, as well as increases in the amount of interference with time. Predictive maintenance, an innovative method involving continuous logging of data through cloud services, marks a shift from the traditional electrical protection system towards a proactive rather than reactive approach. Reactive maintenance is where action is taken after issues occur.

The continuous recording of data will show trends of consistent increase in currents, frequent drops in voltages at certain times, and increased assembly temperatures, hence making it easy for operators to discover and address potential flaws before turning into bigger problems. This has proven to be the strength of IoT connections in electrical engineering.

Chapter 3

Requirement Specifications

3.1 Existing System

In classic electrical systems, the surge protection is usually offered by simple elements such as fuses, miniature circuit breakers, and integrated surge protection modules. These devices are passive in nature and become active after the electrical stress surpasses the pre-set physical limit. Even though these devices offer good protection against surges, they lack intelligence and fail to measure the parameters of the system and make decisions accordingly. Classic surge protection elements use metal oxide varistors and gas discharge tubes to clamp and divert the surges. However, these elements cannot provide information about the condition of the element, number of surges that the device has handled so far, and the rate of wear of the device over a period of time. As a result, the protective device becomes vulnerable after handling a few surges and fails in case of an intense surge.

Another limitation of current technology is the lack of coordinated sensing and control. Voltage and current are not continuously measured at the protection level, and temperature rise within protection assemblies is not monitored. As a result, unusual patterns like intermittent minor surges, overload heating, or voltage instability may be overlooked. Traditional protection solutions also do not allow for automated load switching based on smart logic. Instead, protection relies on programmed hardware reactions, which may not be the best response to specific issues. User awareness is also limited in traditional systems. There is no display, status, or warning function to alert operators about abnormal electrical conditions. Consequently, maintenance becomes reactive rather than preventive.

3.2 Proposed System

In order to address shortcomings in current surge protection mechanisms, a solution through the use of the Intelligent Surge Protection Device will be employed, whereby a combination of surge protection hardware and sensing, computing, and control is used. This particular solution has been tailored towards the use with three-phase electricity supply sources and integrates several layers of safety and monitoring in one package. In the first step, surge protection hardware is applied on the phase line in order to manage high energy transient surges.

A control module that utilizes microcontroller technology analyzes the information and determines the status of the system instantly. Rather than waiting for thresholds to be reached before taking any action, the system utilizes the measured information to perform actions in anticipation of an abnormality being detected. The microcontroller evaluates whether the operational conditions are safe, warning, or faulty through pre-programmed threshold logic and fault detection techniques. The microcontroller then triggers or turns off the solid-state relay depending on the operational conditions. Consequently, this allows for rapid and reliable isolation of the load without stressing any components mechanically.

3.3 Requirement Specifications

The requirements specification outlines the proposed system's intended behavior, capabilities, and limits. The criteria establish the foundation for the creation of both hardware and software. The requirements are divided into functional and non-functional requirements.

- **Functional Requirements**
  - The power supply of the system will consist of three phases having neutral and grounded references. Each phase line will be coupled with a surge protector that can safely transfer the surge of energy to the ground.
  - The phase voltages of the power supply will be monitored continuously through the voltage sensing circuits. Moreover, the load current will be sensed through the current sensing circuits by measuring the load current in each phase. Similarly, the temperature sensing circuitry will sense the temperature at key points of the protective assembly.
  - The sensing circuit outputs will be coupled with the microcontroller through the analog inputs. The microcontroller will acquire these inputs at an adequate sampling rate. The software will process these inputs and convert them into engineering units and then compare them with threshold values.
  - These conditions include overvoltage, under-voltage, over current, surge, and excessive temperature. When any fault condition occurs, the microcontroller will generate a control signal that triggers the solid state relay. The solid state relay will switch the load off when a fault is present. However, when the system parameters are within acceptable values for some time, the load is switched on automatically.
  - The measurement readings of the electrical parameters and other signals indicating the status of the system should be displayed via the LCD screen. The system will use several LEDs to indicate the status of the system. In case of faults or emergencies,

the system will sound an alarm.

- **Non-Functional Requirements**
  - It should satisfy the non-functional requirements concerning performance, safety, reliability, and maintainability. The reaction time of the protective unit should be sufficient to prevent exposure of connected devices to unsafe voltage values. For overvoltage detection and prevention purposes, time delays during measuring and processing of data should be acceptable.
  - There should be a separation of the high-voltage circuit from the low-voltage control circuit. The appropriate protective measures like optical isolation, proper grounding, and the use of protective suppression elements should be considered where required. The system should operate in a reliable way under constant supervision mode, without numerous false operations.
  - The measurements performed by the system should have an acceptable tolerance value to make reliable decisions. The hardware construction should imply using modular approaches in designing a system so that its separate units would be independently tested and replaced.
  - It should be economical and use readily available equipment. The operator interface should be simple and clear, allowing system performance to be determined without any further training. Simulation should be included to test the performance of the system before committing to hardware.

3.4 System Constraints

There are certain factors that affect the design and execution of this system. The ADC input voltage of the microcontroller is the limiting factor that will determine the maximum output voltage of the sensor, which will need to be scaled. The limitations associated with the relay and SSR will set the maximum load that can be supported.

There is a need to provide for a reliable low voltage output despite the disturbances in the input power supply system. There are limitations associated with the PCB layout. Finally, there is the factor of time that will be required for the academic project.

3.5 Use Cases

- **Normal Operation**

  During normal operation, the measurement of voltages and currents of the three phases is performed by the system itself with the help of its sensors. The microcontroller processes the data and ensures that all parameters are at the required level. At the same time, the load remains connected through the solid state relay, while the green indicator LED and measurements displayed on the screen operate normally.

- **Surge or Fault Condition**

  The very first step that the SPDs make during the anomalous increase in the level of voltage is the dissipation of excess electrical energy in the ground. While the sensor circuit detects such abnormality, it informs the microcontroller about it. The latter identifies the problem and, consequently, switches off the relay, thus disconnecting the load from the power supply system.

- **System Recovery**

  When it comes to the return of operating parameters to their normal values and maintenance of such condition for the predetermined period of time, one may consider that everything went well. As a result, the microcontroller verifies it and reverts the relay operation by turning it ON.

- **User Monitoring**

  The system can be checked by the user anytime using the LCD and indicator lights. The values of voltage and current, along with other status messages, will be visible on the screen. The alarm signal alerts users about any problems without looking at the display.

Chapter 4

System Design

This chapter deals with the design specifications for the three-phase surge protection system, which includes both the hardware and software design aspects of the system. The designing of the system involves the integration of numerous components such as Surge protection systems, sensors, STM32 microcontroller, and the isolation of the load from the input power source. The components of the system, the interaction between components, and the functionality of the system will be described in this chapter.

4.1 System Architecture

The ISPD is basically an electrical safety barrier which shields the appliances from unexpected power surges which are experienced during lightning or when there is a power failure. Electrical current is passed to the electrical appliances through the power supply which has three power cables known as phases and the standard neutral and ground lines which are also present in all other factories. In case of power surge, the additional power supplied into the devices goes to the ground wire thereby securing the devices.

This particular system is really easy to imagine since it comprises of some basic components working at once; the component which provides energy, i.e., the power source which draws power directly from the electricity line of the building, the protector which absorbs the voltage surge, the sensor that keeps checking the level of current and voltage, the computer which regulates all activities and also takes decisions instantaneously, and finally, the switch which cuts off the electrical supply. Moreover, there is an indicator that displays the present status and also indicates the change by lighting up differently colored lamps. The system operates in an auto-

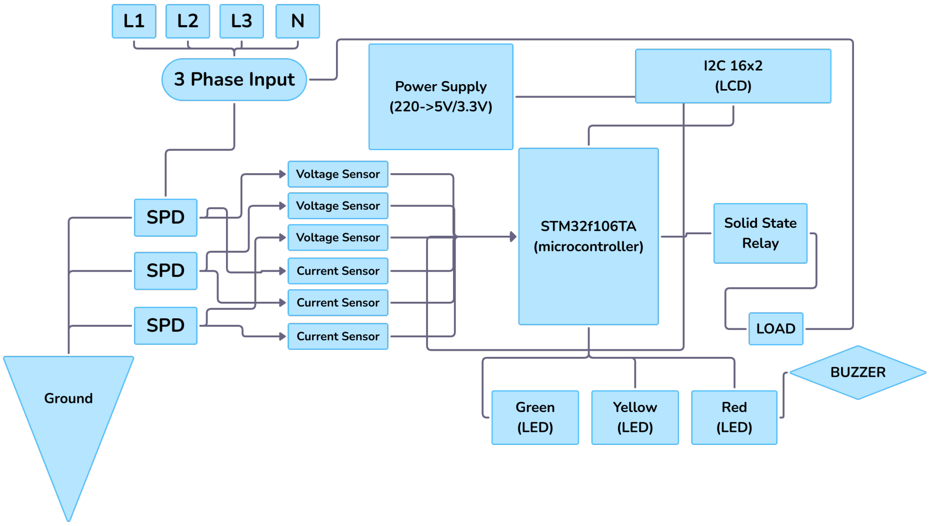

Figure 4.1: System Architecture Diagram

matic fashion through pre-established stages. To begin with, it uses power from the main source. In case of a power surge, all the protective devices take in all kinds of harmful energy for the system. At the same time, the sensors also monitor the environment in which power is being delivered. The sensors detect the conditions such as voltage and current and notify us regarding any problem that could arise in the future.

As long as there is no abnormality in these parameters, the control unit allows power delivery to all other systems that require it (machines, lights, etc.). However, if any kind of abnormality is detected by the center in terms of increased current, voltage, or overheating, the switch is ordered to block the power flow. As soon as all the parameters become normal after a period of time, the power delivery resumes. These intelligent devices not only help in saving our money but keep the system operating well.

4.2 Design Constraints

Constraints that surrounded the design and implementation of the Intelligent Surge Protection Device (SPD) had to be taken into account in the decision-making process, since it was imperative to understand them during the design of the device.

Several constraints were set by technical considerations in terms of the system's implementation:

- **Microcontroller ADC Input Range**

  The next limitation was related to the input range of the microcontroller ADC. Due to the aforementioned factor, the highest output value of the sensors had to be set so that it does not surpass the ADC input range and thus ensure that the signals can be measured properly.

- **Relay and Solid-State Relay (SSR) Specifications**

  In the selection process of a relay, there are a number of criteria considered. The criteria involved include the maximum load current and voltage that can be sustained based on the 2kVA power rating of the JMICC Power Distribution Box. The maximum load current of the 2kVA distribution box with its 220V power voltage rating would be around 9.09A per phase. In addition to ensuring safety considerations, the relay had to be able to sustain the above-mentioned load current continuously.

- **Power Supply Architecture**

  An additional requirement to provide reliable power for the low voltage rails feeding the logic circuit in case of disturbances in the input power constituted one more crucial factor.

- **PCB Layout Limitations**

  There were challenges related to the insulation and noise in the design of the PCB. It is the positioning of the parts on the PCB that will influence the amount of EMI existing between the high voltage and low voltage circuits.

- **Sensor Availability, Cost, and Compatibility**

  The availability of the voltage and current sensors in the market, their affordability, and their compatibility with the selected micro-controller and control system were some of the considerations that made them ideal choices.

- **Time Limitations Due to the Academic Nature of the Project**

  As a result of the nature of the project, which involved an academic project, time constraints affected the choice of components utilized in system development. Several factors had to be taken into consideration to ensure that the project was completed within the allocated time.

- **Maintainability and User-Friendly interface**

  However, although it does not directly affect the functionalities of the system, the need for maintainability and the need for ease of use in the graphical interface should be kept in mind when designing the system.

- **Component Reliability and System Hardware Assumptions**

  The following key assumptions were made for the success of the development process during the design stage. Firstly, it was assumed that under the given operational conditions, the COTS parts selected would behave in the way they are supposed to according to their specifications. It is important to note that the functionality of the chosen protection components will have a huge influence on the effectiveness of the planned SPD. Another key assumption that was made was that the chosen microcontroller would have sufficient capacity to process signals and commands on the spot without any delays.

- **Validation Environment and Testing Assumptions**

  Among the many assumptions made during the design process is that the simulated transient voltages set will be reliable enough to provide valuable information about the system's ability to protect against damage. The underlying assumption here is that the conditions simulated will give a true reflection of real-life scenarios. For instance, the voltage levels generated will accurately mimic the characteristics of real-life voltage spikes, such as their amplitude, waveforms, and time spans.

4.3 Design Methodology

To deal with the problems that come with time embedded systems the Intelligent Surge Protection Device was made and improved. This was done by using an approach that combines engineering methods with object-oriented techniques. The Intelligent Surge Protection Device was designed to do things like measure voltage in real time detect faults quickly separate loads intelligently and respond fast. To understand what the Intelligent Surge Protection Device is supposed to do the projects goals and requirements were carefully looked at. This included all the things the Intelligent Surge Protection Device needs to do and the things it should not do which are talked about in chapter 3. A simple diagram of the Intelligent Surge Protection Device system was made first. This diagram showed the parts of the Intelligent Surge Protection Device like where the power comes in the surge protection devices, the measuring units, the controller and the outputs. Then these main parts were broken down into parts in a more detailed design process. This also involved choosing the hardware like metal oxide varistors, gas discharge tubes and transient voltage suppressors and making complex software algorithms for the Intelligent Surge Protection Device. One of the things about the design approach for the Intelligent Surge Protection Device was that it was modular. This meant making parts for switching, control and measurement. This was important, for dealing with things. It allowed each part to be tested on its own made it easier to find and fix problems and made sure that it would be easy to make improvements or replace parts of the Intelligent Surge Protection Device later without affecting the system.

The connections between the parts of the system were set up carefully to make sure that information gets shared easily. When it comes to the software part, the microcontroller control module, the ideas of object-oriented programming were used in a good way. The software helped to keep data and methods organized allowed us to focus on the parts of the objects and made it possible to reuse code in the future. Safety was a priority because the goal is to make sure the equipment and the people working with the SPDs are safe. We also thought about how to save money when choosing the parts and designing the system. This way the system is both good, at what it does. Does not cost too much. The microcontroller control module and the software work together to make this happen. The SPDs need to be safe. The system needs to be cost-effective.

4.4 High Level Design

The current chapter provides a discussion about the different views of the Intelligent Surge Protection Device, providing additional information concerning its design and working principle. Nevertheless, several points of view had to be modified to match the current hardware system instead of being applied to a software system.

1. **Conceptual or Logical:** With the help of discussing the various functional elements of the system and their relationships, the conceptual view gives a demonstration of the logical nature of the Intelligent Surge Protection Device design. The conceptual view may be regarded as similar to a component diagram, with all components having a range of tasks and communication between them being provided by means of interfaces. All of the six components that compose the system belong to certain stages of the entire process of protection and monitoring.

2. **Power Input and Protection:** This is the input stage of the system. This stage takes input from the building's electrical distribution grid's N connection and earth ground connections together with input AC three phases (L1, L2, L3). Its logical function is to ensure that a continuous supply is fed to all downstream circuitry. In this case, the stage contains no information; instead, it denotes the point at which the supply enters the system. Its components include MOVs and GDTs on each phase of power line. Its function is to dissipate and clamp surge energy before reaching the rest of the circuitry downstream.

3. **Surge Clamping:** This is the major component responsible for pro-

tecting the device. This is electrically connected to the Power Input Component and logically connected in parallel in the power lines across all three phases. Its purpose is to prevent transient voltages from causing damage before it reaches the load or detected by the sensor. The internal sub-modules of this module are the GDT, whose function is to dump surge energy to earth ground, and MOV, which clamps the voltage transients. Its output is a surge clamped power supply to be sent to the load and sensors switching components.

4. **Sensing and Signal Conditioning:** Functionality of the component is monitoring the parameters of the system's electrical and thermal characteristics continuously. The component provides analog signals that are directly dependent on the status of the system. This component consists of three sensory sub-components, which are:

    - **Voltage Sensor**

      A ZMPT101B voltage sensing module is applied in all three phases. ZMPT101B is a small AC voltage transformer designed for measuring high accuracy and linearity AC voltage measurements, with isolation of a high-voltage side (connected to a source of power) and a low voltage side (output signal). Output signal of the module is directly proportional to the voltage of phase, but it is converted to the range of 0 to 3.3 V, which could be processed by ADC inputs of the STM32F106TA microcontroller.

- **Current Sensor**

  For the Current Sensing, ACS712 Hall Effect Sensor is used for all three phases. ACS712 works on principles of detection of magnetic fields, created by current flowing in an inner conductor and converting it into the corresponding output analog voltage signal around VCC/2 with sensitivity of 100 mV/A for 20A version. Therefore, power and signal circuits of the ACS712 are completely isolated. Each ACS712 chip is mounted on the phase conductors and provides three sensing channels.

5. **Processing and Control:** This is the brain of the entire system running on the STM32F106TA microcontroller IC. STM32F106TA is a sturdy microcontroller design based on the ARM Cortex-M platform. It provides sufficient processing capability, peripherals, and ADC resolution required for a surge protection system and real-time monitoring. It processes all the analog input signals received from the sensing component through its ADCs which keep sampling voltage and current measurements of nine inputs in each phase. Next, the microcontroller converts these measured analog values to digital values by scaling them according to certain predefined functions, converting them from ADC counts to units (V, A), and comparing them against safety parameters that are programmed within the firmware of the microcontroller. The firmware within the STM32F106TA functions as a state machine with three main modes of operation. The first mode is Normal Operation where the parameters within the circuit are normal, and the load is powered. The second is Fault Condition where the threshold limit is violated, leading to the disconnection of the load. The third is Recovery where the parameters return back

to their normal limits after the time limit, and the load is powered again. The STM32F106TA is the only device within this circuit that has control outputs while all other devices offer input or output measures to it.

6. **Load Switching:** It gets the ON or OFF instruction signal from the Processing and Control Component block and either connects or disconnects the load with the source based on whether the source is powered. This component consists of Solid State Relays (SSR), which ensure ultra-fast switching operation without any noise or wear. It only has one kind of logic: since it is basically an electric switch, its function is ON or OFF; it passes power through to the load if ON or shuts off power if OFF to protect the load against faults in the source.

7. **User Interface:** This component is the only source of information in human-understandable form about the current status of the system. This unit receives the processed and measured state from the Processing and Control Component block and makes it available to the user via audio and visual output components. This element consists of three components: the 16×2 I2C LCD Display Block, which shows voltages, currents, and other message data; the LED Indicator Array Block, which indicates the performance status with green, yellow, and red light emitting diodes; and the Audible Buzzer Block, which informs the user about system problems regardless of the presence or visibility of the display.

4.5 Low Level Design

This chapter contains the low-level design details for all the hardware and firmware modules that have a vital role to play in the design and development of the Intelligent Surge Protection Device. The system will be decomposed into simple basic components, which will be analyzed thoroughly, discussing its internal components, inputs/outputs, operating conditions, and interaction with other modules. These modules include:

- **Surge Protection**

  The Surge Protection Module: This is the first layer in the hardware structure of the system, which is of utmost importance. Three instances of this module will exist in parallel, one on each phase L1, L2, and L3 along with the earth ground line. The module is made up of three mechanisms acting in phased clamping mechanism. The first clamp in this design is a Metal Oxide Varistor (MOV). This clamp has been decided on the basis of the MOV voltage rating appropriate for 220V RMS AC power input with peak voltage of around 311V. When the voltage becomes equal to the clamping value, the MOV becomes active to act as a clamping device whereby the transient gets taken away through the ground line and protects the other electronic devices from higher voltages. In contrast, the gas discharge tube (GDT) is in parallel to the MOV but series to the ground side of the MOV. With this structure, it can endure high amplitude spikes that arise as a result of nearby lightning strikes. The sparkover DC voltage of the GDT surpasses the line voltage.

- **Power Supply**

  The Power Supply Module is responsible for regulating the low voltage DC current supplied to the system control components such as the STM32F106TA Microcontroller, ZMPT101B and ACS712 sensor modules, I2C LCD screen, LEDs, buzzer and SSR control inputs. As all of the above mentioned components receive their power from the 220V AC power line, a two-stage power conversion strategy was employed. The first stage consists of reducing the 220V AC power line voltage through the use of a custom made step down transformer before rectification. Full-wave bridge rectification is carried out on the secondary winding AC current and the current is smoothed using a bulk capacitor to create a steady DC voltage. The second stage involves use of the LM7805 linear voltage regulator chip for transforming the rectified DC voltage into a regulated 5V DC voltage output. Decoupling capacitors are placed on both the input and output terminals of the LM7805 voltage regulator in order to minimize any remaining ripple voltage. In the case of the STM32F106TA microcontroller, that works on 3.3V, the AMS1117 linear low dropout voltage regulator converts the 5V DC voltage line into 3.3V DC.

- **Voltage Sensing**

  The Voltage Sensing Module was designed such that there is one ZMPT101B voltage sensing module per phase for the phases L1, L2, and L3, giving three different sensing modules altogether. The ZMPT101B is a very accurate miniaturized current transformer having an operational amplifier circuit which can produce small AC voltage signals corresponding to the AC mains voltage being sensed. In the design, the transformer primary winding is used in series with the high burden resistor with the phase lines, while the output of the transformer is the AC signal voltage which is further amplified using the operational amplifier circuit to produce a zero-offset signal corresponding to the mid-point of the STM32F106TA ADC voltage range of 0 to 3.3V. The output voltage signal from each ZMPT101B sensor goes to a specific ADC channel of the STM32F106TA. The software application acquires data fast enough to measure the 50Hz waveform, performs necessary digital calculation to estimate RMS voltage and finally calculates the actual phase voltage in volts using a calibration factor.

- **Current Sensing**

  Each current detecting module comprises one ACS712 current sensor, meaning that the number of current detecting channels is three. The ACS712 current sensor consists of a complete Hall effect-based linear current sensor with three different models, which include 5A, 20A, and 30A. However, considering that this device operates according to the operating principles of 2kVA JMICC power distribution box, the choice made is the 20A model. In other words, with a supply voltage of 220V, the maximum load current for the JMICC distribution box is 9.09A for each phase. As such, the choice made is not the 5A model since the maximum load current is higher than the rated maximum. Nonetheless, the sensitivity of the 30A model is relatively lower at 66mV/A, making its readings less accurate compared to the 20A. Since the sensitivity of the 20A model is at 100mV/A, it offers greater accuracy of the current. Additionally, because the input range for the ADC in the STM32F106TA is 0 to 3.3V, the output signal from ACS712, whose range is 5V, is reduced to below the range using level shift network.

- **STM32F106TA Microcontroller**

  The main components of the system include the STM32F106TA microcontroller that uses STM32 CubeIDE, an integrated development environment for the setting up of its peripheral parts and that uses tools such as STM32CubeMX, HAL, and a GCC compiler. The ADC setup includes activating the scanning mode, which involves scanning all the input channels involved in measuring voltage using the ZMPT101B sensors, including all three voltage reading channels, as well as measuring current using the ACS712 sensors, including three current reading channels. The DMA feature included in the ADC helps to provide constant data transfer from converters to a reserved memory space within an SRAM block. The relay management component helps in managing the output of the SSR GPIO and managing state transitions between Normal, Fault, and Recovery states, as well as the hold-off time before the load reconnection. The display driver uses I2C communication protocol for controlling the LCD display and preparing information data for presentation.

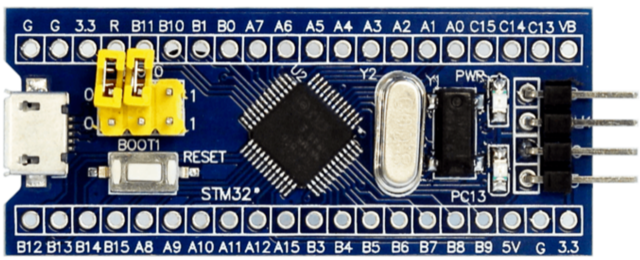

Figure 4.2: STM32 Microcontroller

- **Load Switching**

  The Load Switching Module comprises the use of a Solid-State Relay

(SSR), which is then connected in series with the load's power supply line. An SSR whose specifications surpass the maximum attainable load is selected. The SSR's control end is connected to the output of the STM32F106TA, which runs at 3.3 volts. In order to avoid excessive current, a current limiting resistor is placed in series with the GPIO pin of the STM32F106TA, which is connected to the SSR's input end. Additionally, the SSR is programmed such that in the absence of an instruction signal, it switches off. As a result, protection is guaranteed even if unexpected failure occurs within the software or hardware. In order to avoid switching transients resulting from disconnection of the load, the RC Snubber Circuit is installed on the output contacts of the SSR.

- **User Interface**

  The User Interface Module gets all feedback outputs of the system. The I2C 16×2 LCD display is interfaced to the STM32F106TA microcontroller through the I2C bus using SDA and SCL lines with the help of pull-up resistors at 3.3V supply voltage. The refresh rate of the display is 2-5Hz. The software module of the display driver displays the current status of the system, load current value, and instantaneous phase voltage value on two lines of the display. There are three LEDs such as green, yellow, and red in the LED Module that is interfaced with the STM32F106TA microcontroller through the GPIO line with the help of current-limiting resistors, and this ensures the safe delivery of LED operating current from 3.3V output. Green LED remains ON throughout the operation, while Yellow LED will glow under warning conditions and the reading approaches fault values, whereas Red LED will glow under Fault Conditions. The

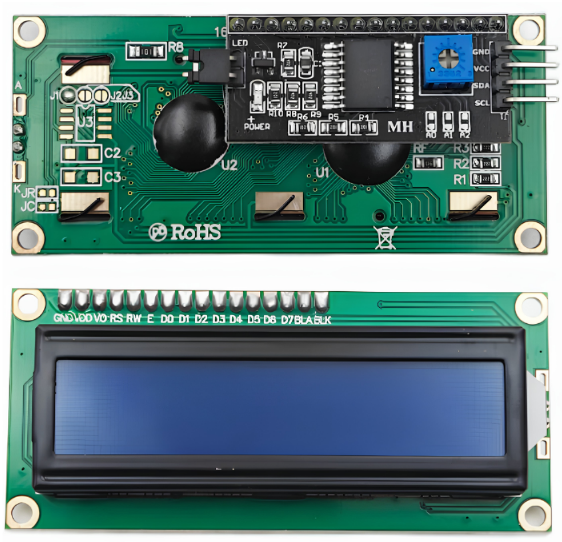

Figure 4.3: 16x2 I2C Lcd Display

buzzer is interfaced with the output GPIO through an NPN Transistor Switch because GPIO does not possess enough current drive capability. The development of this buzzer is done depending upon the tone frequency of the GPIO output pin.

4.6 External Interfaces

This part will provide an elaborated description of the electronic interface between the Intelligent Surge Protection Device and other external systems/subsystems. The STM32F106TA and its corresponding software make up the core system, taking into account the advancement of the system. Any system that interacts with the core system through any form of signal or energy can be referred to as the external interface of the core system. The external sub-systems that interact with the core sub-system include the three-phase power supply sub-system, ZMPT101B based voltage sensing sub-system, current sensing sub-system (ACS712), load switching sub-system, and user interface sub-system.

- **Three-Phase Power Supply**

  The three-phase power supply network represents the system's principal interface to the outside world. At this point in the system's architectural layout, all electrical power entering the system enters via this interface, while at the same time, the transients that the system will need to detect and reduce originate here. Three phase power inputs (L1, L2, L3) along with one neutral line (N) input and one earth ground (GND) input enable communication with the power supply network. The earth ground also provides the path for clamping for the MOVs and GDTs in the surge protection circuits. This is the source of the voltage supply needed to scale-down the 220V AC power input to the appropriate levels (5V DC and 3.3V DC) for the transformer based custom designed power supply. The interface described above only accepts power into the system being developed – it has no function for returning signals back to the power supply network.

- **ZMPT101B Voltage Sensor**

  Before their connection with the STM32F106TA microcontroller, the three ZMPT101B voltage sensors are the means of interfacing the voltages in the high-voltage phase lines. In accordance with the proposed design, each ZMPT101B is an external transducer which gets a high-voltage AC input from a certain phase line and delivers the processed output analog signals to the microcontroller. The interaction between the ZMPT101B and the microcontroller occurs through one analog voltage input biased at 0 and 3.3V. In the given case, three ZMPT101B units are connected to three separate ADC input channels of the STM32F106TA unit using three analog signal lines. The power supply unit of the measuring system provides the required 5V DC power line for the ZMPT101B units. There are no control lines connecting the STM32F106TA controller and the ZMPT101B sensors; the interface is one-directional in that only the sensor data is fed into the controller.

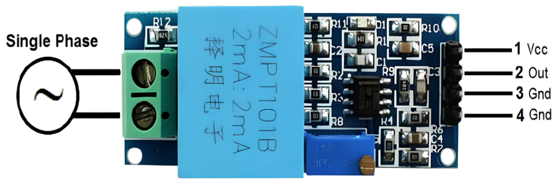

Figure 4.4: ZMPT101B Voltage Sensor

- **ACS712 Current Sensor**

This system utilizes three ACS712 current sensors that monitor the current that is drawn from the STM32F106TA microcontroller towards the phase load wires. In essence, the current sensors work by measuring the magnetic flux within the current using an electromotive force, which then gives out an analog voltage that can be read by the microcontroller. The voltage reading of the three current sensors is at half the supply voltage level and is directly proportional to the current being sensed. To convert the voltage output from the current sensors to levels that can be read by the ADC of the microcontroller, voltage scaling circuitry was used, which converts the output of the current sensor from 5V to 3.3V. This means that there were three interface wires running on 5V DC power source. This is a single-directional channel of communication. There is a connection between the ACS712 sensors and the microcontroller via a straight-

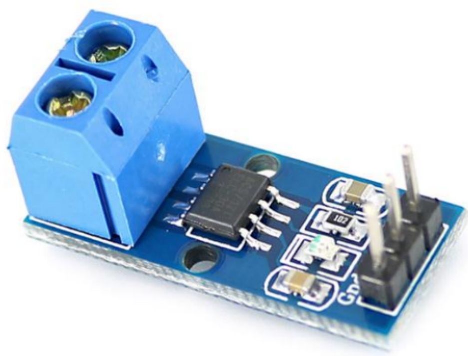

Figure 4.5: ACS712 Current Sensor

forward voltage line that sends the analog voltage signal. Afterward, the signal undergoes processing inside the microcontroller to measure the amount of current passing through the conductor. The employment of three different sensors and ADC channels makes it possible to have accurate measurement of the current in all phases, ensuring proper management of the load. Through a voltage scaling circuit, it will be possible to regulate the output voltage from the sensors such that the signal is always within the required range for the ADC of the microcontroller, making sure that there is no risk of malfunctioning or damage. The 5V DC power supply for the sensors ensures that there is consistency in energy distribution throughout the system.

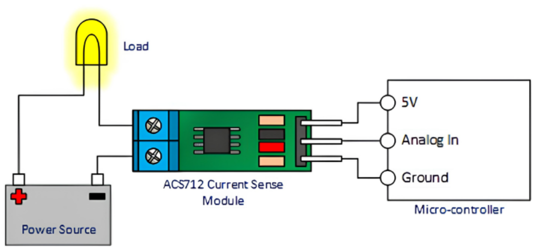

Figure 4.6: Circuit Layout of ACS712

- **Load Switching**

  The load switching module that provides the load with the capacity of being switched ON and OFF can be interfaced to the STM32F106TA microcontroller through the load switching interface. According to the nature of the system development process, the interface is considered as an interface for control outputs, which directs the function of load switching circuitry. The base terminal of an NPN transistor is driven through one of the GPIO output pins of the STM32F106TA microcontroller with the help of a current limiting resistor. Whether current flows into the relay coil or not depends on whether the level of logic input applied to the GPIO pin of the microcontroller is high or low. As soon as there is a malfunction detected, the GPIO level turns out to be low, the transistor turns off, and hence, no more current flows into the relay coil, thus, leading to the opening of relay contact. To overcome the flyback effect that arises due to relay coil, a flyback diode has been attached in reverse order across the relay coil. Since it is a one-sided interface, signals can only be transferred from STM32F106TA to load switching portion.

- **User Interface**

  The 16x2 I2C LCD Display, LED Indication Module, and buzzer are the output devices that act as a connection between the user and the developing system. The I2C communication interface bus is employed in interfacing the 16x2 LCD display with the STM32F106TA CPU using two signal lines; these lines are Serial Data line (SDA) and Serial Clock line (SCL). With regard to the 3.3 volt operation, pull-up resistors are applied in both lines for the I2C interface. The LCD is the slave device while the STM32F106TA is the I2C master interface.

The phase voltage readings, load current readings, and the system status messages are displayed by the STM32F106TA using the I2C interface. The usual I2C interface frequency is 100kHz. The three LEDs, the green, yellow, and red LEDs, are interfaced to the GPIO outputs of the STM32F106TA using three individual current limiting resistors. Each LED has a GPIO pin that provides the necessary current for powering and lighting it up at its correct brightness level. The Normal operation signal status indicator uses the green LED interface, the warning signal status indicator uses the yellow LED interface, while the fault signal status indicator uses the red LED interface. The three LED interfaces are basically output interfaces. Transistor switch connections will be made to this section from the GPIO output pin on the STM32F106TA. An additional resistor is added here to ensure the correct current limiting for this interface from the transistor's base and the GPIO output pin. Since the GPIO output pin does not have enough current sourcing capability, the transistor should provide current gain for the buzzer driving. When the firmware operates the buzzer during malfunctions, the transistor saturates and closes the circuit for the buzzer to generate sounds.

Chapter 5

System Implementation

The process through which the design has been physically created is known as the implementation phase. In this case, the hardware circuit has been physically built, firmware for the STM32F106TA microcontroller was written using STM32 CubeIDE, and other components have been assembled in one single protection device. In this chapter, the different components used in the physical creation of the intelligent protection device, their roles, how they interact with each other, the technologies, and the algorithms used will be discussed.

5.1 System Architecture

As explained in chapter four, the architecture presented refers to the physical design of the Intelligent Surge Protection Device. Six different hardware subsystems form the architecture, and they all interact with each other through specific lines and busses. The STM32F106TA microcontroller that acts as the CPU is the main part of the architecture. Being a closed-loop system, the entire architecture keeps on monitoring electrical information through the hardware systems and analyzing it using the fault detection algorithm.

- **Three-Phase Power Input and Surge Clamping Subsystem**

  Power input in the developed system belongs to the three-phase power input subsystem. For making the connection between the circuit and the AC power supplied through the 2kVA JMICC Power Distribution Box at 220V, three-phase lines L1, L2, and L3, neutral, and earth ground lines are used. Current carrying elements are selected on the basis of 9.09A of current draw per phase at 220V, which is equivalent to the 2kVA capacity of the power distribution box. The surge clamping circuit is mounted in parallel with the phase and earth ground lines as soon as the system is connected with the input terminal in the phase lines. There is a protective circuit in each phase line, including the following parts:

- **Metal Oxide Varistor (MOV)**

  This is the main part of the clamp. It makes sure that the other parts are subjected to the minimum voltage by conducting any excess voltage beyond the clamp level to safely dissipate the spike current into the earth ground.

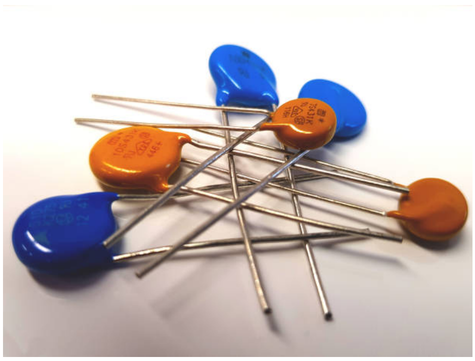

Figure 5.1: Metal Oxide Varistor

- **Gas Discharge Tube (GDT)**

  It acts as a channel that allows a surge to dissipate its energy into the earth in an easy manner. In order to avoid false triggering in ordinary circumstances, the spark-over voltage is set at a higher value than the peak line voltage.

The phase voltage is unchanged and all three units remain inactive under normal operating conditions. But according to the surge power level, all three units operate in succession during transient overvoltage conditions. The reason for doing so is to ensure that the surge power does not enter into either the load or the detection devices but

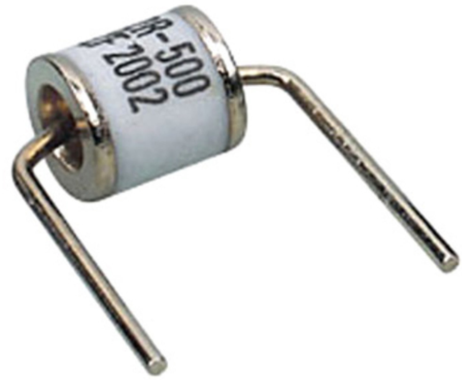

Figure 5.2: Gas Discharge Tube

goes through the earth ground line. There will be no communication between any two of these three units in this sub-system.

- **Power Supply Subsystem**

  The power supply subsystem is responsible for converting the incoming input mains voltage into the regulated voltages needed by each and every element of the system control part. In order to achieve that, the incoming 220V AC mains voltage is stepped down to a reduced AC voltage using the specially designed step-down transformer. Subsequently, the lower AC voltage is passed to the full wave rectifier and then a smoothing bulk capacitor in order to convert it into unregulated DC voltage. Also, the unregulated voltage feeds the linear voltage regulator LM7805 in order to generate regulated 5V DC voltage, which supplies power to all of the system control elements, including ZMPT101B modules, ACS712 modules, relay driver circuit, LED indicators, and buzzer. A secondary regulation process is done using the AMS1117-3.3 voltage regulator, which converts the 5V DC voltage into regulated 3.3V DC voltage to be supplied to the STM32F106TA microcontroller. Decoupling capacitors are used at the input and output sides of each and every regulator. However, other internal subsystems obtain their power from the power supply subsystem, without any interaction with the latter.

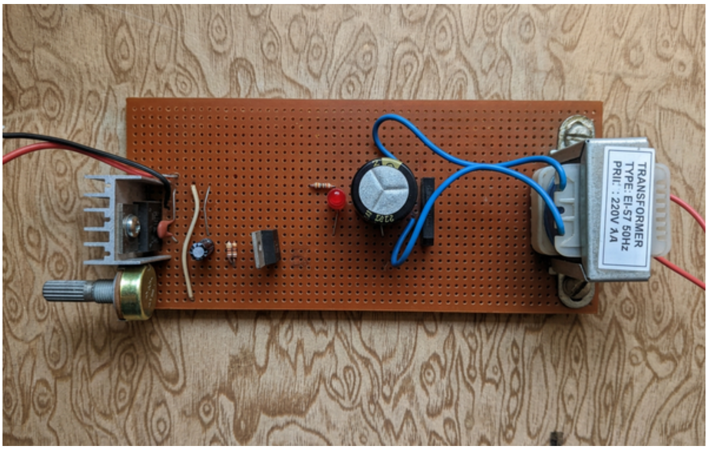

Figure 5.3: Power Supply Subsystem

- **Sensing Subsystem**

  The sensing subsystem transmits the physical variables of the three-phase system into electrical analog quantities in such a way that the STM32F106TA microcontroller can understand them. In this way, the measuring capability of the proposed system is demonstrated. The subsystem consists of three sensing channels that have been designed for the purpose of sensing phase voltage and phase current respectively.

  To measure phase voltages, voltage transformer units ZMPT101B have been utilized. ZMPT101B units' primary winding is connected across the respective phase line by means of burden resistors, while internal operational amplifier circuits within the module's structure amplify the reduced amplitude AC signal received at the secondary windings. A sinusoidal signal with an oscillation range of 0-3.3V is generated by making use of a midpoint reference voltage value. The ZMPT101B units' output is fed into signal conditioning circuits that will subsequently be connected to the ADC inputs of the microcontroller. The ACS712 Hall effect current sensor unit is used for measuring the currents in the phases. The scaled analog voltage output received from the conduction path of the ACS712 unit is then sent to a dedicated ADC input within the microcontroller through a voltage scaling unit.

There is no digital protocol that would be used for data transmission between the STM32F106TA microcontroller and the sensor since there are only analog signals that can be found within the lines of ADC. The fact that the conversion to digital takes place within the ADC of the microcontroller also speaks for this fact.

- **Microcontroller Subsystem**

  STM32F106TA Microcontroller Subsystem acts as the brain of the system and is the main interface between all other subsystems in the project. For coding, the HAL library is employed to program this subsystem with the aid of STM32 CubeIDE software, while STM32CubeMX is utilized to configure its peripherals. Peripheral configurations of STM32F106TA MCU include:

  – **ADC with DMA:** Configured for DMA transfers and continuous scans modes. Therefore, the channels of all the sensors are continually sampled and automatically stored in the SRAM memory without the need for any CPU operations.

  – **I2C Peripheral:** Configured for data transfer to the 16x2 LCD display subsystem at a frequency of 100 kHz.

- **GPIO Output Pins:** Configured for buzzer driver pin, three LEDs and relay.
- **Hardware Timer:** Configured to produce the toggle signal needed for activation of the buzzer when there is some kind of malfunction in the system.

  The microcontroller's firmware can be subdivided into blocks which perform specific functions. The first block, which is responsible for sensor signals processing, computes values for voltage RMS in volts and current in amperes for all three phases during each processing cycle using ADC data received from the DMA buffer. Then the fault detection block utilizes those calculated parameters to detect the system state depending on the specified thresholds. The block which controls indicators is responsible for controlling LED and buzzer output state; the driver block is responsible for generating messages needed for further sending to the LCD display via the I2C interface; and finally, the relay control block is responsible for setting relay GPIO output signal depending on the state of the fault detection block. The STM32F106TA processor exchanges signals with every other internal subsystem, including the signal acquisition subsystem and the display device subsystems.

- **Load Switching Subsystem**

  The Load Switching Subsystem forms the actuation layer of the system that was developed. In response to the command signals generated by the STM32F106TA microcontroller, this layer switches the physical connection or disconnection of the load from the power source. In this work, a relay operated by an electromagnetic control through a transistor switch was used. A current-limiting resistor connects the base of the transistor to the microcontroller's GPIO pin. In normal operation conditions, when the GPIO pin of the STM32F106TA microcontroller goes to HIGH level, the transistor is saturated, allowing the relay coil to be activated and subsequently close the contacts to supply the load. However, in case there is a defect, the GPIO pin will go LOW, causing the deactivation of the relay coil to open the contacts while turning off the transistor. To prevent the inductive kick effect when the relay coil is turned off, a flyback diode was incorporated across the relay coil. This subsystem uses one signal wire from the STM32F106TA microcontroller that performs the on/off switching.

- **User Interface Subsystem**

  The User Interface Subsystem acts as an output subsystem of the designed architecture. It supplies the user with continuous feedback regarding measurement results and status of the whole system. There are three types of output devices in the UI subsystem that perform their specific communication functions:

  - **16X2 I2C LCD Display:** Communicates with microcontroller through the I2C interface where STM32F106TA microcontroller acts as a master unit while the display operates as a slave one. Display shows current status values on two rows: phase voltages, load current consumption and status at the rate of 2-5 Hz.
  - **LED Indicator Array:** There are three LEDs. The green for regular status, yellow for warning condition and red for a faulty situation respectively. They are connected to the corresponding GPIO output ports of the microcontroller with the help of

resistors as current limiters. The user can quickly understand current status of the system by watching color changes without looking at the LCD screen.

- **Audible Buzzer:** Buzzer operates through the NPN transistor switch from the GPIO output port.

The connectivity inside the subsystem is handled by the STM32 microcontroller through which there will be communication via the I2C bus to send data to the LCD display, GPIO ports are used for controlling the LED lights, and the transistor driver line is utilized for creating a buzzer sound.

5.2 Tools and Technology Used

Intelligent Surge Protection Device was created and deployed by various software applications and technologies. Software applications and technologies were involved in a number of stages of product development, such as circuit simulation, hardware design, firmware generation, programming, and testing. The software applications and technologies used are described below.

- **MATLAB**

  The use of MATLAB was involved in the process of analysis and design of the product in order to carry out mathematical modeling and signal analysis in terms of the surge prevention system. It was used to analyze the waveform of the voltage, perform the calculation of the RMS value of sampled data, and verify the correctness of scaling and calibration equations employed in the processing firmware module. In order to ensure the correct implementation of the relationship equations in the STM32F106TA firmware, the use of MATLAB as a means of numerical computations allowed to mathematically prove relationships between sensor voltage and electrical magnitudes measured in volts RMS and amperes, respectively.

- **Proteus Design Suite**

  During the entire process of implementation of the project, Proteus software was utilized as the hardware simulator and circuit design environment. The Proteus schematic design tool was used in designing and simulating the entire circuit design for the Intelligent Surge Protection Device in three phases. This includes the use of voltage sensors (ZMPT101B), current sensors (ACS712), the microcontroller (STM32F106TA), relay driver circuitry, power supply circuitry, and the user interface circuitry. In the virtual environment provided by Proteus software, it was possible to test the circuit design connections, components setting, and signal interfaces before the implementation process. Proteus software helped in the viewing of the signal waveforms output on critical points on the signal interfaces such that the relay circuitry works well and the signal output of the sensors fits the ADC input of STM32F106TA.

- **STM32CubeIDE**

  The main IDE utilized in developing the firmware code for the STM32F106TA is STM32 CubeIDE. It integrates the STM32CubeMX peripheral configuration tool that was used to set up the necessary peripherals on the STM32F106TA microcontroller, such as the ADC working in continuous scan mode with the use of DMA, the I^2C peripheral that helps establish communication with the LCD screen, GPIOs responsible for relaying signals to the relay circuitry and LEDs and buzzers, and the hardware timer for generating tone sequence for buzzers. CubeMX creates the HAL library that provides a hardware abstraction layer and enables one to easily write code without dealing with hardware registers. Currently, CubeIDE integrates the GNU Compiler Collection-based toolchain that enables one to generate and flash the firmware onto the STM32F106TA microcontroller. Finally, debugging capabilities integrated into CubeIDE were extensively used when implementing the code for the sensor processing and fault detection units.

- **STM32CubeProgrammer**

  To load the firmware binary onto the microcontroller, the utility STM32 CubeProgrammer was utilized. When the firmware build for this project was successfully accomplished in STM32 CubeIDE, the utility would import the newly created binary file, which would then be programmed on the STM32F106TA microcontroller using the ST-Link debugger. The STM32 CubeProgrammer was very helpful in facilitating an easy programming process and enabling one to quickly update the firmware within the limited period of development. The utility was also helpful in verifying the content loaded into the Flash memory of the microcontroller after programming.

- **Surge Protection Technology**

  In the case of the technology used in implementing this project, it is the use of surge protection technology. The use of surge protection technology involves the integration of a number of passive components in an efficient multiple-stage clamping system. Each of the three phases of a three-phase electrical supply system has an integrated circuit of Metal Oxide Varistors and Gas Discharge Tubes to ensure efficient protection from transient over-voltages created due to lightning strikes and switching operations. The MOV ensures fast clamping for moderate and short-term surges while the GDT acts as a channel to ground during high energy surges.

- **Embedded System Technology**

  Embedded systems provide the capability to design devices that can have intelligent monitoring and control features through the application of the STM32F106TA ARM Cortex-M family of microcontrollers. Embedded systems incorporate the capability of data acquisition from sensors, real-time data processing, error detection algorithms using set threshold values, and the implementation of control algorithms for switching loads into the same microcontroller to make it operate continuously without user involvement. The STM32F106TA executes the firmware program developed in the STM32 CubeIDE in real-time that comprises analog/digital conversion, signal processing, decision-making algorithms, and control output signals. Thus, an Intelligent Surge Protection Device is smarter compared to conventional protection circuits because of the implementation of embedded system technology.

The integration of these two technologies for hardware protection and intelligent monitoring and control constitutes the technological basis of this research problem. This will enable the development of a hybrid SPD hardware system equipped with intelligent monitoring and control features using a microcontroller to solve issues with conventional SPD hardware systems according to the literature review.

5.3 Development Environment and Languages Used

Intelligent Surge Protection Device Firmware and Hardware designs were effectively and efficiently developed using suitable programming languages. The development environment consists of the software tools that will be employed to code, compile, debug, and program the firmware into the target microcontroller chips. The development environment includes the hardware development environment that enables the creation and simulation of actual hardware circuitry. In this chapter, the development environment of the project, as well as the programming language used during its conceptualization, are described.

- **Programming Language - Embedded C**

  The firmware for the STM32F106TA microcontroller was coded using Embedded C only. Embedded C can be viewed as an extension of the C programming language but with extra features designed for developing applications on embedded systems. For instance, the embedded system must allow direct register and memory-mapped device manipulation, interrupts, and real-time processing capabilities. Embedded C is the official programming language for coding firmware for embedded systems and is fully supported by the ARM GCC compiler provided within the STM32 CubeIDE package.

- **STM32CubeIDE - Integrated Development**

  The STM32 CubeIDE was the principal software platform employed in the complete firmware development process. It served as a central platform where all firmware development processes took place starting from configuring the peripherals up to compiling and debugging the firmware. The CubeIDE is an IDE based on Eclipse that contains the STM32CubeMX configuration software, ARM GCC compiler tools, and debugging software.

Firstly, in CubeIDE firmware development, the STM32CubeMX software was employed to configure the hardware peripherals in the STM32F106TA using a graphical user interface. These configurations include setting up the ADC module to operate in continuous scanning with DMA support, the I2C interface for LCD communication at 100kHz frequency, GPIOs for relay control and LEDs outputs, and the buzzer sound generation, respectively. After completing hardware peripheral configuration, CubeMX will automatically generate the required initialization code in C programming language. The rest of the firmware development was done in CubeIDE with the initial hardware peripheral initialization code generated by CubeMX.

The software sources coded in C have been compiled using the ARM GCC Compiler of CubeIDE. The compiling process took into account various optimization parameters in order to strike a compromise between code size and speed, thus ensuring that the generated code is able to fit into the memory of the microcontroller and process any faults detected within the specified time limit. The internal debugger was extensively used while developing the firmware code in order to debug both the sensor and the fault processing blocks of code.

- **Proteus Design Suite - Hardware Development**

  With respect to hardware implementation, the Proteus Design Suite was used for the entire design and simulation of circuit diagrams in the project. The entire Intelligent Surge Protection Device circuit diagram was drawn on the Proteus Design Suite platform including all three phase sensing circuits made up of ZMPT101B and ACS712 chips, the STM32F106TA microcontroller together with the rest of its peripherals, the relay control circuit, the power supply circuit made up of the LM7805 and AMS1117-3.3, and finally the human interface components comprising of an LCD display, LEDs, and a buzzer. The verification of functionality of the circuit was done on the Proteus Design Suite platform.

5.4 Processing Logic and Algorithms

However, the processing process of the Intelligent Surge Protection unit is wholly based on software programming done using C language via the STM32CubeIDE for the STM32F106TA microcontroller. The processing process is carried out in a very systematic way that follows a sequential process, which involves measurement of real-time information using the sensors, then processing of the data collected, followed by decision-making using fault detection through threshold and thereafter taking action. This whole process takes place during the normal functioning of the system to be able to identify any problems occurring in the supply of electric power to the load.

- **Overall Processing Flow** The complete process of the entire system is based on an infinite loop process that comprises the following five processes as outlined below:
  - **Sensor Data Acquisition:** The STM32F106TA ADC module constantly samples all the sensor input channels and produces raw numbers corresponding to the voltages, currents, and temperatures of the three phases.
  - **Signal Conditioning and Calibration:** The raw numbers obtained from the previous phase are then subjected to condition-

ing and calibration to convert them into meaningful engineering units like RMS volts, amperes, and degrees centigrade.

  - **Threshold Comparison and Fault Detection:** Once calibrated, the outcomes are compared to the established threshold values to find out the state of the system.
  - **Protective Measures:** On the basis of the outcome of the comparison phase, appropriate protective actions, including relay switching and alarms, are taken.
  - **User Interface Update:** Lastly, the outcomes are displayed on the user interface in the form of an LCD display, LEDs, and a buzzer.

All the five phases mentioned above constitute a loop, which continues to cycle as long as the system is running.

- **Sensor Data Acquisition Algorithm**

The ADC module is present inside the STM32F106TA microcontroller, which monitors the value of sensors. This ADC has been developed in such a manner that it can be utilized when DMA is operated under continuous scanning mode. In case continuous scanning is turned on, then this ADC would work such that it would take samples from all ADC channels as per the selection of the programmer. After taking all these samples, DMA sends these samples to SRAM memory location.

The scanning routine will involve all nine channels of sensors as listed below:

  - Voltage channel of phase L1
  - Voltage channel of phase L2

- Voltage channel of phase L3
- Current channel of phase L1
- Current channel of phase L2
- Current channel of phase L3

The sampling time for every channel through the use of the ADC is well-timed in order to give enough time for the settling of the analog signal output from the sensors before the conversion of the signal into digital format. The data in the DMA buffer is always up-to-date during every scanning cycle of the ADC converter function.

- **Signal Conditioning and Calibration**

  The processing of the sensor input in the firmware happens on the basis of the engineering values, since the ADC values have already been stored in the buffer via DMA. The conditioning and calibration of the sensor depends on the kind of sensor employed. For instance, in case of ZMPT101B voltage sensors, the ADC values are nothing but instantaneous readings of the biased sine wave that the sensor generates. Then the RMS value is determined by averaging the above values over a complete cycle of the sine wave at 50Hz, and then modifying the RMS value at the start of the system to determine the engineering phase voltage in Volts RMS.

  For the ACS712 current sensors, the ADC data is used to get the output voltage value from the sensor where there is an absolute value for offset VCC/2 when there is zero current and the error is determined in relation to the amount of current. This data is converted to real current using the ADC firmware by subtracting the absolute value of the offset, which is VCC/2, from the data and then dividing it by the sensitivity value of the current sensor, which is 100mV/A, to get the real current in amperes. This will take care of any error that may result due to offset values in the output of the ACS712 current sensor since they depend on real voltage values. For temperature sensor input, the conversion from volts to Celsius should be done appropriately.

- **Threshold Detection and Fault Classification**

  Threshold detection is the most basic part of the decision-making processes of the system. Calibrated readings from all sensors are compared to thresholds set by the software, which will remain unchanged throughout the system operation. There are several states that the system can be in at any particular time, including the following ones:

  - **Overvoltage Condition:** Detected when the phase voltage exceeds 264V RMS, which equals to 120 percent of the rated 220V phase voltage. This situation is considered to be hazardous since there is an excessive voltage supply that might damage the load of the system.
  - **Undervoltage Condition:** Detected when the phase voltage is lower than 176V RMS, meaning 80 percent of the rated 220V phase voltage. In this case, a hazardous drop of voltage occurs, and it might lead to malfunctioning of the system.
  - **Overcurrent Condition:** Triggered when a phase load current is detected to be larger than the overcurrent threshold of the 2kVA JMICC Power Distribution Box. Taking into account that a rated value for phase load currents in this system is 2kVA with a source voltage of 220V (each phase), the value of maximum current would be about 9.09A. However, in order to detect an

existing issue, an overcurrent limit would be higher.

This fault determination algorithm evaluates all three criteria in every processing cycle and determines the operation state of the system as one of the following:

- **Normal State:** All three criteria have been satisfied. The voltages between phases are between 176V and 264V, the current flowing through all phases does not exceed the overcurrent fault value, and the temperature of the assembly remains under the overtemperature fault value.
- **Warning State:** At least one of the measured values is near, but not exceeding, the fault value. A warning margin, expressed as a percentage, exists for every fault level; when exceeded, the warning state is set into effect.
- **Fault state:** This indicates that at least one of the measured values exceeds the corresponding fault value. Once the fault value is attained, the system status enters the fault state.

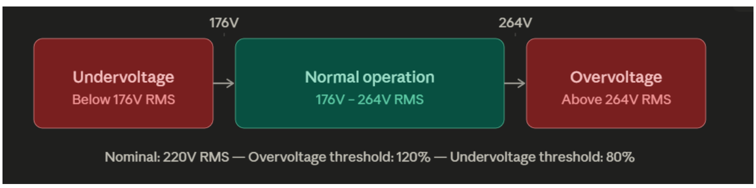

Figure 5.4: Threshold Boundaries For Voltage Measurements

- **System Recovery** Recovery will be taken care of by the algorithm in this case since it will define the time at which the transfer from the fault state to the normal operating state will take place once the load is connected. In this way, we can be assured that there will be no requirement of any manual intervention. The recovery algorithm operates as follows:

- With the entry of the system into the Fault State, the relay switches off, and the fault hold-off timer starts.
- For each processing period, the firmware re-analyzes all the inputs checking them against the defects criterion.
- In case the fault persists, the hold-off counter resets, and the system reverts to Fault State where the load will again lose its power supply.
- However, in case of no faults, the hold-off timer continues counting.
- As soon as the hold-off time is about to expire, meaning that all conditions were favorable during the hold-off time, the firmware will change the system state to the Recovery mode, and turn on the GPIO pin, which controls the relay operation.
- The system returns to normal operation and continues monitoring.

A recovery procedure of this nature would guarantee that the establishment of the power link takes place only after all the power disruptions have been sorted out, thereby ensuring that there are no switching effects experienced by the load.

Chapter 6

System Testing and Evaluation

System testing refers to testing of an integrated system according to its requirements to ensure that all the parts as well as the overall system operates correctly. The testing of the Intelligent Surge Protective Device system as developed in this project would include the testing of hardware performance, firmware performance, sensors performance, protective measures performance, and interface performance in different normal and abnormal situations. Relative and absolute system testing are among the testing methods involved in this project. Absolute system testing will involve verifying whether the system does what it is supposed to do, while relative system testing involves comparison of the system's performance to other surge protection systems.

6.1 Graphical User Interface Testing

This is the methodology of ensuring whether the graphical displays of the system are working properly, displaying correct data, and notifying the user about the system status. The 16x2 I2C LCD Display, three LED lights (green, yellow, and red), and the buzzer form the Graphical User Interface of the Intelligent Surge Protection Device. These components ensure that the operator can monitor the status of the system throughout its operation and detect any unusual electric behavior. The aim of GUI testing was to confirm the accuracy and readability of each component under the three operational modes of the system.

- **LCD Display Testing**

  The 16×2 I2C LCD is employed to provide information such as the phase voltage and the load current readings, alongside the status messages for two lines of characters to the operator. The LCD was tested to check whether it could be able to initialize itself upon power up, read and display the right data when the machine was running, and update itself in case of a mode change in the system. It was noted that at power up, the LCD could initialize itself and display the start-up message at the right time. When the system was running, the upper row of the LCD would display the real-time values of the phase voltage and load current, while the lower row would give the status message that all systems were okay. To verify whether or not

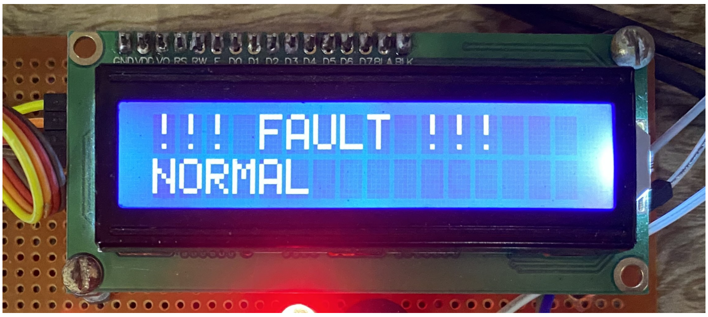

Figure 6.1: LCD display during Normal Operation

the firmware scaling functions and sensor calibration processes were able to produce accurate engineering values at the display output, the displayed values were benchmarked against reliable reference values. When the overvoltage simulation was performed by increasing the test voltage input past the required overvoltage threshold level of 264V RMS, the LCD immediately changed its display to indicate the nature of the fault event together with the faulty phase involved in the scenario. The display driver component is able to respond immediately to any state transition because it was noted that the transition from the normal status display to fault status took place within the time frame of the firmware's display update interval. The LCD display successfully started up and displayed real-time data from the sensors, as well as updated information based on the system

Figure 6.2: LCD display during Fault Operation

status changes, which were clearly indicated in the test results.

- **LED Indicator Array Testing**

  Without looking at the readings on the LCD display, the color indication of the LED lighting is a quick and clear way of knowing the status of the machine. If the measured values approach the fault value but do not exceed it, then the yellow light denotes the warning stage, the red light means the fault stage while the green light represents normal operation stage. Based from the LED indicator light testing, it can be concluded that only the LEDs that should come on actually comes on, and only those that should be off actually goes out. The green LED lit up during the test under normal condition with the measured voltages falling within the range of 176V to 264V and no overcurrent loading condition. The green LED was switched off, and the yellow LED was switched on upon the entry of the circuit into the simulated mode of caution, wherein the voltage of one phase was introduced within the caution range from overvoltage. This indicated that the operation of the LEDs was normal, and no preventive measures were taken by the system. Upon increasing the test voltage beyond the overvoltage threshold, resulting in a fault condition, the yellow LED was switched off, while the red LED was switched on immediately. This indicated that the LEDs were activated based on the correct system state and that their operation was correct in all states considered for analysis.

- **Buzzer Alert** Whether there is anything going on in the LCD display and LEDs or not, the buzz is used as an alternative means of alerting the user of a fault condition. In addition, the function is designed in such a way that even when the user cannot see the whole system, alerts will always come through the buzz. Testing the buzzer involves discovering whether the buzz triggers in case of a fault condition and turns off once the system recovers from the fault condition. The buzzing control function takes place at the same time as the fault condition, as demonstrated by the results obtained from causing the fault condition. The buzz triggers immediately after the red LED lights up, and it turns off when the system returns to normalcy after clearing the fault condition.

6.2 Usability Testing

The usability test involves measuring how easy or straightforward it is for users to operate, observe, and understand the ISPD without the use of any special devices or sophisticated technological skills. Usability test is essential for the performance measurement of an embedded protection system that will be used as part of the company's power distribution system, like the JMICC Power Distribution Box, where the system should convey its status clearly and effectively to the operator. The hardware components that were designed to make up the system, including the three phase protection board, microcontroller perfboard, voltage sensor, current sensor, solid state relay, circuit breaker panel, 16x2 LCD, and three phase light bulb load, were subjected to usability tests for purposes of evaluating the system in terms of the following areas.

- **LCD Display Readability**

  The main source of quantitative data in the operation of this device is the 16x2 LCD display that shows present phase voltage, load current, and status parameters of the system. The goal of the test of readability was to check whether the operator was able to see and understand information shown on the screen at a standard working distance. As a result, the screen showed clear data with a blue backlight, thus providing good contrast between the background color of the display and information shown on the screen that allows for easy reading in low light conditions. The voltage and current values together with the phase indicator were clearly shown, which made it possible to understand the monitored phase. Although the firmware showed separate readings for Phases A, B, and C, the display screen was tested for each phase separately. Besides the fact that the status messages, shown during normal, warning, and fault modes were quite informative, the readings for each of the phases seem to be available and accurate.

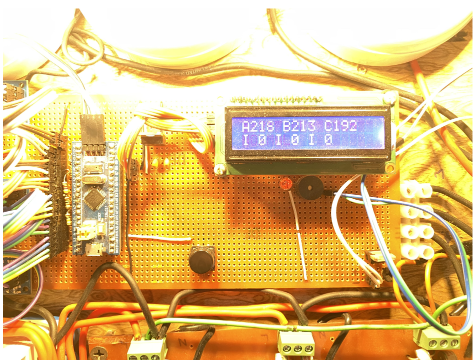

Figure 6.3: LCD Display showing Three Phases

- **Per-Phase LED Indicator Interpretability**

  The SPD protection board now features LED per-phase indication lights. This way, the user gets notified right away when there is any problem regarding the protection of a specific phase. Being able to determine right away which exact phase line needs to be checked out is certainly a very important benefit of having per-phase LED indication lights. Testing the usability of the device involved figuring out how easy it would be for the user who has no prior knowledge about the SPD protection board to understand how per-phase LED indication lights work. During usability testing, the per-phase LED lights on the SPD protection board blinked due to the status of the respective phase lines in the circuit. If you have prior knowledge about three-phase circuits, it is obvious how the per-phase LED lights in the SPD protection board can help determine which exact phase line is having trouble.

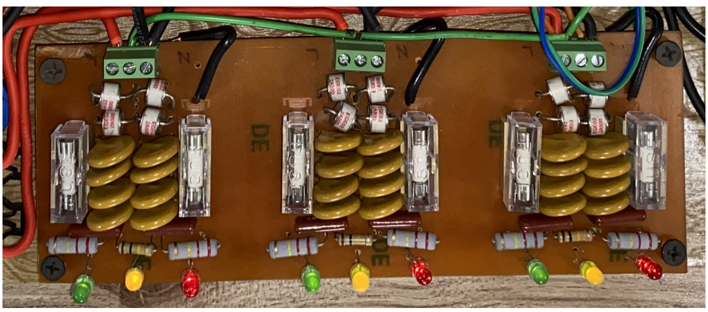

Figure 6.4: ISPD Board with LED Indicators

- **System Status Identification Speed**

  Usability of the protective system will depend on how fast the operator is able to get the complete status of the device. The test was performed according to the effectiveness of the LCD display, per-phase SPD board LEDs, and the main status LED on the microcontroller perfboard in providing the observer with a status of the system upon approaching it, including whether all three phases were working properly, whether there was any faulty phase, and if yes, which one. The test showed that combination of color coding of the per-phase SPD board LEDs together with information provided on the LCD gave sufficient status information of the system upon approaching to understand the status of the system. All that was needed to do was to get color status information of the whole situation through the LEDs and then search for additional information on each phase via the LCD display.

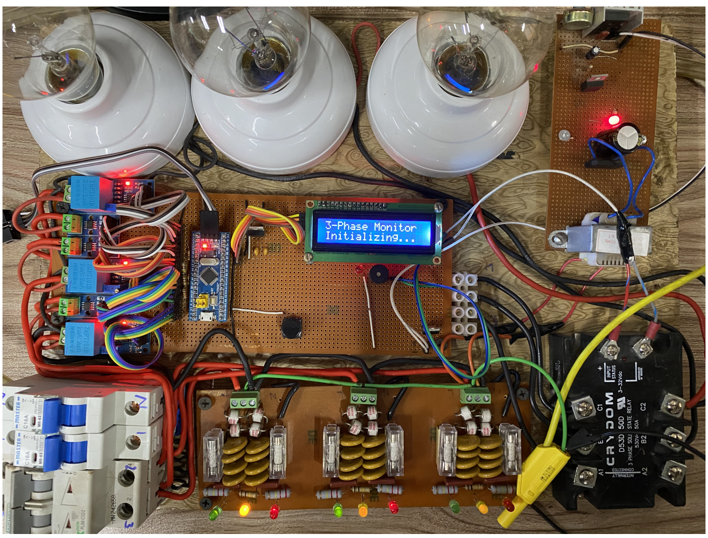

Figure 6.5: ISPD System Status

- **Three-Phase Load Switching Observability**

  The component responsible for controlling the operation of the load by signals from the microcontroller is the three-phase solid-state relay. Concerning usability issues, it is important that the end-user understands how load switching occurs in the system, which means that the load will be turned off upon detection of a fault by the solid-state relay and restored to normal operation automatically following the removal of the fault without using any measurement devices. With the three-phase bulb load connected to the solid-state relay output, there was very clear evidence of load switching, with the bulbs turning on when the relay was closed normally and off when the relay was turned off as a result of a fault in the circuit. It could be determined that this was one of the most effective solutions to a usability issue that existed in the system based on feedback on the load switching process.

- **Circuit Breaker Panel Accessibility**

  The manual overcurrent protection mechanism and the system's manual isolation point are situated on the upper left corner of the circuit breaker panel, which includes the three-phase circuit breakers. In terms of usability, the circuit breaker panel should be easily accessible to the operator for manual intervention and easily distinguished from other circuit components as the location for manual intervention in the event that the operator needs to do so. The circuit breaker panel was found to be readily visible and usable during the usability testing procedure.

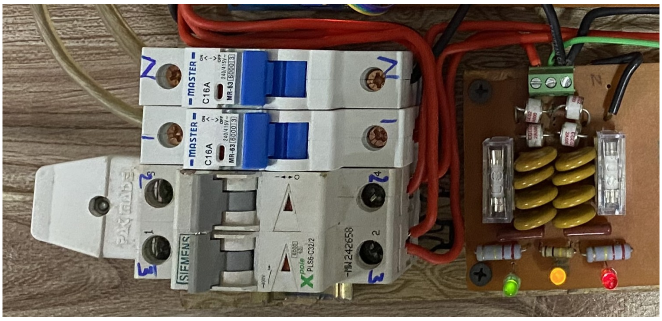

Figure 6.6: Circuit Breaker Panel

- **Overall Operator Experience**

  The capability of an individual who has some background in electrical systems yet lacks familiarity with the inner mechanisms of the intelligent surge protection device system was utilized in order to assess how well the entire system could be observed and analyzed based on whatever visual outputs the user can perceive. It has been concluded that the visual outputs produced by the LCD screen, the LEDs located on each SPD per phase board, the main status LED, the loud buzzer, and the load switch visibility provided enough outputs in order to monitor the system efficiently without the use of any technical equipment whatsoever or special expertise on the subject matter. The LCD screen and the microcontroller perfboard, which contained most of the information available on the board, were strategically placed at the center of the physical prototype built, with the SPD protection board situated to its left side, the circuit breaker box situated at its upper left corner, the solid state relay to its lower portion, and the three-phase load situated at its right side.

6.3 Software Performance Testing

Software performance test was conducted on the software platforms where the Intelligent Surge Protection Device was designed and tested, including the Proteus Design Suite, MATLAB Simulink, and STM32 CubeIDE. Each software platform provided some level of software testing to ensure that the system design worked as intended.

- **Proteus Circuit Simulation**

  Before assembling the circuit, its simulation was carried out using the Proteus simulator in case of the whole three-phase circuit. This proved that the signals had adequate voltage levels at the interfaces, output of the sensors with values in the range of 0 to 3.3 volts for the ADC of the microcontroller, relay activation, and I2C communication with the LCD display. Several difficulties associated with the interfaces were found from the simulation, such as the necessity of an interface between the output of the sensors and the ADC of the microcontroller.

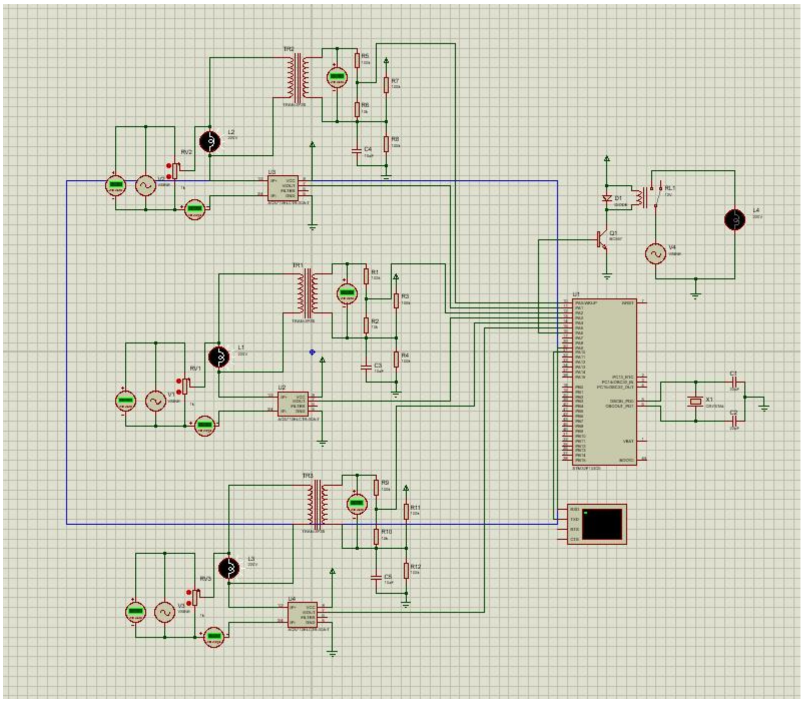

Figure 6.7: Proteus Circuit Design

- **MATLAB Simulink Surge Behavior Modeling and Results**

  The simulation model for this protection circuit has been modeled on the platform of MATLAB Simulink. The Surge Protection circuit assembly is in the form of a circuit having input current channel, output current channel, and an output voltage channel connected to the scope block. Some surges were applied at certain points in the simulation to evaluate the effectiveness of the surge protection assembly with regards to its clamping operation.

  This has been revealed by analyzing the three waveforms from the scope block outputs. First, the input current wave shows the existence of two peaks of high current of about 175A at places where surge has been applied, indicating the effective suppression of surge energy. Second, the output current waveform shows constant sine

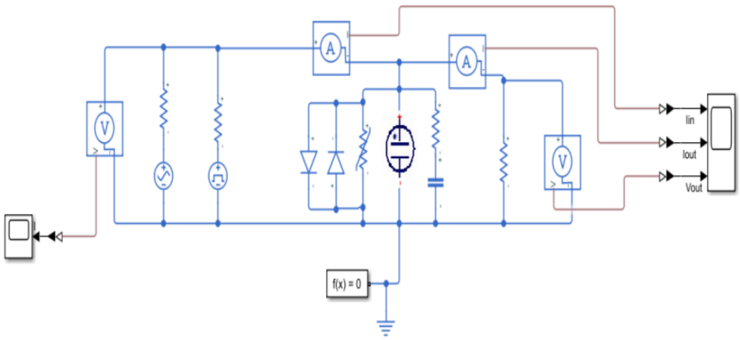

Figure 6.8: Matlab SPD Design

waveform without the peaks of surge current and therefore, there is suppression of the surge current. Third, output voltage waveform shows the sine waveform as well without any surges, meaning that output voltage is free form surges.

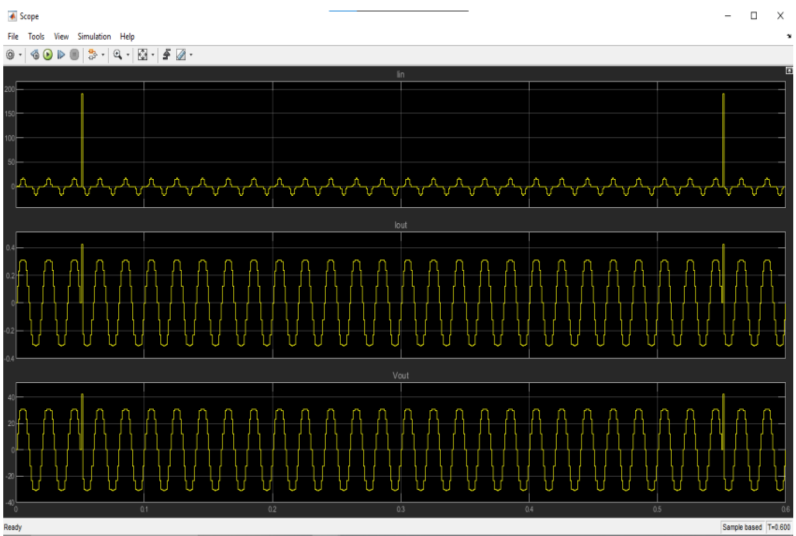

Figure 6.9: Graphical Results

- **Stm32CubeIDE Firmware Verification**

  Firmware was designed, programmed, and debugged using the STM32 CubeIDE platform. The modules of the firmware like the sensors, fault management, relays, LCD screen driver, and LED drivers were separately debugged using the debugging capabilities of the IDE before adding them to the firmware development process. The memory capacity of the firmware was checked to ensure that the final firmware would fit into the microcontroller's memory limitation in terms of Flash memory and RAM. The final firmware could be uploaded to the microcontroller and run smoothly upon the initial power up.

6.4 Compatibility Testing

Compatibility testing will help assess the seamless integration of all components that make up the Intelligent Surge Protection Device, ensuring there are no clashes or communication problems. Below are some interface areas that have been analyzed for compatibility with the ISPD prototype.

- **Sensor and Microcontroller Compatibility**

  Inputs on the microcontroller board from the voltage and current sensors will be used to communicate with the microcontroller. Analog output signals from the sensor modules should never exceed the limits of the analog to digital converter input voltage range for compatibility. Input signals for the microcontroller board are in the 0-3.3 volts range because the microcontroller is supplied 3.3V power source. The current sensors create an analog signal at mid-range Vcc/2 voltage, which is 0-3.3 volts. Voltage sensors generate a sine wave analog signal at 0-3.3 volts based on the Op Amp circuit inside the module. It is important to note that all the sensor values lie within the 0 to 3.3 volts of the ADC input even when current and voltages are at their peak on the three-phase circuit due to compatibility tests. The nonexistence of cases where ADC input is above the range proves the efficiency of the conditioning and scaling circuit used to maintain the sensor values within the allowed input range of the microcontroller. It is due to the constant collection of sample data from the sensors through the ADC using DMA that stable digital values could be obtained by the firmware processing unit.

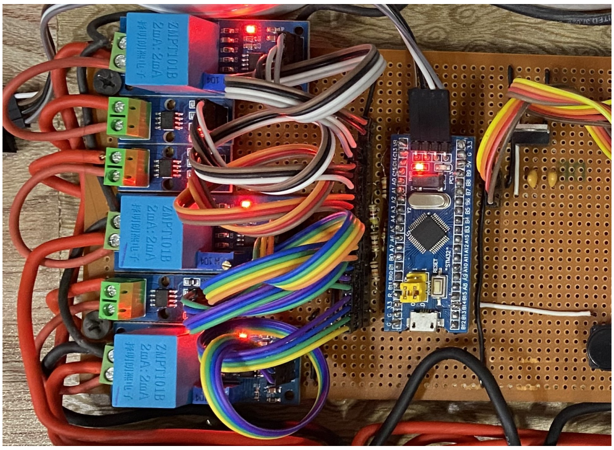

Figure 6.10: STM32 Microcontroller Interface with Connected Sensors

- **Power Supply Compatibility**

  All the components on the control side of the system, including microcontroller, voltage and current sensors, LCD display, LED indicator, buzzer, and SSR control signal input need to be powered concurrently by the power supply subsystem from one regulated source, which is the product of converting 220V AC three-phase power. To obtain the 3.3V DC rail, the AMS1117-3.3 regulator uses the 5V DC rail as its input source, whereas to generate the 5V DC rail power supply, the customized transformer and LM7805 regulator were used. The stability of both the 5V and 3.3V DC rail power sources was checked during the testing of maximum power loading of the respective components. The voltage drop or variations did not occur during the testing and it was noted that the 5V DC rail power source was capable of supplying electricity to the sensors, relay control module, LEDs, and buzzer. However, the microcontroller received power from the 3.3V DC rail when it switched GPIO pins, scanned ADC values, and sent the data via I2C.

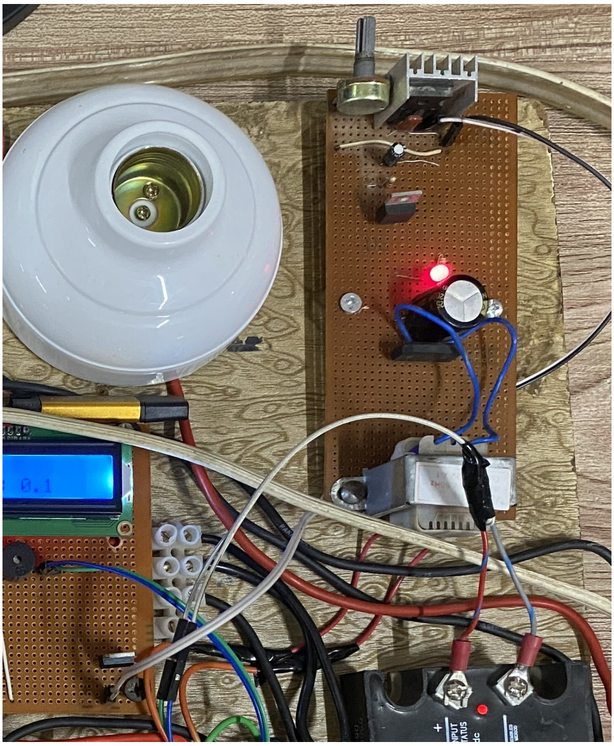

Figure 6.11: Power Supply Connectivity

- **Microcontroller and LCD Display Compatibility**

  The serial bus interface of I2C, which needs compatibility in terms of I2C peripheral configuration, I2C protocol, and I2C addressing on both sides, is used to interconnect the display with the microcontroller. The configuration of the I2C peripheral of the STM32 CubeIDE microcontroller is made according to 100 kHz clock frequency, and the I2C interface uses the display module address that was taken as the default in the firmware display driver module. For testing the compatibility of the I2C interface between the I2C peripheral of the microcontroller and the display, the test is performed with the constant operation of the I2C interface. All of the data coming from the firmware display driver module are successfully displayed on the LCD display without any errors or malfunctions in I2C operations between the microcontroller and the display. Phase live voltage, current, and status information of each of the three operational modes are included in these data.

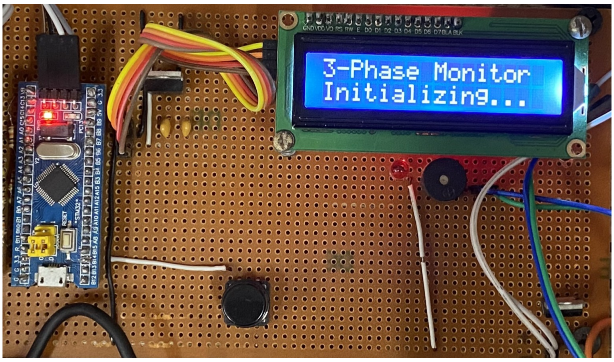

Figure 6.12: Microcontroller and LCD Display Connectivity

- **SSR and Microcontroller Compatibility**

  Contacts in the solid state relay cannot be activated unless an activation signal is provided to the solid state relay from within the range of its DC input voltage level. In this setup, the solid state relay is interfaced to the microcontroller, and in turn, the microcontroller uses one of its GPIO pins for sending an activation signal to the solid state relay. It is necessary for the microcontroller to have sufficient output voltage and current level to activate the relay input. Tests have shown that there is no problem with the compatibility between the solid state relay and microcontroller GPIO pins in this setup.

Contacts of the solid state relay were activated whenever the light bulb was operating under normal conditions as the GPIO pin was activated, while contacts of the relay remained OFF whenever the GPIO pin was not activated because of some fault.

- **SPD Protection Board and Three-Phase Supply Compatibility**

  The MOV and GDT protection modules utilized for the first, second, and third phases comprise the SPD protection circuitry, which is connected parallel to the phase wires. The 220V AC three-phase power supply will not be impacted by the employment of SPD protection circuitry, and the voltage will not be affected by the employment of SPD protection circuitry, irrespective of any standby current produced by SPD protection circuitry while operating at the standard supply voltage. Since none of the MOV and GDT protection modules behaved as anticipated during the standard supply voltage levels, test findings show that the SPD protection circuitry works fine when connected to the live three-phase power supply. No distortion occurs in the supply voltage levels when the SPD protection circuitry is connected to the phase wires and therefore, the SPD protection circuitry does not affect the supply voltage levels when operated normally.

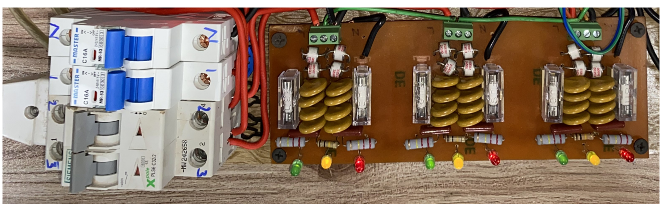

Figure 6.13: SPD Board Power Interface

- **Three-Phase Load and SSR Compatibility**

  The load for the three phases selected for the experiment becomes the load for the entire circuit. It must be such that it matches the ratings of the solid state relay used. Since the solid-state relay can operate with three-phase AC loads, the selected load must conduct current within the limits of the ratings of the solid-state relay. The compatibility test showed that the solid state relay could supply and interrupt the load without experiencing any trouble with overheating and switching.

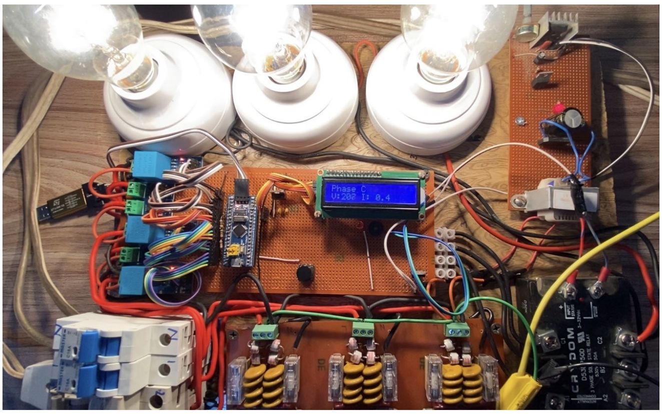

Figure 6.14: Three-Phase Output Load Demonstration

6.5 Exception Handling

An exception handling test is an assessment that is performed to evaluate the behavior of the system when encountering unexpected and borderline circumstances, in addition to usual circumstances in normal operations. Exception handling of a three-phase protection system working in real-time is as important as the usual operations when working normally in business operations. Below are some of the exceptions covered in the test.

- **Power Interruption Exception**

  One of those critical exceptions is a power failure that must be assessed in the system. In cases where there could be any kind of an expected power failure in the control-side power supply, instead of leaving the load open, it is crucial to ensure that the system is brought to a safe position. The following describes the test done in case of power failure whereby the system was in a normal operation mode with the SSR and a three-phase load. Within a fraction of a second, the solid-state relay very quickly became open at its default state after the removal of the source of power from the control unit. This results in the disconnection of the three-phase load from the source of power. It is quite evident from the experiment conducted above that the solid-state relay has been configured appropriately for the default state. This ensures that in case of any failure of the source of power to the relay, the load would not be connected.

- **Phase Lose Exception**

  The other issue that affects the three-phase distribution system is known as the phase loss. Phase loss can be defined as the total loss of electrical power within one phase among the three phases under observation. The reason for this anomaly is that it may pose danger to the three-phase loads in the distribution system if it is not dealt with in time. In order to determine whether the phase loss exception exists, the researcher disconnected one of the three phases of the three-phase system when it was working. Once the phase was disconnected from the three-phase system, the voltage sensor fitted within the phase detected that the voltage level was below the preset undervoltage level. Therefore, the fault detection algorithm was able to detect the deficiency in the phase. As a result, the distribution system entered into fault mode, causing the solid-state relay to switch off and disconnecting the distribution network from the three-phase loads. Furthermore, the buzzer and the red LED light alarm were switched on. Lastly, the display of the faulty phase was made through the LCD monitor.

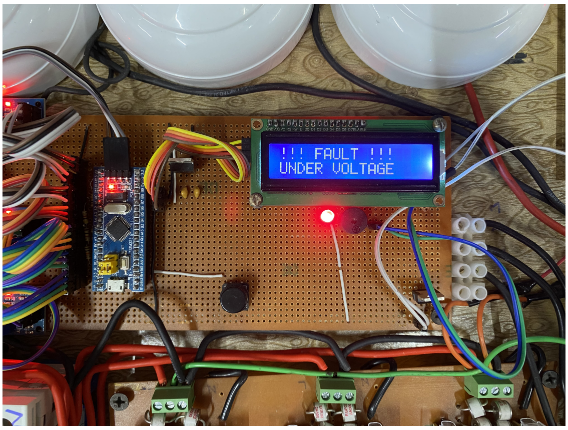

Figure 6.15: LCD Displaying Fault Message

- **Simultaneous Multi-Phase Fault Exception**

  In a scenario where there is disturbance of the voltage or a voltage surge in a three-phase distribution system due to a storm, it will be possible to detect the presence of electrical faults in different phases. Whether the algorithm for fault detection utilizing the firmware could successfully deal with faults occurring simultaneously in different phases and hence failing to prioritize the faults was tested. Faults in the test were introduced simultaneously in two phases of the test while another phase continued to work normally. The process involved in handling a fault was successful without delay and prioritization problems due to faults in the two phases. Additionally, the presence of faults in the two phases at once was successfully detected by the algorithm in the same cycle of processing and the system entered fault mode.

- **Extreme Overvoltage Exception**

  In the extreme overvoltage testing, an extremely high voltage situation was simulated which would normally occur as a result of events like lightening and switching within the power distribution grid. This was done through analysis of the behavior of the system under a high voltage level, which was way above the fault overvoltage level established for the system. During the extreme overvoltage test, there were two instances where there was a concurrent protection activation because of the high input voltage, compared to the 264V RMS overvoltage level. The excess voltage was directed to earth ground using MOVs on the SPD protection board. Further, the fault detection method used in the firmware testing used the voltage sensors to detect overvoltage and activate fault alarms for certain phases as well as switching off the load using SSR.

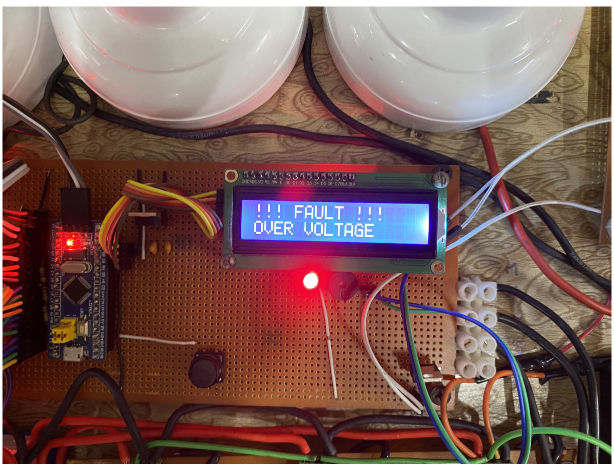

Figure 6.16: Extreme Overvoltage Condition

6.6 Load Testing

The effectiveness of the operation of the Intelligent Surge Protection Device in the handling of electrical loads was assessed through the load test. This was accomplished by the use of three-phase bulb as an artificial load for the three phases in connection to the Intelligent Surge Protection Device that was completed.

- **Normal Load Operation**

  The monitoring ability of the device to sense all three phases and ensure the connection without fault alarm during normal operation can be verified through the Normal Load Test. The Intelligent Surge Protection Device ensures that its solid state relay stays continuously closed whenever there is connection with the three-phase bulb load and all three phases are in the designated voltage range of 176V to 264V RMS. The LCD monitor accurately displays the measurements, rotating among Phases A, B, and C.

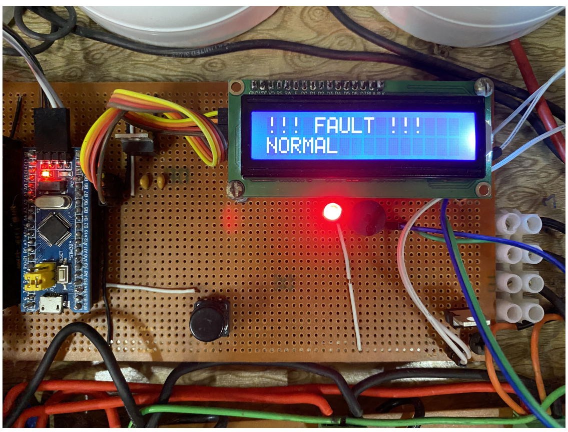

Figure 6.17: Normal Condition

- **Overvoltage Load Test**

  When the voltage input of each phase exceeds the maximum value of RMS overvoltage of 264 volts, the microcontroller detected the error and activated the relay to disconnect the power supply to all three phases. It led to the immediate shut-down of the phases, turning on the red LED, sounding the buzzer, and displaying an error message on the LCD screen.

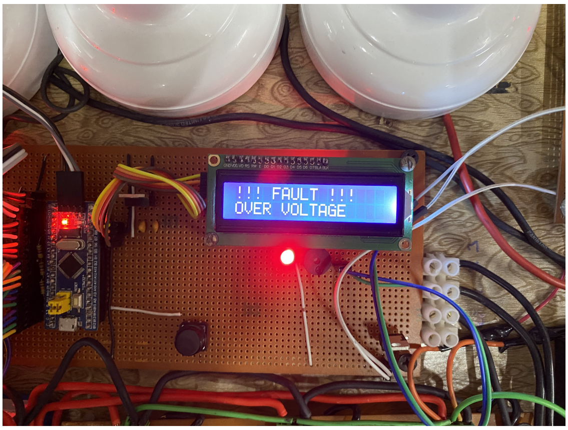

Figure 6.18: Overvoltage Condition

- **Undervoltage Load Test**

  Whereas, in the scenario where the supply voltage was lower than the 176V RMS, the voltage sensor detected the low voltage value, which triggered the firmware to detect the undervoltage problem and turn on the solid-state relay, causing disconnection between the three-phase load and the source. Furthermore, an indication of the problem was displayed by the red light, LCD screen, and buzz. The supply of energy to the load will only occur when the voltage becomes higher than the threshold value during the hold-off time.

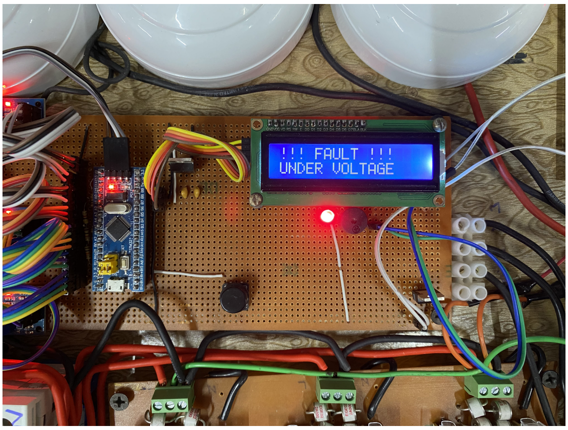

Figure 6.19: Undervoltage Condition

- **Overcurrent Load Test**

  In the event where the current in the phase exceeded the specified threshold, the current sensor detected the overcurrent problem and communicated the problem to the firmware. As a result, the firmware turns on the relay to disconnect the load from the power source. Also, there were indications of the problem with the red LED light, LCD screen, and buzz.

- **Load Disconnection and Recovery Cycle Test**

  The recovery test confirmed the operation of the circuit based on the Fault, Recovery, and Normal Operation conditions such that the load would automatically be restored back to the system once the fault ceases to exist. The fault was induced by manipulating the voltages of the supply lines; once the fault ceased to occur, the voltage supply was brought back to its normal value. After this, the system began operating within the Recovery mode, during which the load was left disconnected for a predetermined 5 seconds period. During this time, the voltages and currents of the three-phase supply were monitored to ensure safety. Once the hold-off period expired, the solid state relay was turned on to switch on the three-phase bulb load.

6.7 Security Testing

The technique that will be employed in conducting security tests for the Intelligent Surge Protection Device is establishing the extent of safety and security offered by the system, together with the possibility of failure of the system exposing the load or consumers to danger. This is due to the fact that the system being embedded does not have networking capabilities. In other words, the safety and security of the system will depend on the level of security from external interference.

- **Electrical Isolation**

  The ability to provide adequate isolation of the low voltage control section, comprising the microcontroller, sensors, and display, from the high voltage mains constitutes some of the key safety features in the system under consideration. The reason being that without providing such an isolation feature, both the low voltage circuits and potentially even the user will end up being exposed to high voltages emanating from the mains. Physical and logical isolation capabilities of the low voltage microcontroller from the high voltage phase lines were evaluated during the security testing phase. The voltage sensors, because of its transformer arrangement, ensured that there was proper galvanic isolation between the low voltage microcontroller input signal and the 220V AC phase lines. Just like in the voltage sensors case, the current sensors provided isolation of the phase and output lines using the Hall effect principle.

- **Relay Protection and Safety Response**

  This is due to the fact that the reliable performance of the switching circuit for the load becomes the security element in this context. Any protection apparatus should be designed in a way that will not allow itself to malfunction to an extent where the connection between the load and the system cannot be disconnected even if the system suffers from a fault or loss of control power source. In this specific case, the Solid State Relay was programmed to operate in its 'Open' position if no control signal was produced by the microcontroller. The test was conducted in a way that the solid state relay was unable to receive control signals while operating normally. This leads to the fact that the relay turns on and off the three phase load.

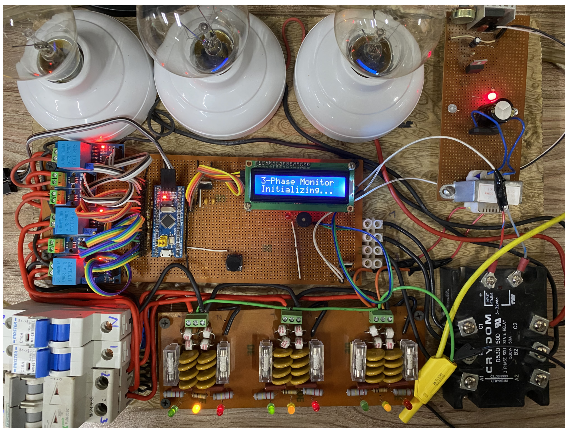

Figure 6.20: Disconnected Load in Fail-Safe Open State

- **Surge Energy Diversion Security**

  The SPD protection board serves as the main protector in the electric circuit and ensures that all excess energy is directed towards earth ground in order to protect the load and also any other control circuit from the excess energy. During the testing process, it became evident that the MOVs and GDTs for all the phases in the circuit were well-grounded on the earth ground reference, hence allowing any excess energy that might be a problem to the system components to be dissipated. Additionally, it was established that the earth ground itself was safe and appropriately wired within the circuit.

- **Overvoltage Protection of Control Circuitry**

  Besides the assurance of the voltage protection of the load, it is crucial for the circuit to ensure self-protection from any possible overvoltage conditions emanating from the voltage of the power supply source. The voltage sensors have been constructed with voltage clamping circuits in their output channels, whereby the signal voltage input to the ADC unit of the microcontroller does not exceed the voltage limit of 3.3V regardless of the supply voltage. When the practical test was carried out at a high supply voltage above the usual voltages to simulate an overvoltage condition, there was no occurrence of overvoltage at the microcontroller's pin terminals.

6.8 Installation Testing

Objectives of installation testing include ensuring that the Intelligent Surge Protection Device operates effectively and safely following installation and its connection to the three-phase power source. In this research work, the Intelligent Surge Protection Device was installed in the Electrical Engineering Laboratory of Bahria University, Islamabad, with the Lab-Volt three-phase power source being used to simulate the actual condition of the high voltage power supply. This is done in order to conduct installation testing. It should be noted that the Lab-Volt power source facilitates accurate control of the three-phase power source voltage.

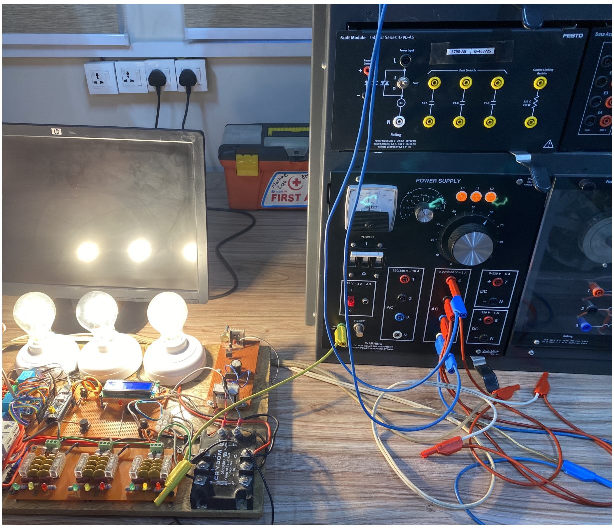

Figure 6.21: Installed System with Lab-Volt Three-Phase Supply

- **Three-Phase Supply Connection and Power-Up Test**

  With the physical installation completed and the device connected to the Lab-Volt three-phase high-voltage source, the device was activated for the first time. In the course of the activation, the device underwent automatic initialization without any external interference. During the process of this initiation, the power supply unit generated controlled voltage output values of 5 volts and 3.3 volts from the three-phase high-voltage source, and at the same time the microcontroller initiated the process of the firmware booting. Lastly, the LCD screen showed the messages regarding initialization, along with the values of voltage and currents in all three phases during the initialization time span. The green LED glowed to confirm successful circuit operation, and the SSR functioned properly to operate the three-phase bulb load.

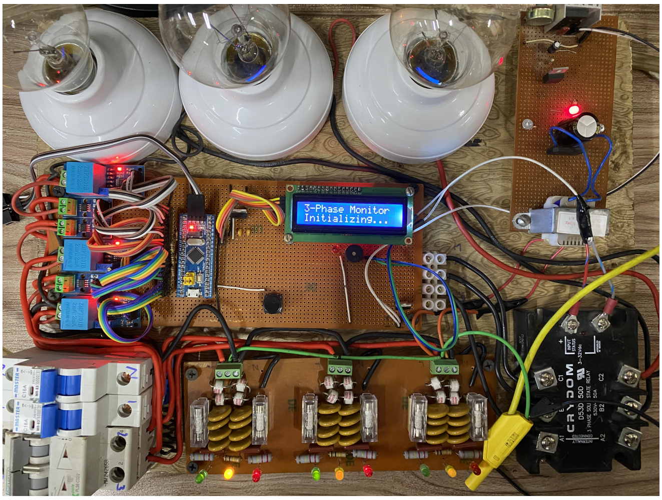

Figure 6.22: ISPD System Status

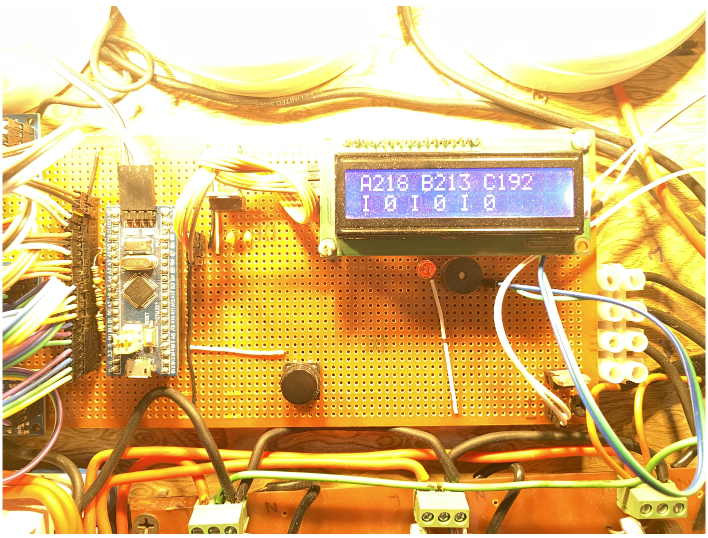

Figure 6.23: LCD Display Presenting 3-phase readings

- **Voltage Level Verification Under Real Supply Conditions**

  With respect to this, after connecting the system with the Lab-Volt three-phase power source, the accuracy of the voltage measurement data shown on the LCD was verified with reference to the output setting to validate the performance of the sensors in measuring and displaying the correct voltages produced by the source. In particular, the output level of the Lab-Volt power source was set at 220 volts per phase, whereas the values obtained in Phases A, B, and C were compared with the set values. It was observed that the values were almost equal to the set values, thus validating the accuracy of the measurement performed by the sensor.

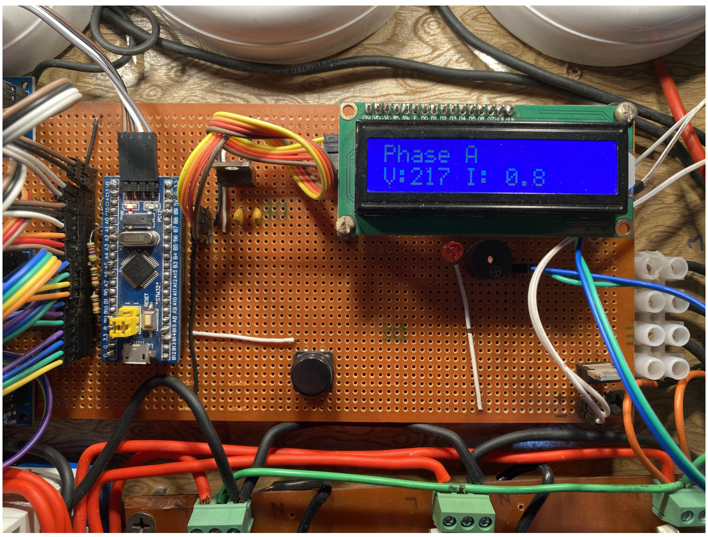

Figure 6.24: Phase A Voltage Interface

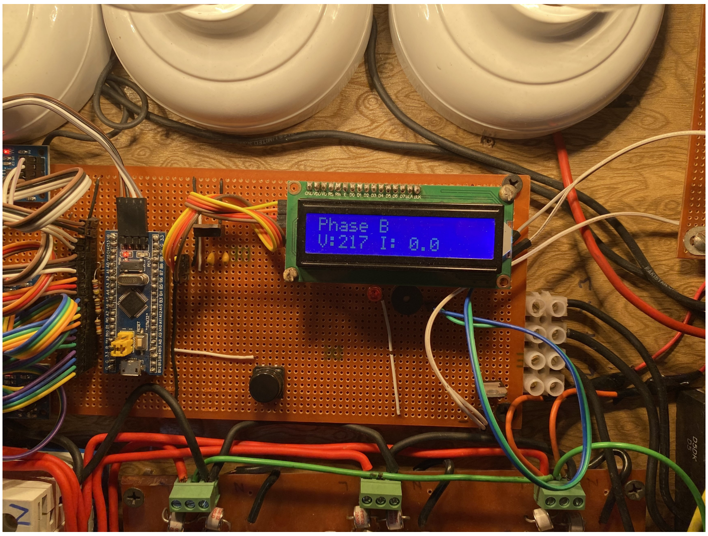

Figure 6.25: Phase B Voltage Interface

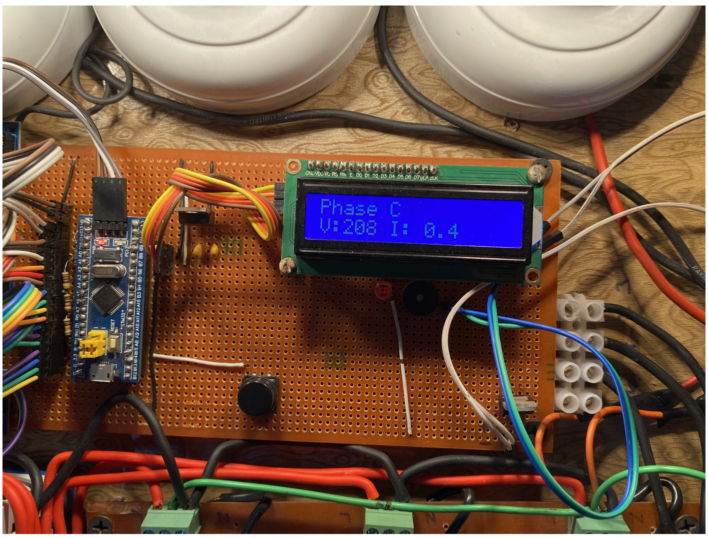

Figure 6.26: Phase C Voltage Interface

- **Protective Response Verification Under Real Supply Conditions**

  The most important thing in verifying the performance of the system can be verified through the successful performance of safety systems, such as fault detection, load disconnection, and recovery of the system. This is carried out by testing the system using three-phase high voltage rather than inputting dummy data. When performing the experiment in the Lab-Volt system, the value of the voltage on one phase was raised above the overvoltage fault threshold. At that time, the load remained connected in the three-phase system. The overvoltage fault was successfully detected, and thus the solid state relay functioned well to disconnect the load. The red indicator lights up, and there is an alarm sound generated by the system, displaying a fault display on the LCD screen. After reverting the voltage level to the normal state, the load reconnects in five seconds.

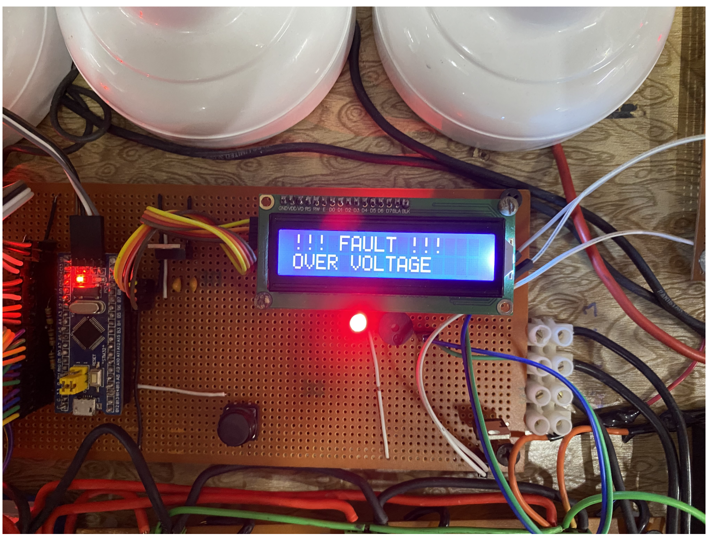

Figure 6.27: System Protective Response

- **Sustained Operation Stability Test**

  The stability and consistency of the operations tests for the system have been carried out on the basis of observing the performance of the system even when it continues to function effectively after connecting it to the actual three-phase power source for quite some time to show that the operations of the system are indeed stable. In simpler terms, the system has been connected to the actual three-phase power source and its performance has been observed for some time. From the observations made during this test, it became apparent that both the readings shown on the LCD screen and the presence of green light indicated that no errors were recorded and the SSR was never triggered.

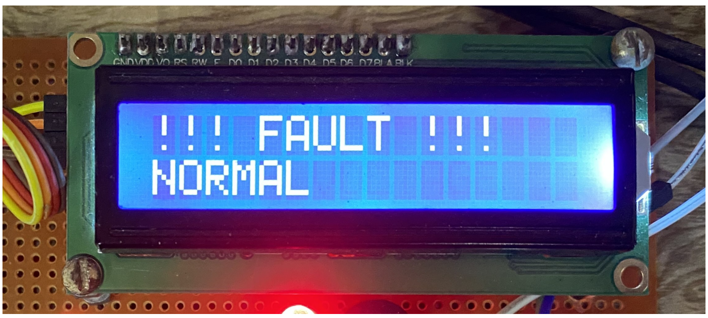

Figure 6.28: System Stability Test

Chapter 7

Conclusion

This project has been successful in realizing its main objective of coming up with an intelligent surge protection device in order to counter some of the weaknesses of current passive surge protection devices. The intelligent device that has been developed shows that when intelligence is added to a surge protection device, its passive nature changes to be proactive, hence making it possible to monitor and respond to abnormal electrical conditions without the aid of a person. From the above study, it can be said that it is necessary to design an intelligent protection in light of the high level of reliance of organizations on sensitive electrical and electronic parts, which the current Metal Oxide Varistors and Gas Discharge Tubes cannot do. There is still the necessity for passive devices as they work quickly in clamping the energy, although they lack intelligence in detecting machine faults, notifying the user of such a fault, and shutting down the load from the faulty voltage states.

Indeed, the incorporation of a fault classifier having three stages namely normal, warning, and fault was the best choice made when designing the overall system architecture. Currently, protection mechanisms operate under on and off conditions with no additional third option that will notify operators about the worsening of a situation without interrupting the connection of the electrical loads. In this case, a warning stage enables operators to diagnose and rectify any faults occurring in the electric circuitry before a fault condition triggers the automatic disconnection of power. It is equally worth noting that the research also showed that it is possible to achieve effective and accurate measurement of three-phase voltage and current data using affordable sensors while using the embedded microcontroller platform for processing. This is an important achievement considering that it eliminates the cost factor that used to confine intelligent protection monitoring to costly industrial equipment only. From the systems engineering point of view, this experiment showed that the reliability and maintainability of the embedded protective system would depend not only on correct hardware design but also on the quality of its software architecture. Firmware, which is well-architected and modularized, dividing sensory perception, decision-making and control of output signals, leads to predictable behavior of the system, diagnosable errors and the possibility of improving it without reducing its protective capability. Though it might seem to be a matter of pure theory at first glance, these considerations become vital when thinking about the dangerous nature of the protective system being implemented. Utilizing simulation software like Proteus to validate the circuit design and MATLAB for algorithms proved the importance of employing simulation-oriented development approach in embedded hardware design. Detecting and correcting errors in design by means of simulations was invariably faster and more cost-efficient than physical tests of the actual hardware.

The results from this project have shown that we can make a design, for intelligent Surge Protection Devices that work well in the JMICC Power Distribution Box and other systems that distribute power in three phases. The intelligent Surge Protection Device system has helped to fix some problems with the technology and it is still affordable and simple to use in an embedded system. The system is also made in a way that makes it easy to upgrade without changing the thing. We can just add parts to the intelligent Surge Protection Device system without messing with the way it is built.

7.1 Future Work

This system operates properly as it should. However, there are some improvements that could enhance its performance. Firstly, we could add a temperature sensor module in order to accomplish our aim at the stage of designing this system. It means that this system should have sensors. Adding such module in the system would allow monitoring of everything and also provide thermal protection of the system. Moreover, another important improvement could be the addition of an Internet of Things (IoT) system based on modules such as ESP8266 and ESP32. It means that one would be able to access this system from remote locations. In particular, operators and managers of this system would receive information about its operations and notifications in case any problems arise; thus, they would not need to visit the distribution box for control purposes. Thus, adding a temperature sensor module and IoT system to this system would be a very good improvement. Our system would operate properly, and also, it could be managed remotely which was our main idea at the stage of designing this system.

Along with remote accessibility, a GUI needs to be introduced, which can be either achieved locally via the use of color TFT screen display or through an Internet-based mobile phone application. In this way, not only will the system become easy to understand, but also it will be more informative, since everything from measurements, faults, and system statuses can be recorded in graphic form. Using the external modules of EEPROM/SD card, as well as the real-time clock module, it was possible for us to record faults and perform Condition-Based Maintenance, by having an overall record of all the faults recorded during the whole lifetime of the system. We can find out about any repeating problems that we would not see with the usual ways of checking. If we add a part that figures out how much energy is made when there is a surge and how long an SPD will last and it also checks the order of the phases on its own it will work a lot better at protecting things. This will help us keep an eye on how thingsre working and replace them when needed so the system can work with other kinds of loads that are sensitive to phases that are not balanced like electric motors. The last thing we need to do to make a system that works is make a PCB board that fits in a strong case, for factories.

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Appendix A

User Manual

A.1 Introduction

The intelligent SPD incorporated in the 2 kVA power distribution box has been provided in the user manual along with other details such as safety, installation procedures, and maintenance. The intelligent SPD was designed to safeguard the electrical system from dangers such as voltage spikes, over-voltage, overloading, and interruptions in supply. It incorporates monitoring and control with traditional security techniques. The intelligent SPD automatically cuts off the load from the power source when its operation is unsafe.

A.2 System Overview

With a maximum capacity of 2 kVA, Intelligent SPD is a compact machine designed for low-power electricity generation and distribution. It can be employed in equipment distribution panels, offices, residences, laboratories, and small industrial installations.

The System Includes:

- System of surge arresters
- voltage detection unit
- Current Load Monitoring unit
- Control Unit
- Solid-State Switching Relay unit
- Fault Alarm Indications
- LCD Display Unit

A.3 Technical Specifications

Parameter	Value
Rated System Capacity	2 kVA
Supply Type	Three Phase AC
Protection Type	Intelligent Surge Protection
Monitoring	Voltage / Load Status
Display	LCD Module
Switching Device	Relay / Solid State Relay
Alarm Output	LED + Buzzer
Control Unit	STM32 Microcontroller

Figure A.1: Specifications Table

A.4 Main Functions

The device performs the following functions:

- Protects from transients and overvoltages.
- Constantly monitors the voltage level.
- Identifies undesirable conditions and overload.
- The Device disconnects the load in a fault condition.
- Displays operational condition.
- Fault indicators both visual and audible.
- Restoring the power supply after the operating conditions become normal.

A.5 Safety Precautions

The safety precautions should include:

- Only trained persons should conduct installations.
- Turn off the power source before installing the device.
- Ensure proper earthing of the distribution box.
- Do not overload the device more than its capacity of 2 kVA.
- Prevent exposure of the device to dust, moisture, and heat sources.
- Bypassing the relay circuitry should never be attempted.
- Loose terminals and damaged wires should be fixed immediately.
- During operation under voltage, do not touch the terminals.

A.6 LCD Display Messages

Display Message	Meaning
System Ready	Normal startup completed
Voltage Normal	Supply voltage within safe range
Over Voltage	Input voltage exceeds limit
Low Voltage	Supply below operating threshold
Load Trip	Output disconnected due to overload
Fault Detected	Protection event active
Restore Mode	System returning to normal

Figure A.2: Table of Messages

A.7 Installation Procedure

- Securely mount the device within or beside the power distribution box.

- Ensure adequate space between the control/switching circuitry and the ventilation area.
- Ensure adequate spacing between the high voltage and low voltage circuits.
- Connect the earth, neutral, and incoming phase lines to their respective input terminals.
- Connect the output load lines to their respective output terminals.
- Ensure that the unit is well-grounded.
- Ensure that all connections are properly secured and polarized.
- Check that there are no exposed terminals or loose wires.
- Ensure that the total load that is connected does not exceed the 2 kVA rating.
- After ensuring that all safety precautions have been observed, switch on the power supply.
- Look out for any signs that show that the unit has been energized on the LCD screen.

A.8 Operating Instructions

- Switch on the power to the system.
- Do not start working until the system initialization is completed.
- Pay close attention to the LCD messages displayed while booting.
- Make sure that the voltage value falls within the allowed limits.
- The load should not exceed 2kVA
- Both voltage and load are controlled in normal operation mode.
- LCD displays the system status information.
- An automatic shutdown takes place if the system registers an abnormal voltage level or an overload.
- In case of any faults, light signals and the buzzer warn you about this.
- Eliminate the source causing such a situation.
- Start up the system manually or automatically based on how the program was designed.
- Ensure that each component of the system is functioning before connecting any electronic devices by considering the notifications on the LCD screen.
- Manage the system by monitoring the indicators.

A.9 Device Applications

- Power Distribution Box
- Electrical Panels
- Laboratory Power Systems
- Commercial and Residential Installations
- Easily Affected Equipment Protection