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Abstract

This project develops an intelligent electrical protection system designed to improve the safety of residential electrical installations. It provides real-time monitoring and rapid detection of electrical faults in order to reduce risks and damage. The system combines control, monitoring, and intelligent protection functions through a distributed architecture. This solution ensures reliable, efficient, and modern electrical protection.

Résumé

Ce projet développe un système intelligent de protection électrique destiné à améliorer la sécurité des installations domestiques. Il permet la surveillance en temps réel et la détection rapide des anomalies électriques afin de réduire les risques et les dommages. Le système combine des fonctions de contrôle, de surveillance et de protection intelligente à travers une architecture distribuée. Cette solution assure un fonctionnement fiable, efficace et adapté aux besoins des habitations modernes.

ملخص

يهدف هذا المشروع إلى تطوير نظام ذكي للحماية الكهربائية بهدف تحسين سلامة التجهيزات المنزلية. يسمح النظام بالمراقبة اللحظية والكشف السريع عن الأعطال الكهربائية من أجل التقليل من الأخطار والأضرار. كما يجمع بين وظائف التحكم والمراقبة والحماية الذكية من خلال بنية موزعة. تضمن هذه المنظومة عملًا فعالًا وموثوقًا يتناسب مع متطلبات المنازل الحديثة.

TABLE OF CONTENTS

Acknowledgments……..I

Abstract……II

Table of Contents……III

Table of Abbreviations……VII

Key Words……VII

Tabl of Figure……...VIII

General Introduction……2

Chapter I: General Study of Residential Electrical Protection Systems……..3

I. Introduction……4

II. Domestic Electrical Installation……5

II.1 Structure of a Residential Installation……...5

II.2 Meter, Circuit Breaker and Electrical Panels……6

III. Electrical Risks in Homes……7

III.1 Short Circuits……...7

III.2 Leakage Current……...7

III.3 Overvoltage……..7

III.4 Cable Overheating……...7

IV. Classical Protection Devices……...8

IV.1 Fuses……8

IV.2 Circuit Breakers……...8

IV.3 Differential Switches……...9

IV.4 Limitations of Conventional Protection Systems……9

V. Intelligent Protection Systems……..9

V.1 Principle of Intelligent Systems……9

V.2 IoT and Electrical Monitoring……10

V.3 Wireless Communication in Embedded Systems……...11

VI. Conclusion……11

Chapter II: Design and Architecture of the Proposed System……12

I. Introduction……..13

II. General Architecture of the Proposed System……13

II.1 Central Unit…….14

II.2 Secondary Units……..14

II.3 Communication Between Modules…….14

III. Hardware Components……..15

III.1 ESP32 Development Board……...15

III.2 Current Sensor (ACS712)……..15

III.3 Voltage Sensor (ZMPT101B)……16

III.4 Relay……..16

III.5 OLED Display……...17

III.6 Buzzer……17

III.7 LEDs……..18

III.8 Push Buttons……..18

III.9 Wi-Fi and Bluetooth Communication……... 18

IV. Power Supply Design…… 19

IV.1 AC/DC Converter……..19

IV.2 Voltage Regulator……..19

IV.3 Electrical Protection and Safety……20

IV.3.1 Fuse……...20

IV.3.2 Metal Oxide Varistor……20

IV.3.3 Electrical Isolation and Safety Distances…….21

V. Electronic Schematics of the System……..22

V.1 Central Unit Schematic……...22

V.2 Secondary Unit Schematic……..22

VI. Prototype Implementation…… 23

VI.1 PCB Design……... 23

VI.1.1 Central Unit PCB……..23

VI.1.2 Secondary Unit PCB…….24

VI.2 System Assembly……..25

VI.2.1 Central Unit……..25
VI.2.2 Secondary Unit…….26
VII. Conclusion……27
Chapter III: Software Development and System Integration…….28
I. Introduction……..29
II. Development Environment…….29
II.1 Arduino IDE……29
II.2 ESP32 Programming……...30
III. Monitoring Functions……31
III.1 Voltage Monitoring……...31
III.2 Current Monitoring……32
III.3 Electrical Fault Detection……..33
III.4 Decision-Making Algorithm……..34
IV. Alert Management…….35
IV.1 LED Indicators…….. 35
IV.2 Audible Alarm……...36
IV.3 Fault Display on OLED Screen…….36
V. Wireless Communication……37
V.1 Wi-Fi Configuration……... 37
V.2 Data Exchange Between Units……... 38
V.3 Communication Security…… 39
VI. Electrical Disconnection Strategy…… 40
VI.1 Total Disconnection……...40
VI.2 Selective Disconnection…… 41
VII. System Algorithms and Flowcharts……..……... 42
VII.1 Main Unit Algorithm……42
VII.2 Secondary Unit Algorithm……...43
VIII. Application Developer……44
VIII.1 Login Interface……44
VIII.2 Monitoring and Notification Interface……45

VIII.3 Configuration Interface…….. 47
VIII.4 Control Interface…… 48
IX. Conclusion…… 48
Chapter IV: Tests, Results and Perspectives…… 50
IV.1 Introduction……. 51
IV.2 Test Methodology……51
IV.2.1 Overvoltage Test…… 51
IV.2.2 Undervoltage Test…….. 52
IV.2.3 Warning Condition Test……. 52
IV.2.4 Overcurrent Test…… 53
IV.2.5 Short-Circuit Test…….. 54
IV.2.6 Wireless Communication Test……... 54
IV.3 Experimental Results…….. 55
IV.3.1 Reaction Time…… 55
IV.3.2 Detection Reliability…….. 55
IV.3.3 Relay Performance……. 56
IV.3.4 Energy Consumption……. 56
IV.4 Analysis and Discussion of Results…… 57
IV.4.1 Analysis of Protection Performance…….. 58
IV.4.2 Analysis of Communication Performance……. 58
IV.4.3 Analysis of System Reliability…….. 58
IV.5 Improvement Perspectives…….. 59
IV.6 Conclusion…….. 59
General Conclusion…… 61
Bibliography…… 64

Table of Abbreviations

Abbreviation	Full Meaning
ESP32	Espressif Systems 32-bit Microcontroller
PCB	Printed Circuit Board
ZMPT101B	Voltage Transformer Sensor Module
ACS712	Current Sensor Module (Hall Effect)
HLK-PM05	Hi-Link Power Module (220V AC → 5V DC)
LD1117S33	3.3V Low Drop-Out Linear Voltage Regulator
OLED	Organic Light-Emitting Diode Display
I2C	Inter-Integrated Circuit Communication Protocol
SPI	Serial Peripheral Interface
ESP-NOW	Espressif Peer-to-Peer Wireless Communication Protocol
NC	Normally Closed (Relay Default State)
NO	Normally Open (Relay Alternate State)
AC	Alternating Current
DC	Direct Current
RMS	Root Mean Square
ADC	Analog to Digital Converter
GPIO	General Purpose Input/Output
IoT	Internet of Things
PWM	Pulse Width Modulation
UART	Universal Asynchronous Receiver-Transmitter

Key Words

• Intelligent Electrical Protection • ESP32 Microcontroller • ESP-NOW Wireless Protocol
• Voltage & Current Monitoring • Relay-based Disconnection • PCB Design (Proteus 8)
• Real-Time Fault Detection • Residential Electrical Safety • 220V AC / 50Hz Systems

TABLE OF FIGURES

Figure I.1 : Structure of a residential electrical installation 5
Figure I.2 : Residential electrical meter..... 6
Figure I.3 : Main electrical circuit breaker 6
Figure I.4 : Residential electrical distribution board 7
Figure I.5 : Electrical fuse 8
Figure I.6 : Electrical circuit breaker..... 8
Figure I.7 : Differential protection switch 9
Figure I.8 : Intelligent electrical protection system..... 10
Figure I.9 : IoT-based electrical monitoring system..... 10
Figure I.10 : Wireless communication in embedded systems 11

Figure II.1 : General architecture of the proposed system 13
Figure II.2 : ESP32-WROOM-32 development board..... 15
Figure II.3 : ACS712 current sensor 16
Figure II.4 : ZMPT101B voltage sensor 16
Figure II.5 : SRD-05VDC-SL-C relay 17
Figure II.6 : OLED display module..... 17
Figure II.7 : Active buzzer module 17
Figure II.8 : Light Emitting Diodes (LED) 18
Figure II.9 : Push button..... 18
Figure II.10 : HLK-PM05 power module 19
Figure II.11 : LD1117V33 voltage regulator 20
Figure II.12 : Fuse 20
Figure II.13 : Metal Oxide Varistor (MOV)..... 21
Figure II.14 : Isolation between high-voltage and low-voltage sections 21
Figure II.15 : Schematic diagram of the central unit..... 22
Figure II.16 : Schematic diagram of the secondary unit 23
Figure II.17 : PCB layout of the central unit..... 24
Figure II.18 : PCB layout of the secondary unit..... 25
Figure II.19 : Assembled central unit..... 26
Figure II.20 : Assembled secondary unit..... 26

Figure III.1 : Arduino IDE development environment 29
Figure III.2 : ESP32 programming process..... 30
Figure III.3 : Voltage Monitoring Algorithm..... 31
Figure III.4 : Current Monitoring Algorithm 32
Figure III.5 : Electrical Fault Detection Algorithm 33
Figure III.6 : Decision-Making Algorithm..... 34

Figure III.7 : LED Status Indication Algorithm 35
Figure III.8 : Audible Alarm Management Algorithm 36
Figure III.9 : OLED Display Management Algorithm 37
Figure III.10 : Wi-Fi Communication Process 38
Figure III.11 : ESP-NOW Communication Process 39
Figure III.12 : Communication Security Process 40
Figure III.13 : Total Disconnection Algorithm 41
Figure III.14 : Selective Disconnection Algorithm 42
Figure III.15 : Main Unit Algorithm 43
Figure III.16 : Secondary Unit Algorithm 44
Figure III.17 : Login Interface 45
Figure III.18 : Communication and System Status Interface 46
Figure III.19 : Main and Secondary Unit Monitoring Interface 46
Figure III.20 : Real-Time Trends Interface 46
Figure III.21 : Event Log Interface 46
Figure III.22 : Threshold Configuration Interface 47
Figure III.23 : Communication and Cloud Configuration Interface 47
Figure III.24 : Application Preferences Interface 47
Figure III.25 : Protection Control Panel 48
Figure III.26 : Relay Management Interface 48

Figure IV.1 : Central Unit During Overvoltage Fault 51
Figure IV.2 : Overvoltage Fault Detection in the Mobile Application 51
Figure IV.3 : Central Unit During Undervoltage Fault 52
Figure IV.4 : Undervoltage Fault Detection in the Mobile Application 52
Figure IV.5 : Central Unit During Warning Condition 53
Figure IV.6 : Mobile Application During Warning Condition 53
Figure IV.7 : Mobile Application During Overheating Warning Condition 53
Figure IV.8 : Mobile Application During Overheating Danger Condition 53
Figure IV.9 : Mobile Application During Short-Circuit Condition 54
Figure IV.10 : Communication Between Main and Secondary Units 55
Figure IV.11 : Real-Time Monitoring Through the Mobile Application 55
Figure IV.12 : Relay Operation During Fault Conditions 56

GENERAL

INTRODUCTION

Introduction

Electrical installations are an essential part of modern residential and industrial environments due to the increasing use of electrical and electronic equipment. They provide electrical energy for lighting, communication, automation, and many daily applications. However, electrical systems are exposed to several dangerous faults such as overvoltage, overcurrent, short circuits, and cable overheating, which may cause equipment damage, electrical fires, and serious safety risks. [1]

Conventional electrical protection systems are mainly based on traditional devices such as fuses and circuit breakers. Although these devices provide basic protection, they remain limited in terms of real-time monitoring, intelligent fault analysis, and rapid intervention. In addition, the absence of continuous supervision reduces the ability to detect electrical anomalies before dangerous situations occur [2].

Intelligent electrical protection projects combine real-time monitoring, wireless communication, and smart control technologies to improve the safety and reliability of electrical installations. These systems use sensors and embedded communication technologies to continuously monitor electrical conditions and react rapidly in abnormal situations. Through distributed monitoring and intelligent fault isolation, they reduce risks and improve operational efficiency in residential environments [3].

The project addresses several important challenges including fast fault detection, reliable monitoring, intelligent electrical isolation, and efficient system management. By integrating modern technologies, the proposed system aims to improve electrical protection performance and contribute to the development of advanced smart protection solutions adapted to modern environments.

The structure of this thesis consists of several comprehensive chapters. **Chapter One** presents a general study of residential electrical protection systems and related technologies. **Chapter Two** discusses the general architecture of the proposed system, including hardware design and component selection. **Chapter Three** focuses on software development, communication, monitoring strategies, and system integration. **Chapter Four** covers implementation, testing, performance evaluation, and analysis of the obtained results. Finally, the document concludes with a **general conclusion** and future **perspectives**.

Chapter **I**:

General Study of Residential Electrical Protection Systems

Chapter I: General Study of Residential Electrical Protection Systems

I. Introduction:

Electrical installations constitute a fundamental part of modern residential environments, making their safety, reliability, and continuity of power supply a major concern. They provide the electrical energy required for lighting systems, household appliances, communication devices, and various electronic equipment used in everyday life. As the dependence on electricity continues to increase, ensuring the proper protection of residential electrical networks has become essential. [4]

Residential electrical installations are exposed to several faults and abnormal operating conditions, including short circuits, earth leakage currents, overvoltages, overloads, and cable overheating. These faults may cause equipment damage, power interruptions, electrical fires, and serious safety risks. To reduce these hazards, conventional protection devices such as fuses, circuit breakers, and differential switches are widely used in residential electrical systems. Although effective, these devices remain limited in terms of real-time monitoring and advanced fault management capabilities. [5]

Recent advances in embedded systems, wireless communication, and Internet of Things (IoT) technologies have contributed to the development of intelligent electrical protection systems. These systems enable continuous monitoring of electrical parameters, rapid fault detection, and improved supervision of electrical installations. [6]

This chapter presents a general study of residential electrical protection systems. It introduces the structure of domestic electrical installations, the main electrical hazards encountered in residential environments, conventional protection devices, and the evolution toward intelligent protection systems based on modern monitoring and communication technologies. [6]

II. Domestic Electrical Installation:

Residential electrical installations are designed to distribute electrical energy safely inside houses and residential buildings. These installations include several interconnected components responsible for electrical distribution, protection, and energy management. They provide electrical power for lighting systems, household appliances, communication devices, and many other applications used in everyday life [7].

II.1 Structure of a Residential Installation:

Residential electrical installations are composed of several electrical components connected together in order to ensure the transmission and distribution of electrical energy throughout the building. These components work together to provide a safe, stable, and reliable electrical supply for different residential applications [8].

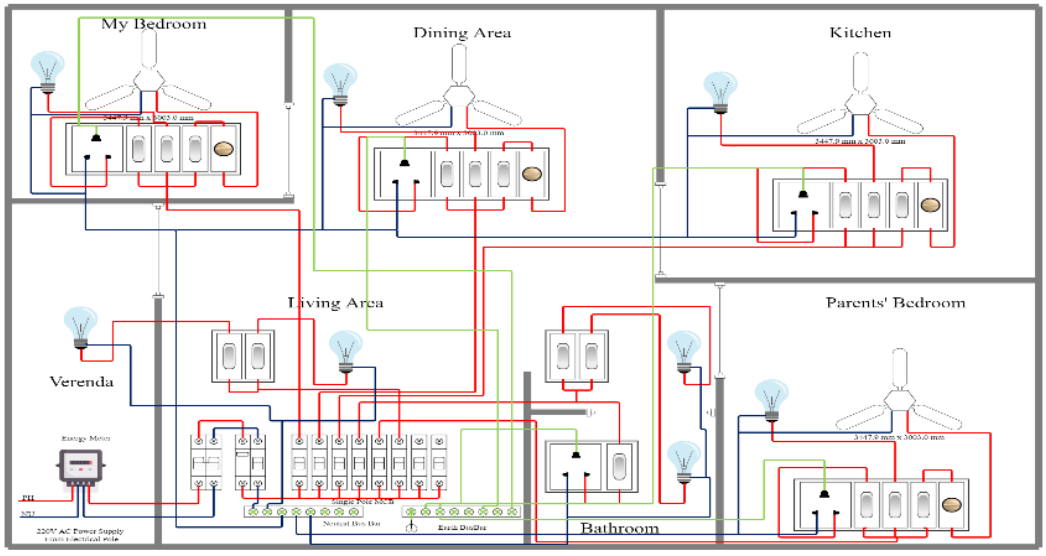


Figure I.1 : Structure of a residential electrical installation

A residential electrical installation generally includes an electrical meter, a main circuit breaker, electrical panels, protection devices, and multiple electrical circuits connected to different areas of the house. The electrical meter is responsible for measuring energy consumption, while the main circuit breaker protects the installation against overloads and short circuits. Electrical panels are used to organize and distribute electrical energy between the different circuits of the installation [9].

Modern residential installations are designed according to electrical safety standards in order to reduce electrical risks and improve operational reliability. Proper installation and maintenance of

electrical systems are essential to ensure user safety and prevent electrical accidents that may affect both people and electrical equipment [10].

II.2 Meter, Circuit Breaker and Electrical Panels:

The electrical meter is one of the main elements of residential electrical installations. Its role is to measure the amount of electrical energy consumed inside the house in order to calculate energy usage. Modern electrical meters provide accurate measurements and improve energy management in residential environments [11].



Figure I.2 : Residential electrical meter

The main circuit breaker is designed to protect electrical installations against overloads and short circuits. It automatically disconnects the electrical supply when abnormal electrical conditions occur, helping to reduce electrical damage and improve user safety. Circuit breakers are considered essential protection devices in modern residential electrical systems [12].



Figure I.3 : Main electrical circuit breaker

Electrical panels are used to organize and distribute electrical energy between the different circuits of the installation. They contain several protection devices such as circuit breakers and differential switches arranged to ensure safe and reliable electrical distribution throughout the building. Proper

organization of electrical panels improves maintenance operations and increases electrical safety. [13]



Figure I.4 : Residential electrical distribution board

III. Electrical Risks in Homes:

Residential electrical installations are exposed to several electrical risks that may affect both electrical equipment and human safety. These risks are generally caused by abnormal electrical conditions, damaged equipment, or excessive electrical loads. Electrical protection systems are therefore essential to ensure safe and reliable operation of residential electrical installations [14].

III.1 Short Circuits:

A short circuit occurs when an abnormal connection is created between electrical conductors, causing a sudden increase in electrical current. Short circuits may generate excessive heat, equipment damage, and electrical fires if protection devices are not properly implemented [15].

III.2 Leakage Current:

Leakage current occurs when electrical current flows outside the normal electrical path due to insulation damage, humidity, or electrical contact. This phenomenon may increase the risk of electrical shock and affect user safety [16].

III.3 Overvoltage:

Overvoltage is an abnormal increase in electrical voltage that may damage electrical equipment and reduce system reliability. It may be caused by lightning, switching operations, or disturbances in the electrical network. [17]

III.4 Cable Overheating:

Cable overheating is generally caused by excessive electrical loads, poor electrical connections,

or unsuitable cable dimensions. This phenomenon may damage cable insulation and increase the risk of electrical fires [18].

IV. Classical Protection Devices:

Classical electrical protection devices are used to protect residential electrical installations against abnormal electrical conditions and dangerous faults. These devices help reduce electrical risks and improve the safety and reliability of electrical systems inside houses and buildings [19].

IV. 1Fuses:

Fuses are among the oldest electrical protection devices used in residential installations. They are designed to disconnect the electrical circuit when the electrical current exceeds a specific limit. The fuse contains a metallic element that melts under excessive current conditions, interrupting the electrical flow and protecting the installation from damage [20].



Figure I.5 : Electrical fuse

IV.2 Circuit Breakers:

Circuit breakers are automatic protection devices widely used in modern electrical installations. Their role is to disconnect the electrical supply during overloads and short circuits in order to protect electrical equipment and reduce electrical hazards. Unlike fuses, circuit breakers can be reused after resetting [21].



Figure I.6: Electrical circuit breaker

IV.3 Differential Switches:

Differential switches are designed to protect users against electrical shock caused by leakage current. They detect differences between incoming and outgoing electrical currents and disconnect the electrical supply when abnormal leakage occurs. [22]



Figure I.7 : Differential protection switch

IV.4 Limitations of Conventional Protection Systems:

Although conventional protection devices provide basic electrical safety, they remain limited in terms of real-time monitoring, intelligent fault analysis, and remote supervision. These limitations have encouraged the development of intelligent electrical protection systems capable of improving monitoring, fault detection, and operational reliability [23].

V. Intelligent Protection Systems:

Intelligent protection systems have become an important solution for improving the safety and reliability of modern electrical installations. Unlike conventional protection devices, these systems combine monitoring, automatic fault detection, communication technologies, and intelligent control functions in order to ensure continuous supervision of electrical systems and rapid reaction during abnormal electrical conditions [24].

V.1 Principle of Intelligent Systems:

Intelligent electrical protection systems are based on the continuous monitoring of electrical parameters such as voltage, current, temperature, and energy consumption. These systems use sensors, embedded controllers, and communication technologies to analyze electrical conditions and detect dangerous faults in real time [25].

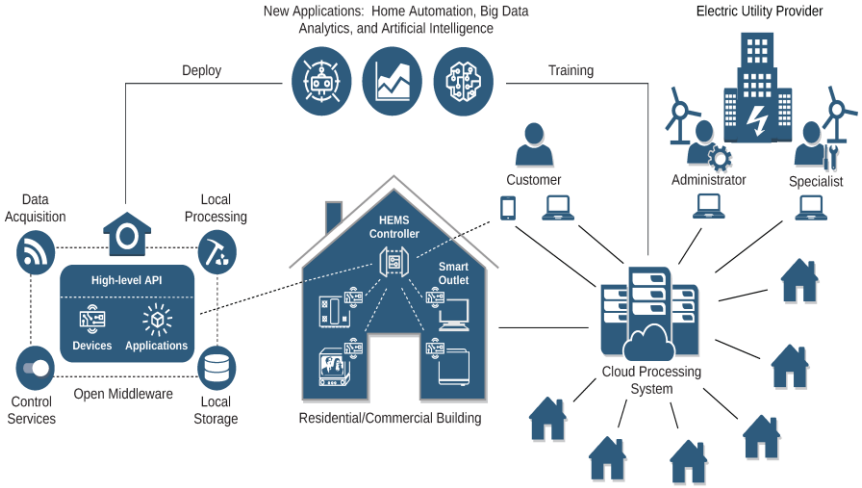


Figure I.8 : Intelligent electrical protection system

Through automatic monitoring and intelligent fault management, these systems improve operational reliability and reduce electrical risks inside residential environments [25].

V.2 IoT and Electrical Monitoring:

The development of Internet of Things technologies has significantly improved modern electrical monitoring systems. IoT-based protection systems allow real-time data acquisition, remote supervision, and communication between different electrical devices and monitoring platforms [26].

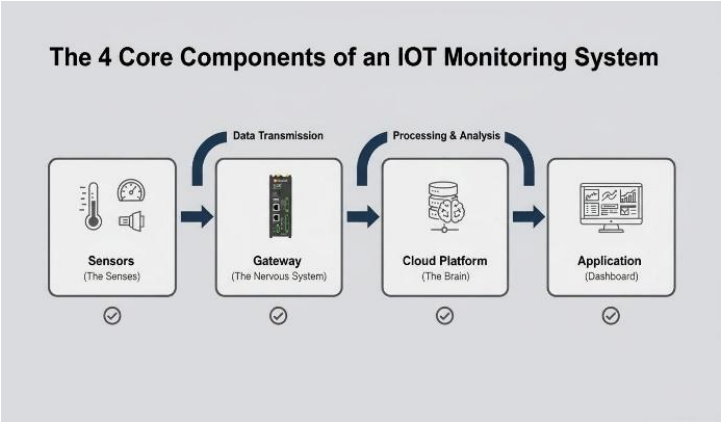


Figure I.9 : IoT-based electrical monitoring system

These technologies improve system flexibility and enable users to monitor electrical installations remotely through connected applications and smart monitoring interfaces [26].

V.3 Wireless Communication in Embedded Systems:

Wireless communication technologies are widely used in intelligent electrical protection systems in order to exchange data between sensors, controllers, and monitoring devices. Technologies such as Wi-Fi, Bluetooth, and ESP-NOW allow reliable communication and real-time supervision of electrical installations [27].

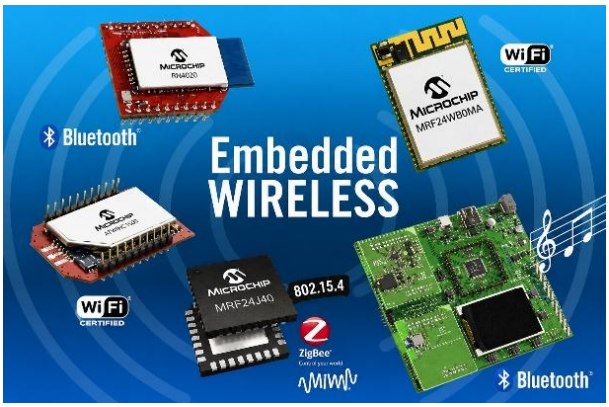


Figure I.10 : Wireless communication in embedded systems

The integration of wireless communication improves system scalability, simplifies installation, and enhances the overall efficiency of intelligent electrical protection systems [27].

VI. Conclusion:

This chapter presented a general study of residential electrical protection systems and related technologies. It introduced the structure of residential electrical installations, the main electrical risks found in residential environments, and the conventional protection devices commonly used to ensure electrical safety. The chapter also discussed intelligent protection systems and the role of modern communication and monitoring technologies in improving the reliability and efficiency of electrical installations. The next chapter will present the general architecture of the proposed system and the different hardware components used in the implementation.

CHAPTER II:

Design and Architecture of the Proposed System

Chapter II: Design and Architecture of the Proposed System

I. Introduction:

This chapter presents the design and architecture of the proposed intelligent electrical protection system. It describes the overall structure of the system, the hardware components used, and the communication technologies that ensure data exchange between different system units. The chapter also explains the operating principle of the proposed solution and the role of each component in monitoring, fault detection, and electrical protection.

II. General Architecture of the Proposed System:

The proposed system is designed to provide intelligent monitoring and protection of residential electrical installations. It is based on a distributed architecture composed of a main control unit and one or more secondary units installed at different locations within the electrical installation. These units continuously monitor electrical parameters and cooperate to detect abnormal conditions and improve protection efficiency.

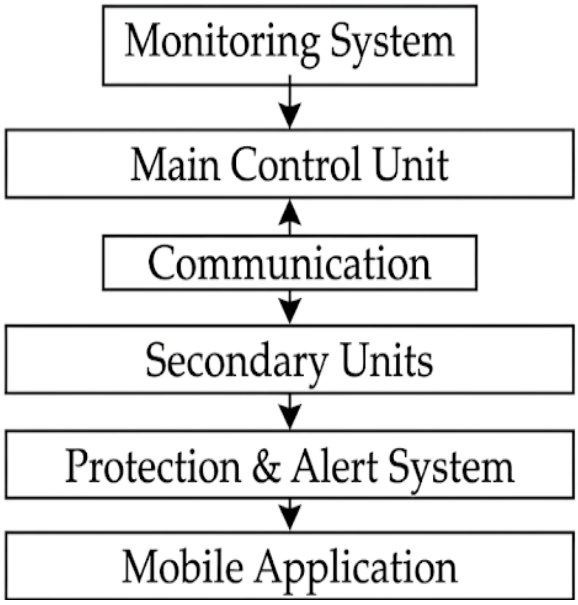


Figure II.1 : General architecture of the proposed system

II.1 Central Unit:

The main unit acts as the central controller of the system. It collects data from the sensors, processes electrical measurements, manages communication with the secondary units, and supervises the protection mechanisms. It is also responsible for sending alerts and providing monitoring information to the user.

The central unit plays a key role in ensuring the proper operation of the entire system. It coordinates all monitoring and protection functions and serves as the decision-making element of the proposed architecture.

II.2 Secondary Units:

The secondary units are installed near specific electrical circuits or areas of the house. Their role is to acquire local electrical measurements and transmit them to the main unit. This distributed approach improves fault localization and allows selective isolation of affected circuits when necessary.

Each secondary unit operates independently while remaining connected to the main unit. This architecture improves system scalability and enhances monitoring efficiency throughout the electrical installation.

II.3 Communication Between Modules:

Communication between the different modules ensures reliable data exchange and coordination within the system. It allows the transmission of monitoring data, fault information, and control commands between the main unit and the secondary units. This communication improves system responsiveness and contributes to efficient monitoring and protection of the electrical installation.

Reliable communication is essential for maintaining synchronization between all system components and ensuring rapid reaction when abnormal electrical conditions are detected.

III. Hardware Components:

The proposed S-PROTECTION system is based on several hardware components that work together to ensure monitoring, communication, and electrical protection functions. These components were selected according to the requirements of the system in terms of performance, reliability, and ease of implementation.

III.1 ESP32 Development Board:

The ESP32-WROOM-32 is a microcontroller widely used in embedded systems and Internet of Things (IoT) applications. It integrates Wi-Fi and Bluetooth communication technologies, allowing wireless connectivity and real-time data exchange. The module offers high performance, low power consumption, and multiple input/output interfaces, making it suitable for monitoring and control applications [28].

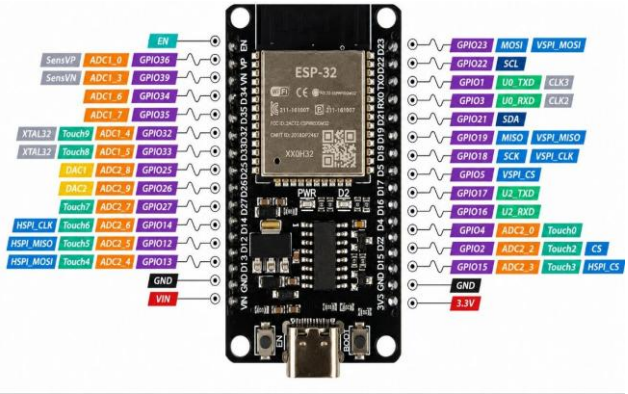


Figure II.2 : ESP32-WROOM-32 development board

III.2 Current Sensor (ACS712):

The ACS712 is a current sensor based on Hall-effect technology and is widely used for current measurement applications. It provides accurate current measurements and electrical isolation between the measured circuit and the control system. The sensor is available in different measurement ranges, making it suitable for various monitoring and protection applications [29].

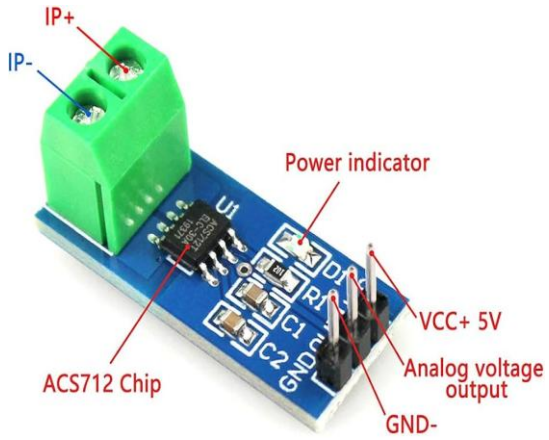


Figure II.3 : ACS712 current sensor

III.3 Voltage Sensor (ZMPT101B):

The ZMPT101B is a voltage sensor module designed for AC voltage measurement applications. It provides accurate voltage monitoring while ensuring electrical isolation between the high-voltage circuit and the control system. The module is compact, reliable, and suitable for real-time voltage monitoring applications [30].

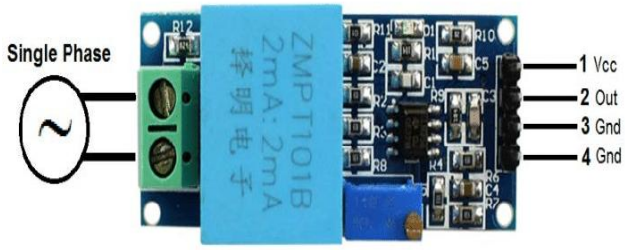


Figure II.4 : ZMPT101B voltage sensor

III.4 Relay:

The relay is an electromechanical switching device used to control high-voltage electrical circuits through low-voltage control signals. It provides electrical isolation between the control circuit and the power circuit, ensuring safe and reliable operation. Relays are widely used in control, automation, and electrical protection applications [31].



Figure II.5 : SRD-05VDC-SL-C relay

III.5 OLED Display:

The OLED display is a compact electronic screen widely used in embedded systems for real-time information visualization. It offers low power consumption, high contrast, and good readability, making it suitable for displaying measurements, system status, and monitoring data [32].



Figure II.6 : OLED display module

III.6 Buzzer:

The buzzer is an electronic sound-generating device used to provide audible alerts and warning signals. It is commonly integrated into monitoring and protection systems to notify users when abnormal conditions or fault situations are detected [33].



Figure II.7 : Active buzzer module

III.7 LEDs:

Light Emitting Diodes (LEDs) are electronic components used for visual indication and status signaling. They are characterized by low power consumption, fast response time, and long operating life. LEDs are widely used in electronic systems to indicate operating conditions and fault states [34].



Figure II.8 : Light Emitting Diodes (LED)

III.8 Push buttons:

Push buttons are simple electromechanical input devices used to send commands and interact with electronic systems. They provide a reliable and user-friendly method for controlling system functions and navigating through different operating modes. Due to their simplicity and low cost, push buttons are widely used in embedded and monitoring applications [35].



Figure II.9 : Push button

III.9 Wi-Fi and Bluetooth Communication:

Wi-Fi and Bluetooth are wireless communication technologies integrated into the ESP32 microcontroller. They enable data exchange between devices without the need for physical

connections and provide flexible communication solutions for embedded and IoT applications. These technologies offer reliable connectivity, low power consumption, and support for real-time monitoring and control systems [36].

IV. Power Supply Design:

The power supply is an essential part of the proposed system, as it provides the electrical energy required for the operation of all electronic components. A reliable power supply design ensures stable system performance, protects sensitive devices, and guarantees continuous operation under different conditions

IV.1 AC/DC Converter:

The HLK-PM05 is a compact AC/DC power module designed to convert 220V AC mains voltage into a regulated 5V DC output. It provides electrical isolation, high efficiency, and stable operation, making it suitable for embedded and IoT applications. Its compact size and reliability make it an effective solution for powering electronic circuits [37].

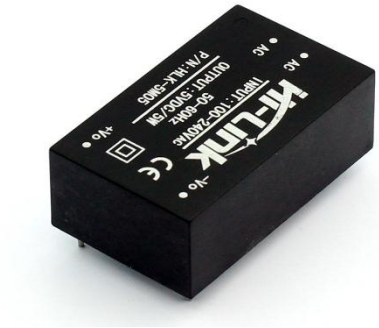


Figure II.10 : HLK-PM05 power module

IV.2 Voltage Regulator:

The LD1117V33 is a low-dropout voltage regulator used to provide a stable 3.3V output from a 5V supply. It is widely used in embedded systems due to its reliability, low cost, and ability to deliver the regulated voltage required by microcontrollers and electronic components. The regulator ensures stable operation and protects sensitive devices from voltage fluctuations [38].

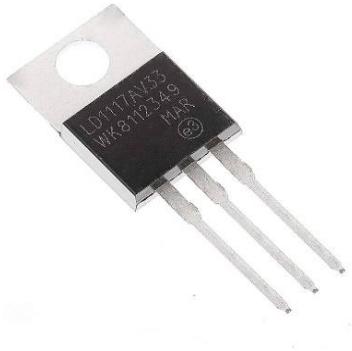


Figure II.11 : LD1117V33 voltage regulator

IV.3 Electrical Protection and Safety:

IV.3.1 Fuse:

The fuse is a protection device used to disconnect the circuit when the current exceeds a predetermined limit. It protects the system against short circuits and overcurrent conditions, reducing the risk of damage to electronic components and electrical wiring [39].



Figure II.12 : Fuse

IV.3.2 Metal Oxide Varistor:

A Metal Oxide Varistor (MOV) is a protection component used to suppress voltage surges and transient overvoltages. It protects sensitive electronic devices by limiting excessive voltage levels that may occur due to switching operations or disturbances in the electrical network [40].



Figure II.13 : Metal Oxide Varistor (MOV)

IV.3.3 Electrical Isolation and Safety Distances:

Electrical isolation is essential in systems connected to the mains voltage. Proper separation between high-voltage and low-voltage circuits reduces electrical hazards and improves system safety. Maintaining adequate safety distances on the PCB contributes to reliable operation and protects both users and electronic components [41].

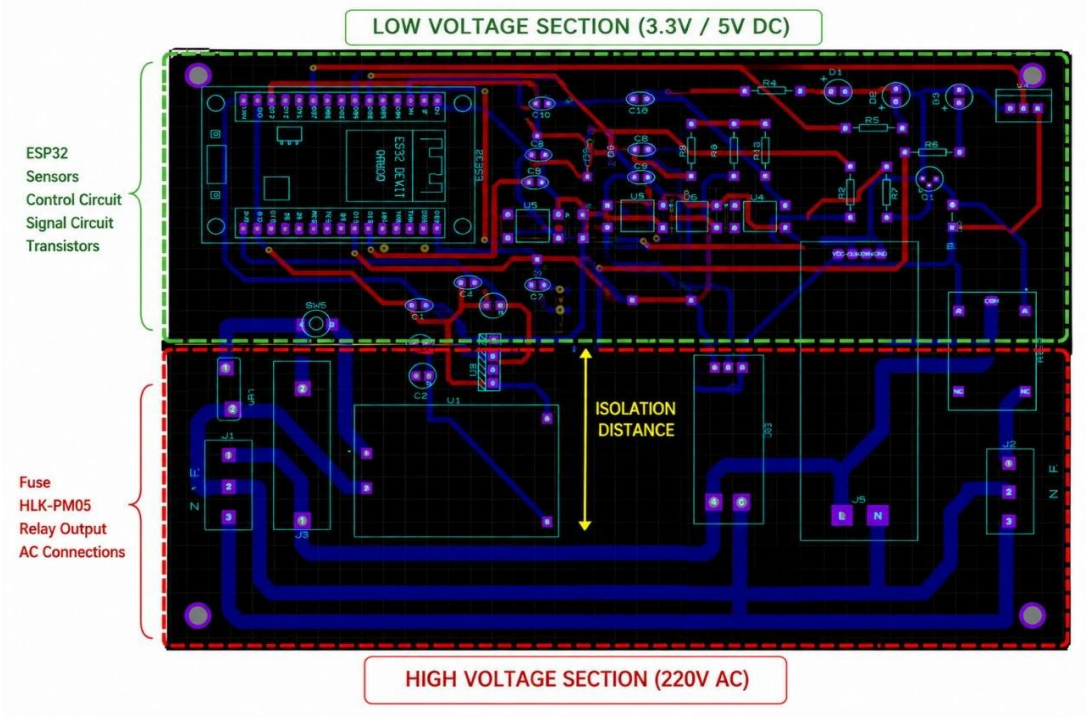


Figure II.14 : Isolation between high-voltage and low-voltage sections

V. Electronic Schematics of the System:

This section presents the electronic schematics of the proposed system. These schematics illustrate the connections between the different hardware components and provide a detailed view of the electrical architecture of both the central and secondary units.

V.1 Central Unit Schematic:

The central unit schematic represents the main hardware architecture of the proposed system. It integrates the ESP32 microcontroller, sensing circuits, relay control stage, OLED display, user interface components, and the power supply section. These components work together to perform monitoring, fault detection, communication, and protection functions.

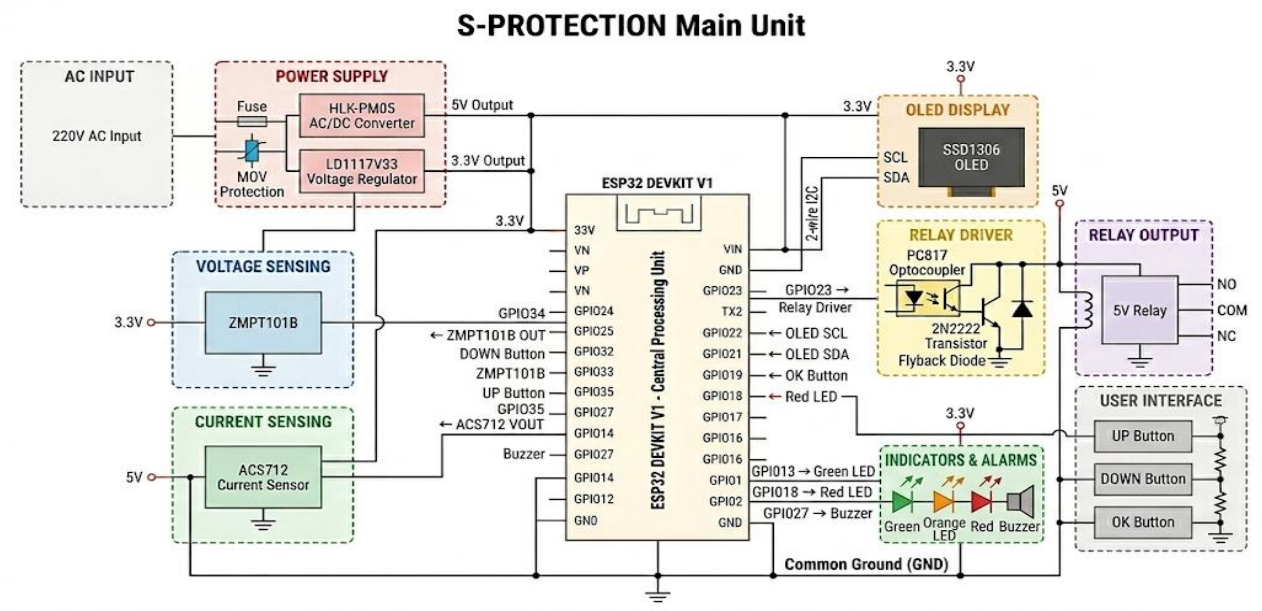


Figure II.15 : Schematic diagram of the central unit

V.2 Secondary Unit Schematic:

The secondary unit schematic illustrates the hardware architecture of the distributed monitoring node. It includes an ESP32 microcontroller, sensing circuits, and a relay used for local protection. The secondary unit communicates with the central unit and contributes to the monitoring and protection of specific electrical zones.

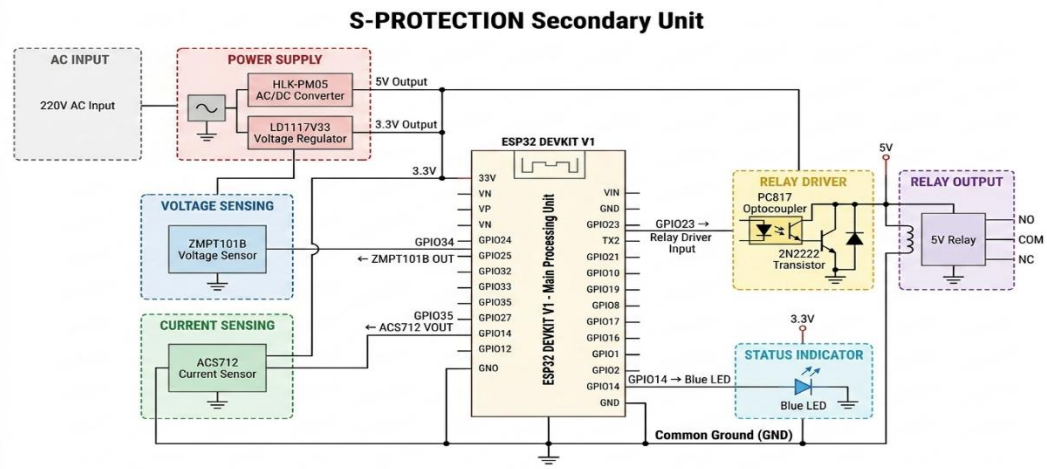


Figure II.16 : Schematic diagram of the secondary unit

VI. Prototype Implementation:

After designing and validating the electronic schematics, the hardware prototype of the proposed system was developed. This stage includes the PCB design, component assembly, and practical implementation of both the central and secondary units. The prototype was built to evaluate the functionality, reliability, and performance of the proposed protection system.

VI.1 PCB Design:

VI.1.1 Central Unit PCB:

The printed circuit board of the central unit was designed to integrate all the required monitoring, control, communication, and protection components in a compact and organized layout. Particular attention was given to component placement, signal routing, and the separation between high-voltage and low-voltage sections to improve safety and reliability.

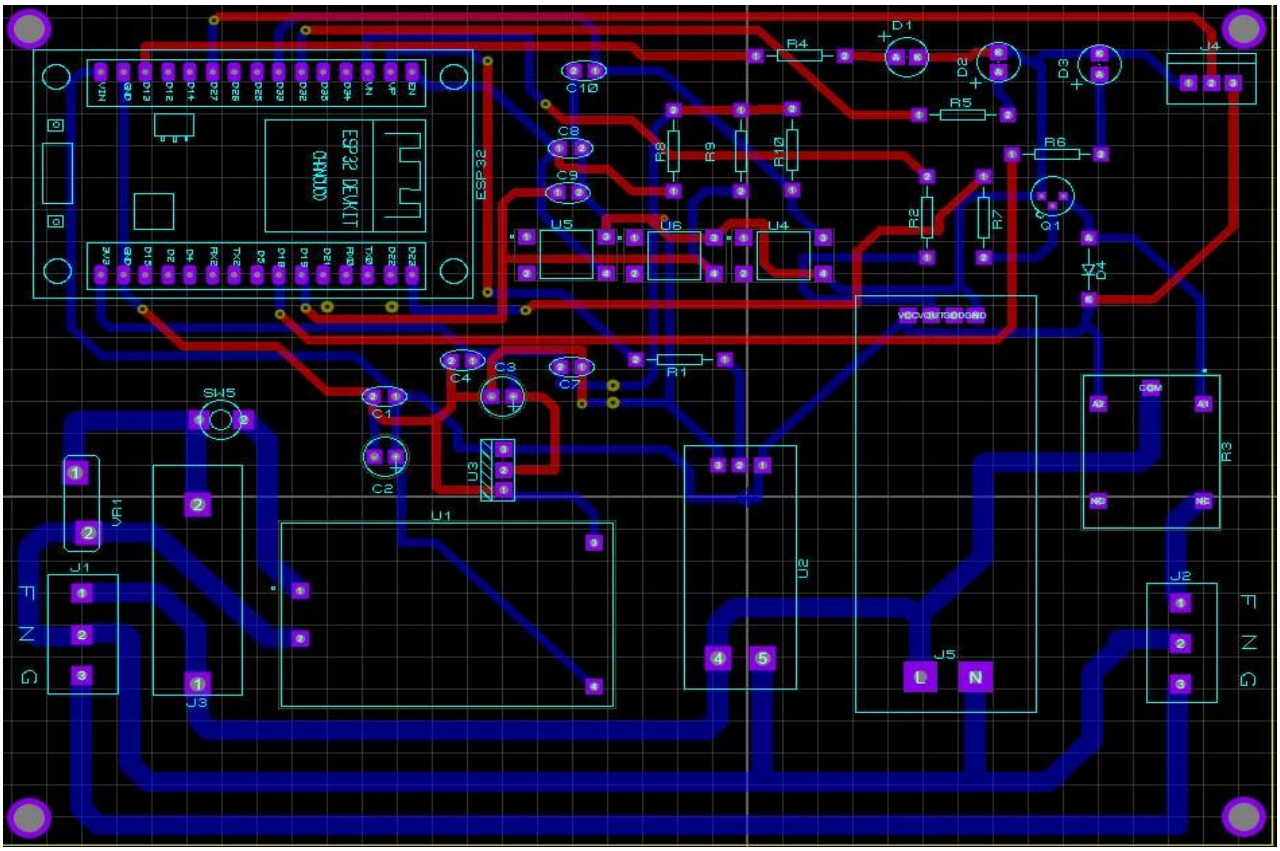


Figure II.17 : PCB layout of the central unit

VI.1.2 Secondary Unit PCB:

The printed circuit board of the secondary unit was designed to provide a compact and efficient solution for local monitoring and protection. The layout includes the sensing circuits, relay control stage, communication unit, and power supply components required for distributed operation.

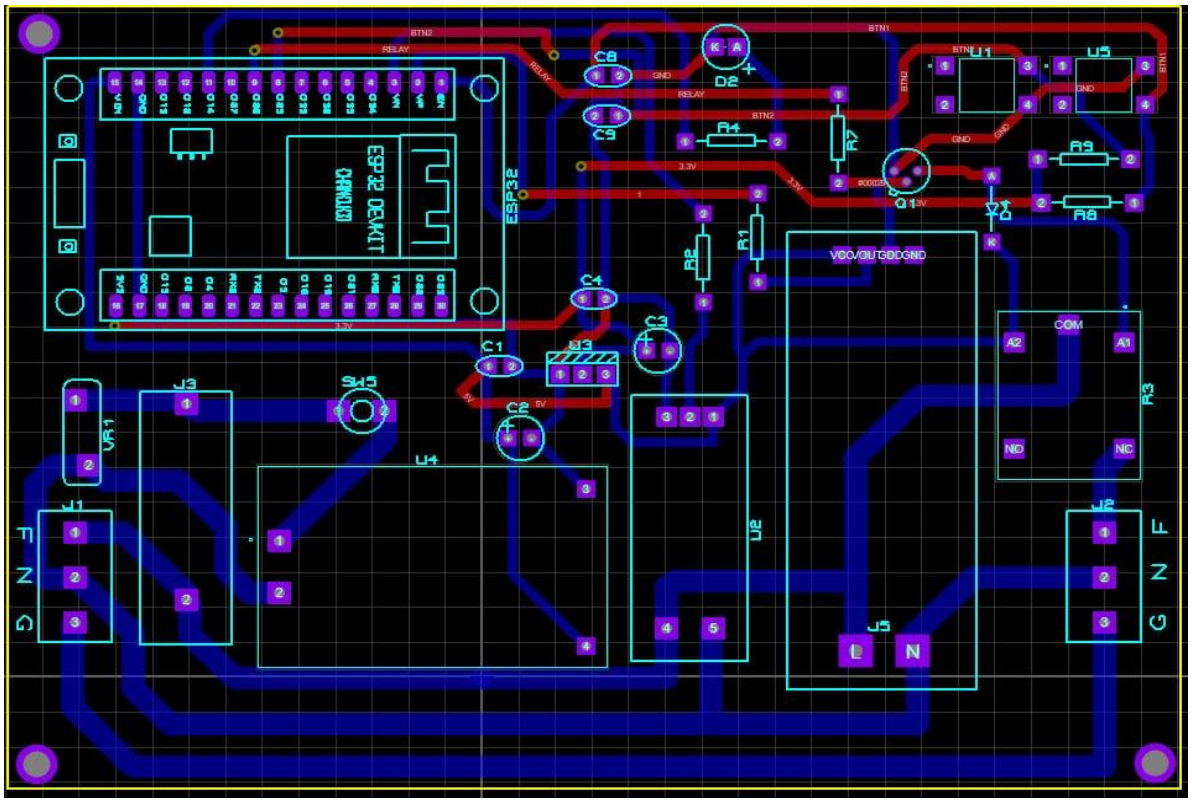


Figure II.18 : PCB layout of the secondary unit

VI.2 System Assembly:

VI.2.1 Central Unit:

The central unit was assembled by integrating the ESP32 microcontroller, voltage and current sensing circuits, OLED display, relay control stage, LEDs, buzzer, push buttons, and power supply components. This unit represents the core of the S-PROTECTION system and is responsible for monitoring, processing, communication, and protection functions.



Figure II.19 : Assembled central unit

VI.2.2 Secondary Unit:

The secondary unit was assembled using an ESP32 microcontroller, sensing circuits, relay control components, and a status indicator. Its compact design allows installation near specific electrical zones, where it performs local monitoring and protection tasks while cooperating with the central unit.



Figure II.20 : Assembled secondary unit

VII. Conclusion:

This chapter presented the hardware design and implementation of the proposed S-PROTECTION system. The overall architecture, electronic components, power supply design, electronic schematics, PCB development, and prototype assembly were discussed. The developed hardware platform provides the necessary infrastructure for monitoring, communication, fault detection, and protection functions. The next chapter focuses on the software development and integration of the proposed system.

CHAPTER III:

Software Development and System Integration

Chapter III: Software Development and System Integration

I. Introduction:

This chapter presents the software development and system integration of the proposed S-PROTECTION system. It describes the programming environment, the implementation of monitoring and protection functions, communication mechanisms, and the interaction between the different hardware modules. The chapter also explains the software strategies used to ensure reliable monitoring, fault detection, alert management, and intelligent protection of residential electrical installations.

II. Development Environment :

II.1 Arduino IDE :

Arduino IDE is an open-source software development environment widely used for programming microcontrollers and embedded systems. It provides a simple interface for writing, compiling, and uploading programs to development boards. In this project, Arduino IDE development environment was used to develop and upload the firmware of both the central and secondary ESP32 units. Its extensive library support and compatibility with ESP32 boards simplify the implementation of monitoring, communication, and protection functions. [42]



Figure III.1 : Arduino IDE development environment

II.2 ESP32 Programming:

The ESP32 microcontroller was programmed using the Arduino framework to implement the different functions of the S-PROTECTION system. The developed software is responsible for acquiring sensor data, processing electrical measurements, managing communication between modules, controlling relays, generating alerts, and supervising system operation. The flexibility and processing capabilities of the ESP32 make it suitable for intelligent monitoring and protection applications. [43]

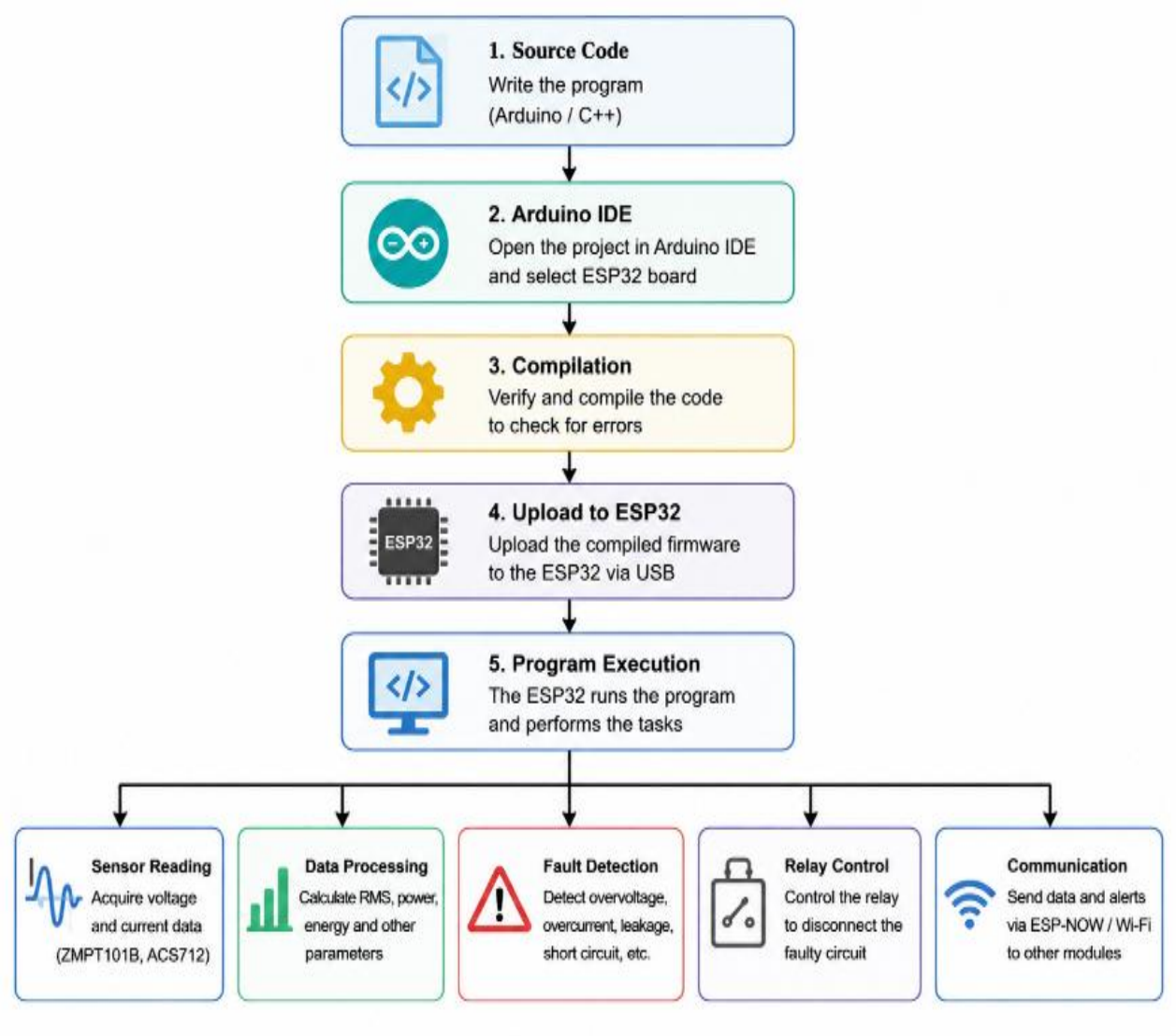


Figure III.2 : ESP32 programming process

III.3 Monitoring Functions:

The monitoring functions play a vital role in the S-PROTECTION system. They ensure the continuous acquisition and analysis of electrical parameters in order to identify abnormal operating conditions. The collected measurements are processed by the ESP32 microcontroller and used to activate the appropriate protection mechanisms when necessary.

III.3.1 Voltage Monitoring:

Voltage monitoring is performed using the ZMPT101B sensor connected to the ESP32 microcontroller. The acquired voltage values are continuously analyzed and compared with predefined safety thresholds in order to detect abnormal operating conditions

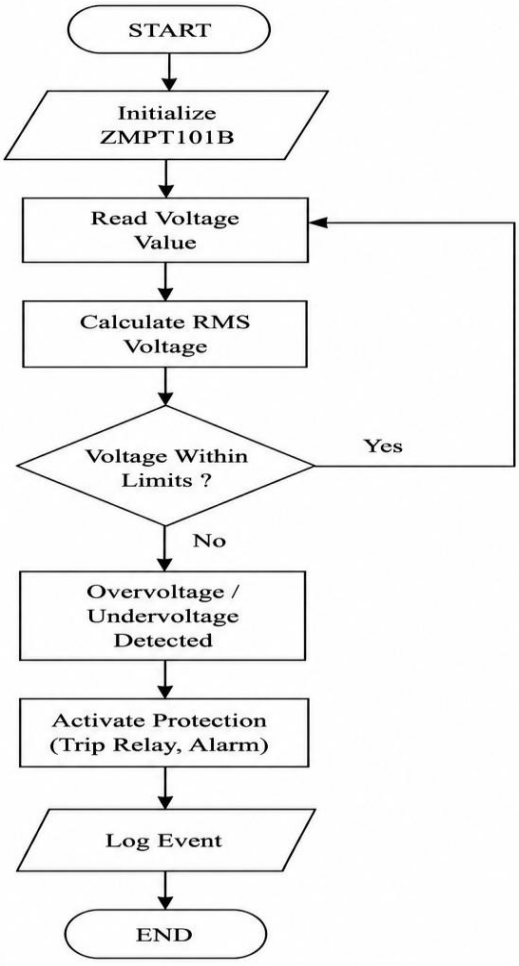


Figure III.3 : Voltage Monitoring Algorithm

III.3.2 Current Monitoring:

Current monitoring is achieved using the ACS712 sensor connected to the ESP32 microcontroller. The measured current values are continuously analyzed and compared with predefined current limits in order to detect overload conditions and abnormal current consumption.

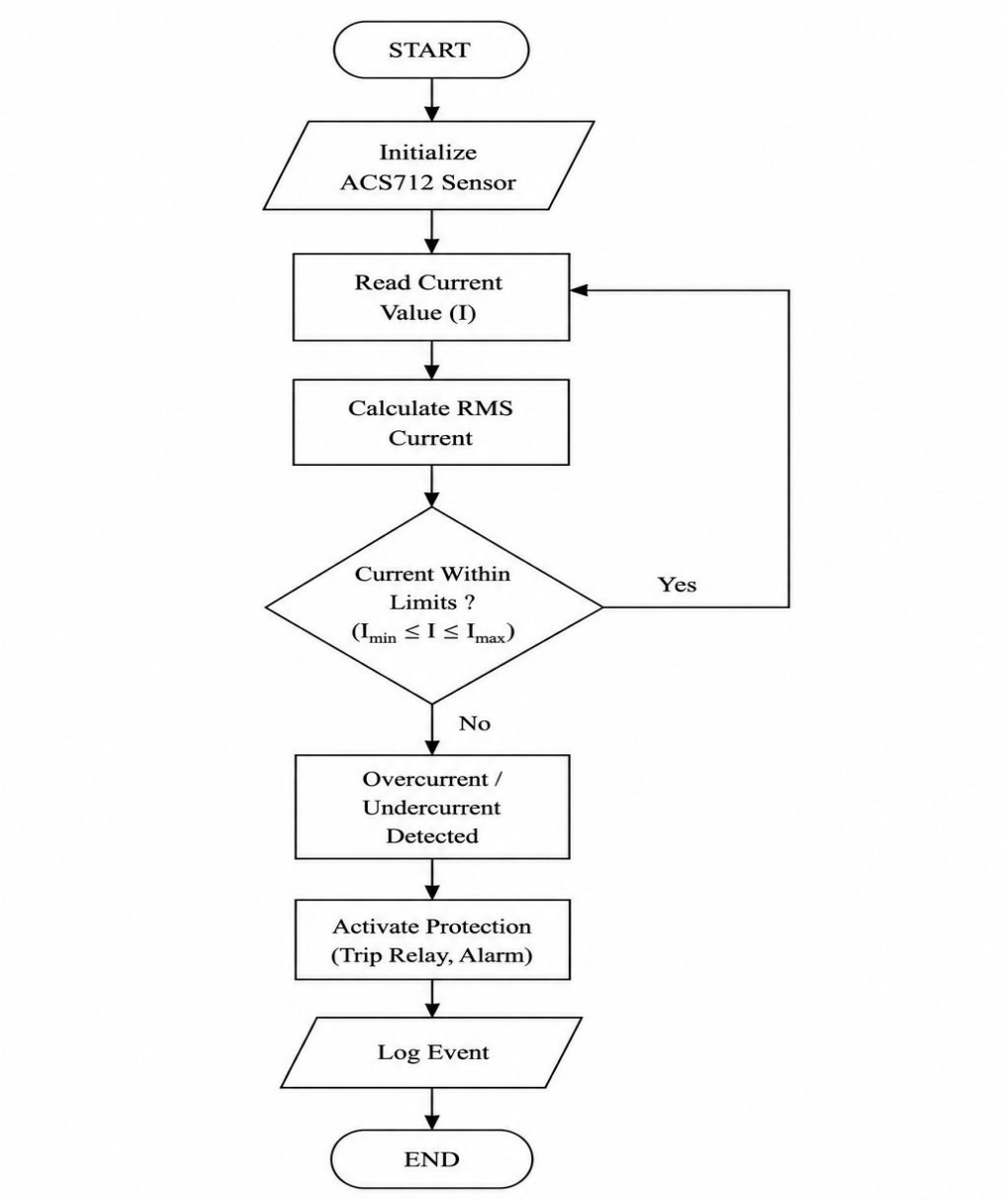


Figure III.4 : Current Monitoring Algorithm

III.3.3 Electrical Fault Detection:

Electrical fault detection is based on the continuous analysis of voltage and current measurements. The system compares the acquired values with predefined thresholds in order to identify abnormal conditions such as overvoltage, undervoltage, and overcurrent.

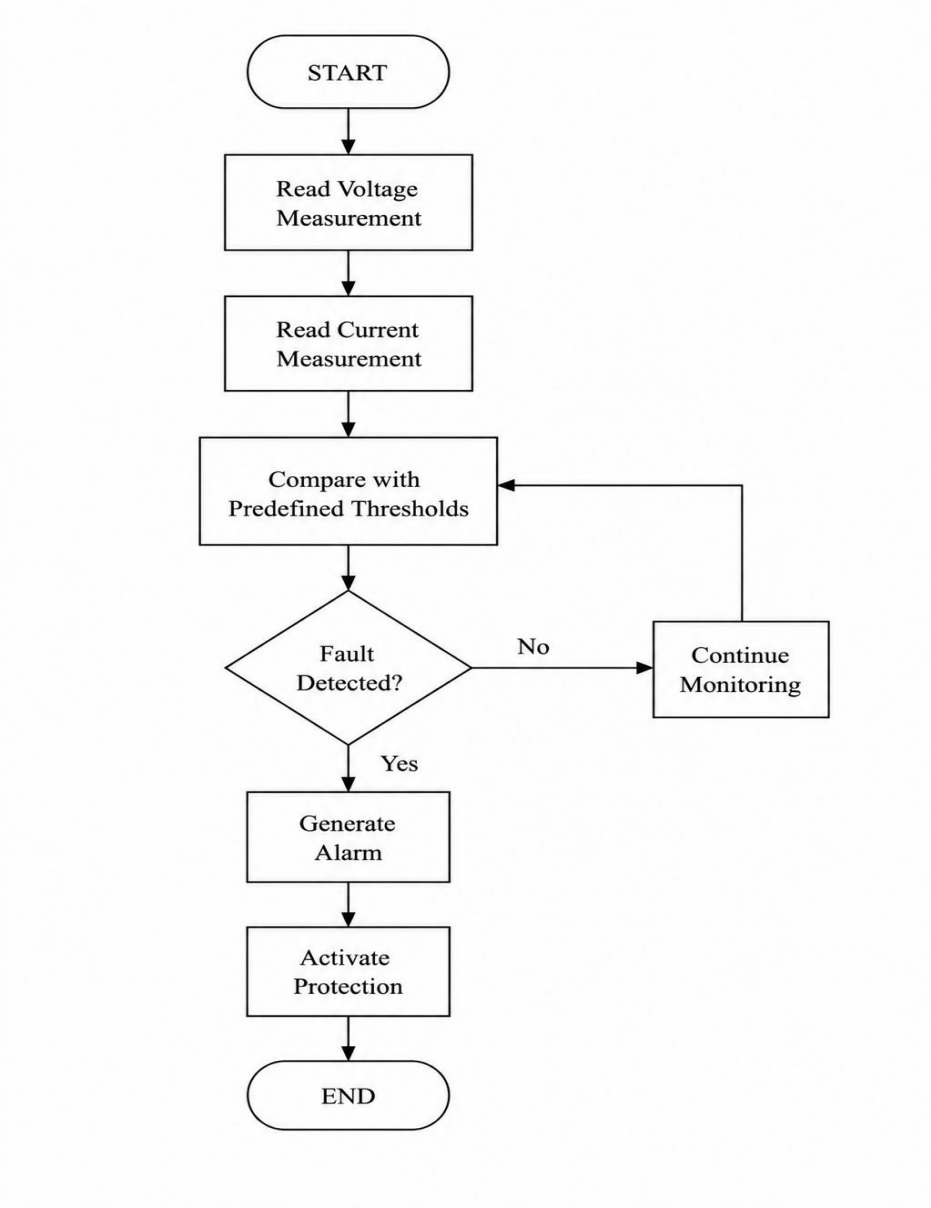


Figure III.5 : Electrical Fault Detection Algorithm

III.3.4 Decision-Making Algorithm:

The decision-making algorithm determines the appropriate protection action according to the detected fault condition. Depending on the severity of the event, the system can maintain normal operation or activate the corresponding protection mechanisms.

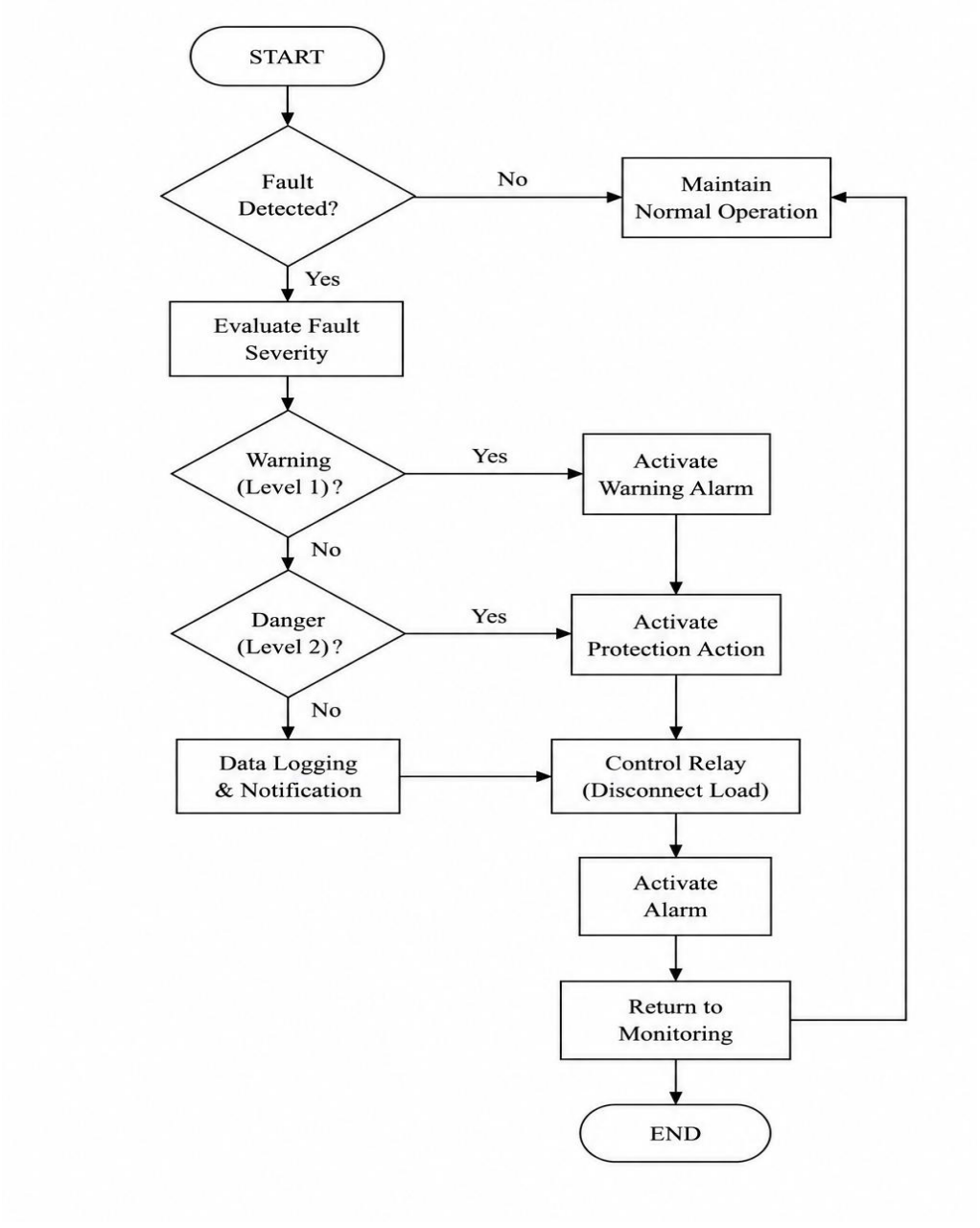


Figure III.6 : Decision-Making Algorithm

III.4 Alert Management:

The alert management system is responsible for informing the user about the operating state of the electrical installation. Different visual and audible indicators are used to signal normal operation, warning conditions, and dangerous fault situations.

III.4.1 LED Indicators:

LED indicators provide a visual representation of the system status. The green LED indicates normal operation, the orange LED signals a warning condition, and the red LED indicates a dangerous fault requiring immediate attention.

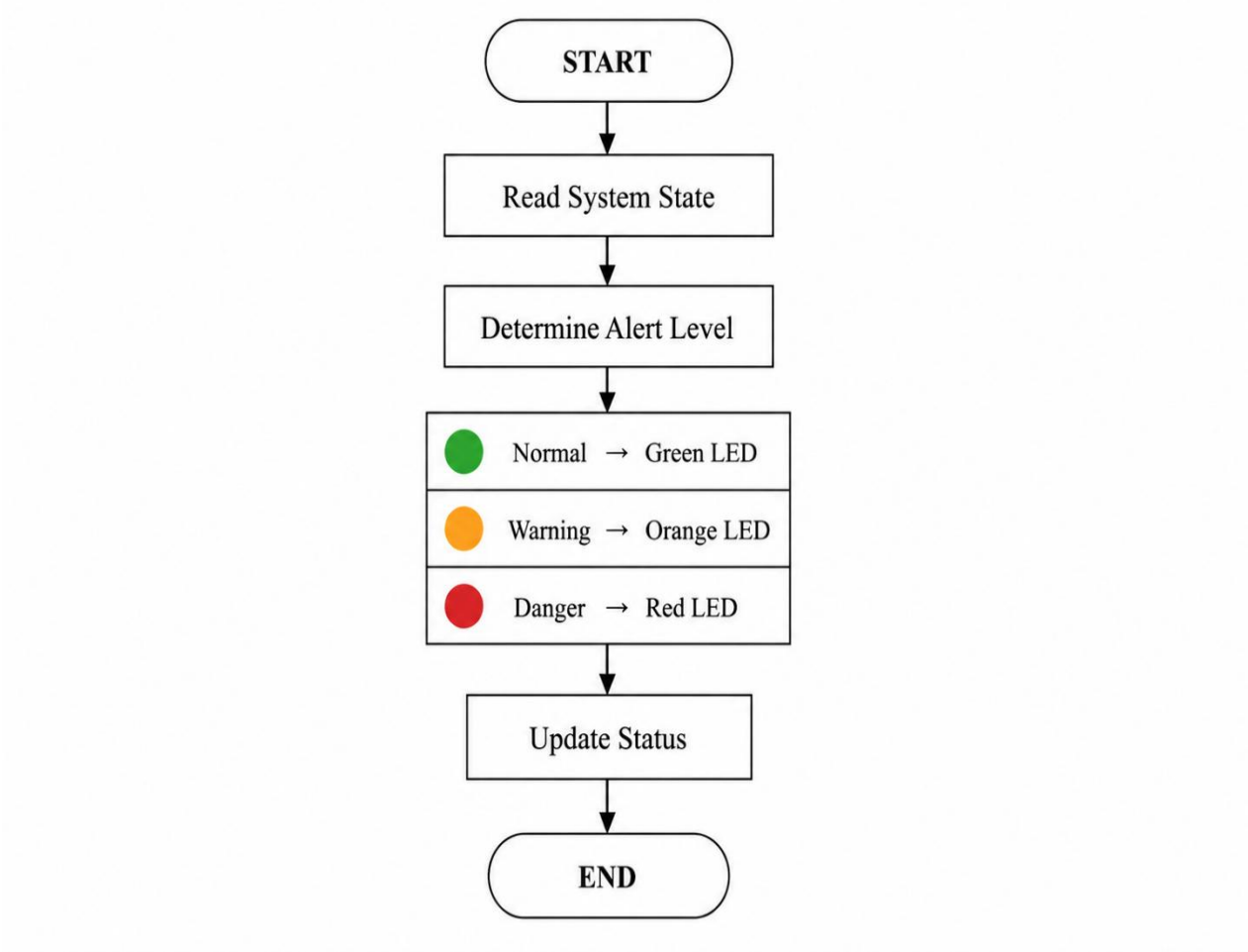


Figure III.7 : LED Status Indication Algorithm

III.4.2 Audible Alarm:

The audible alarm is activated when a dangerous electrical fault is detected. It provides an immediate warning to the user and remains active until the fault is cleared or acknowledged.

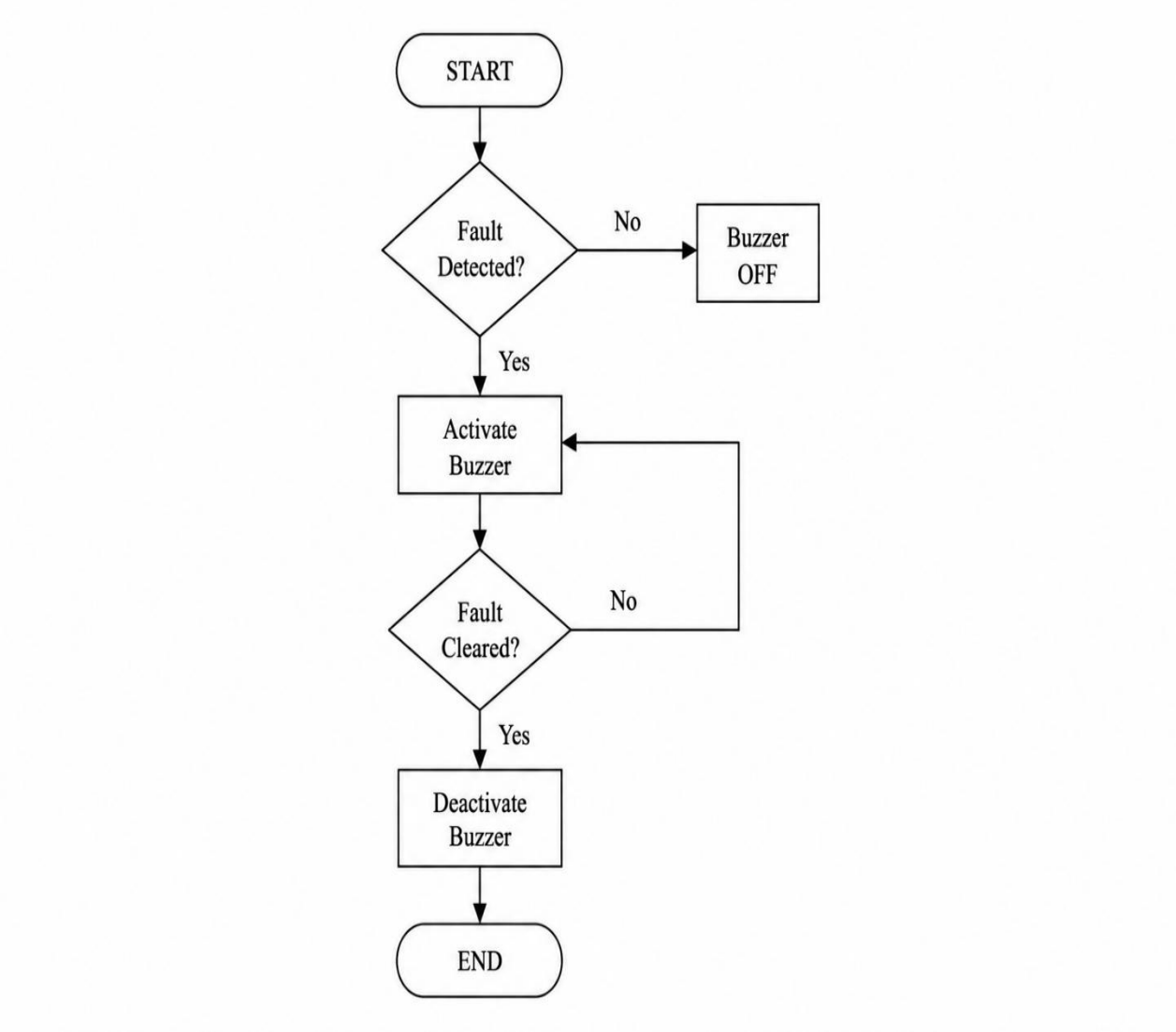


Figure III.8 : Audible Alarm Management Algorithm

III.4.3 Fault Display on OLED Screen:

The OLED display provides real-time information about system measurements and detected faults. Voltage, current, power values, and fault messages are displayed to assist the user in monitoring the electrical installation.

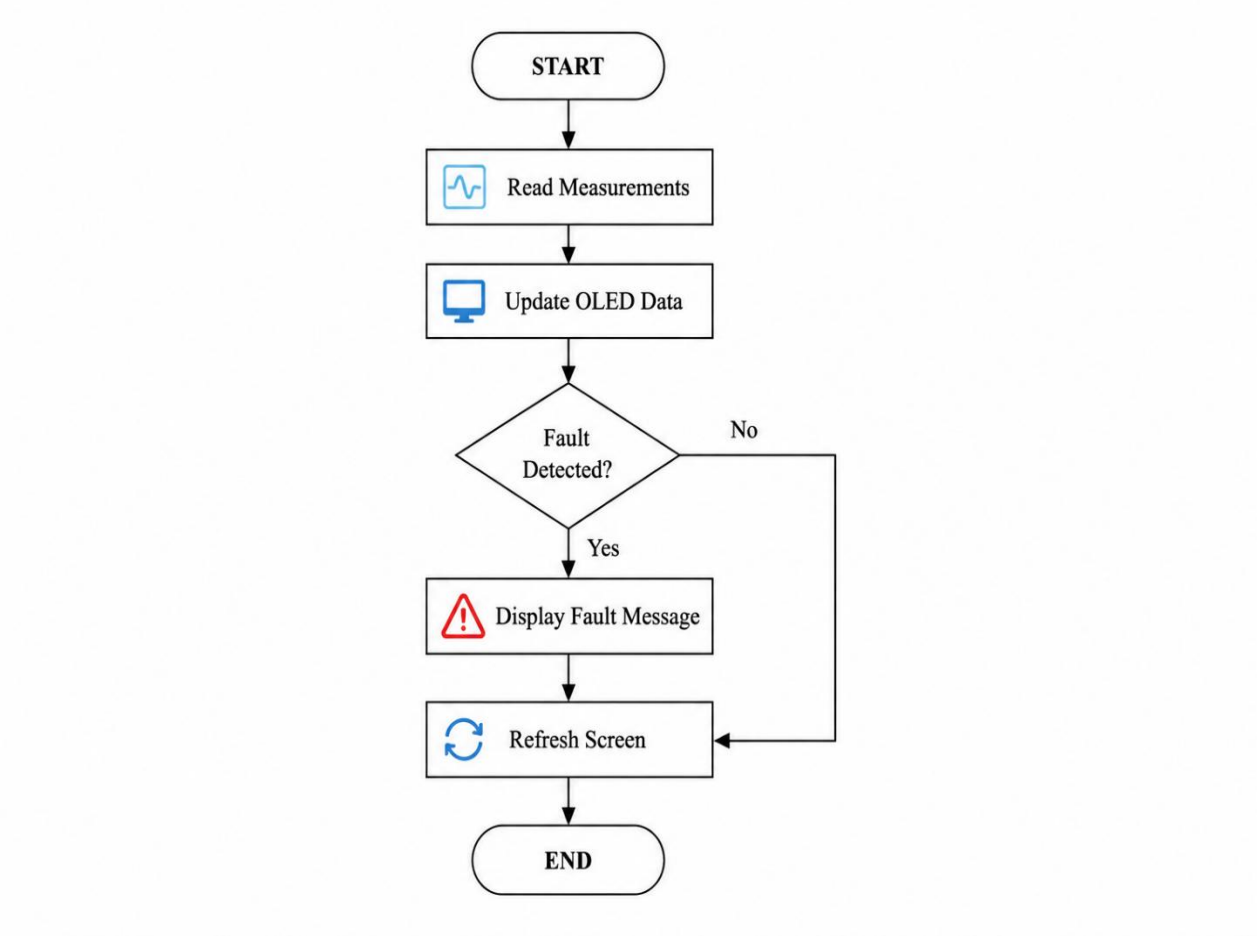


Figure III.9 : OLED Display Management Algorithm

III.5 Wireless Communication:

Wireless communication plays an important role in the S-PROTECTION system. It enables data exchange between the central unit, the secondary units, and the mobile application, ensuring real-time monitoring and control.

III.5.1 Wi-Fi Configuration:

Wi-Fi communication is used to connect the central ESP32 unit to the local network. This connection allows the mobile application to access system data, display measurements, and send control commands in real time.

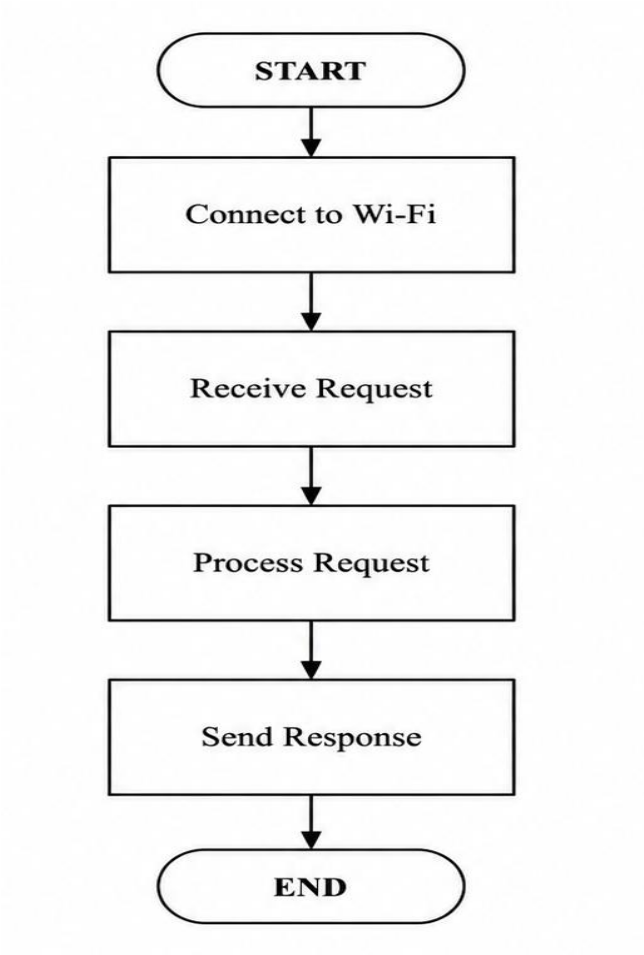


Figure III.10 : Wi-Fi Communication Process

III.5.2 Data Exchange Between Units:

Data exchange between the central unit and the secondary units is achieved using the ESP-NOW communication protocol. This protocol allows fast and reliable wireless transmission of monitoring data and control commands without requiring an internet connection.

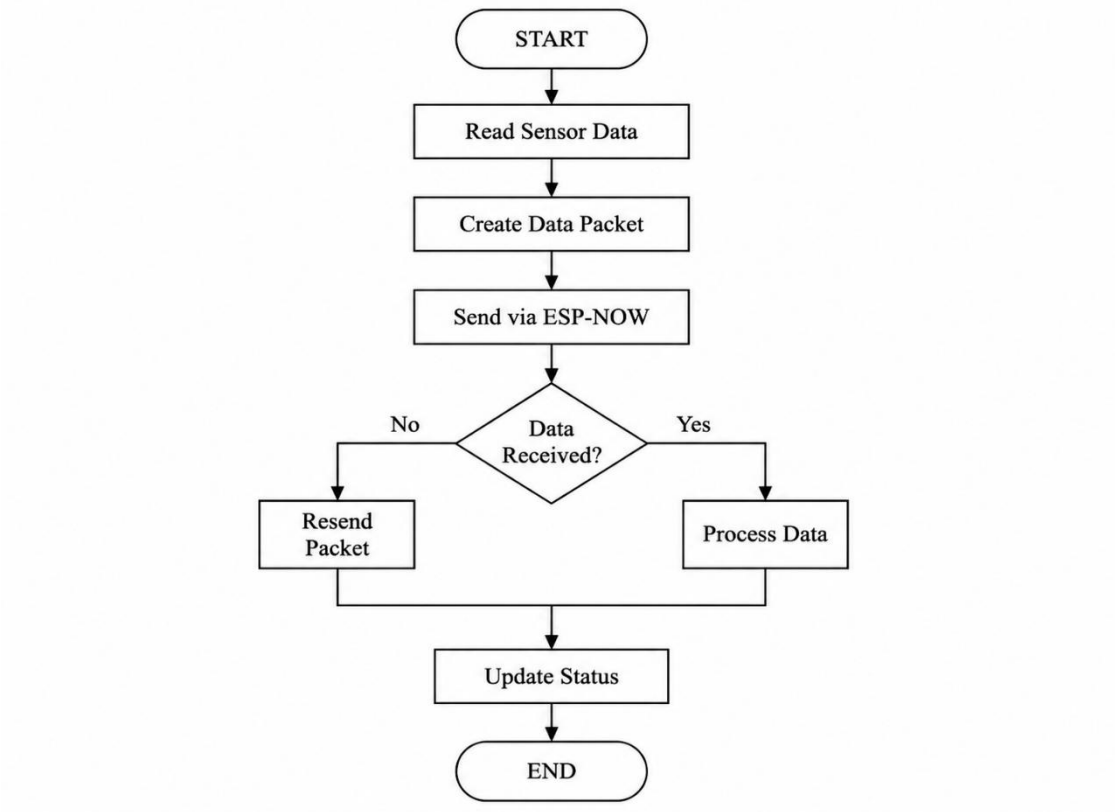


Figure III.11 : ESP-NOW Communication Process

III.5.3 Communication Security:

Communication reliability is ensured through device pairing and the use of unique MAC addresses. These mechanisms help guarantee secure and stable data transmission between the different modules of the system.

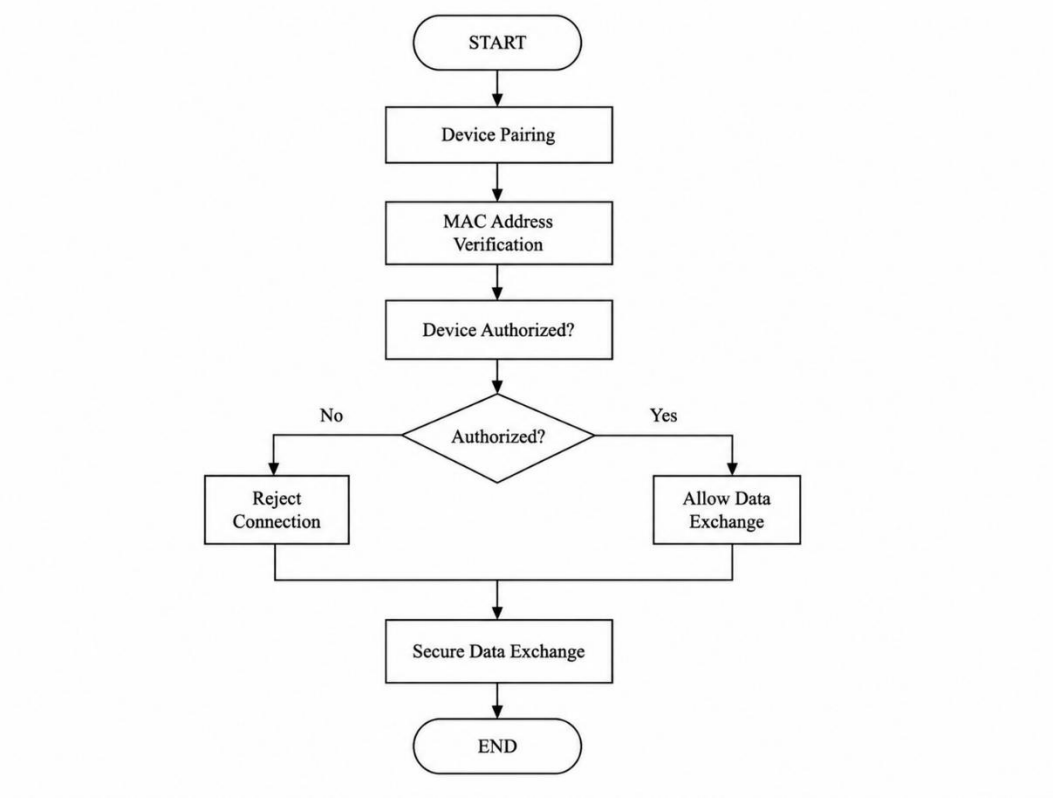


Figure III.12 : Communication Security Process

III.6 Electrical Disconnection Strategy:

The electrical disconnection strategy is designed to protect the electrical installation and connected equipment by isolating the affected circuit when a dangerous condition is detected. The proposed system supports both total disconnection and selective disconnection according to the type and location of the detected fault.

III.6.1 Total Disconnection:

Total disconnection is performed when a critical fault is detected in the main electrical installation. In this case, the central unit deactivates the main relay, disconnecting the entire electrical system to prevent damage and ensure user safety.

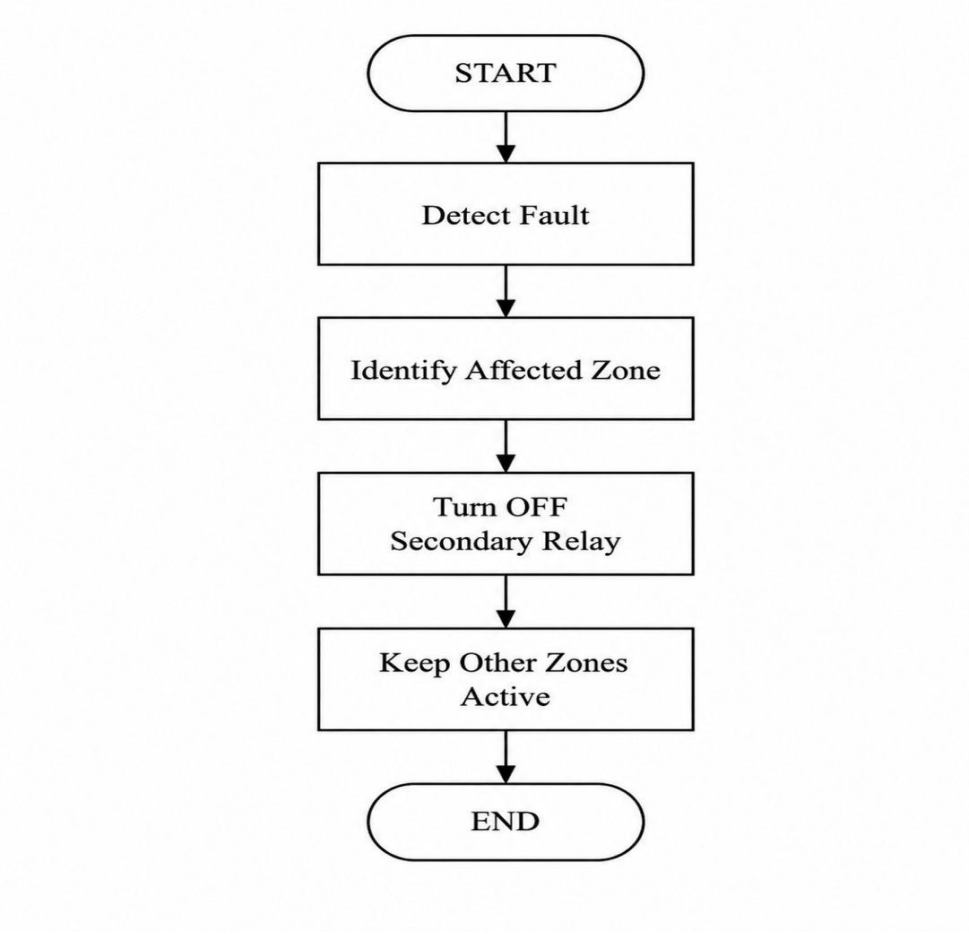


Figure III.13 : Total Disconnection Algorithm

III.6.2 Selective Disconnection:

Selective disconnection is applied when a fault is detected in a specific zone monitored by a secondary unit. Only the affected circuit is disconnected while the remaining parts of the installation continue operating normally.

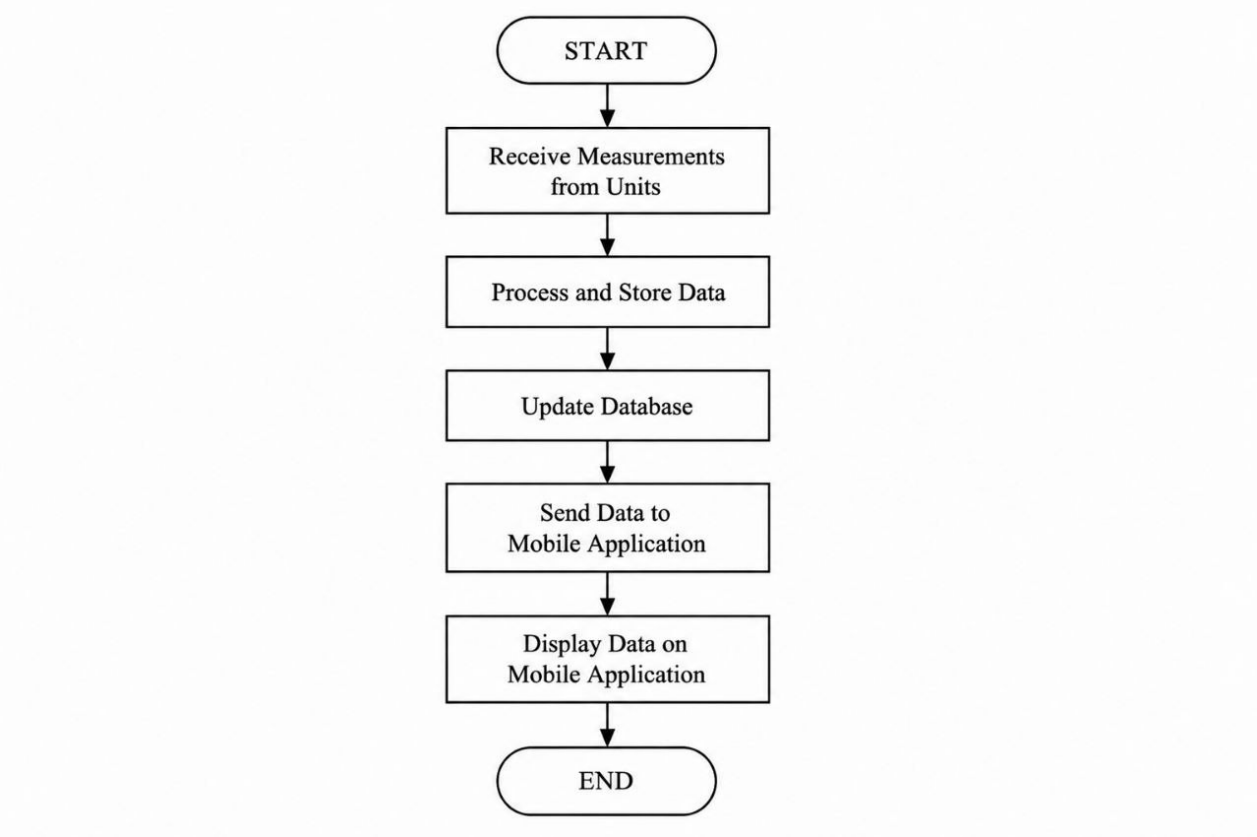


Figure III.14 : Selective Disconnection Algorithm

III.7 System Algorithms and Flowcharts :

This section presents the main flowcharts describing the operation of the S-PROTECTION system. These diagrams illustrate the sequence of operations performed by the central and secondary units, including data acquisition, communication, fault detection, and protection actions.

III.7.1 Main Unit Algorithm:

The main unit algorithm represents the central control process of the S-PROTECTION system. It manages sensor measurements, receives data from secondary units, analyzes operating conditions, and executes the required protection actions when abnormal situations are detected.

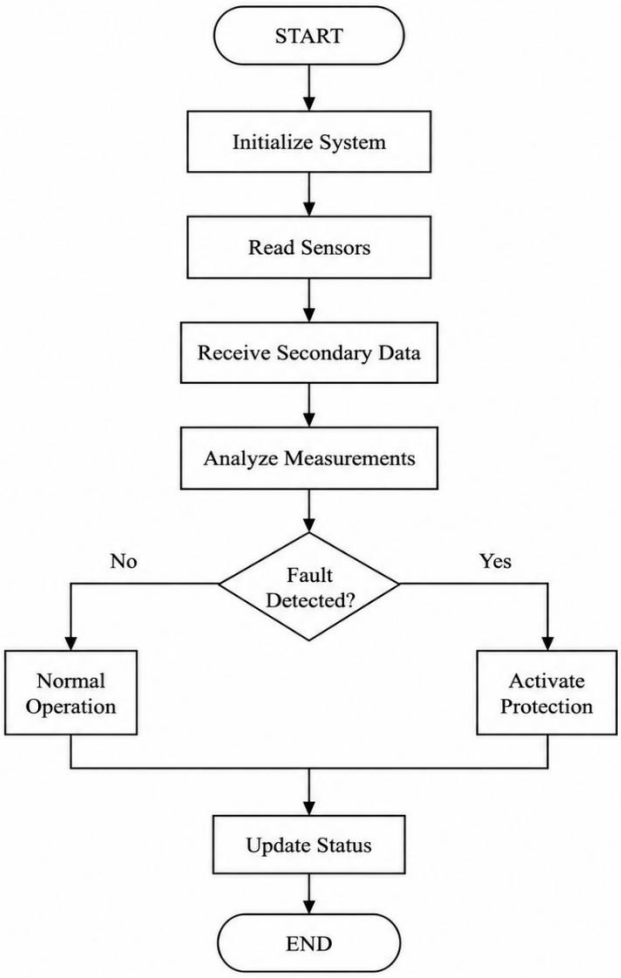


Figure III.15 : Main Unit Algorithm

III.7.2 Secondary Unit Algorithm:

The secondary unit algorithm is responsible for monitoring local electrical parameters and transmitting the collected information to the central unit through ESP-NOW communication. It ensures continuous supervision of the protected electrical zone.

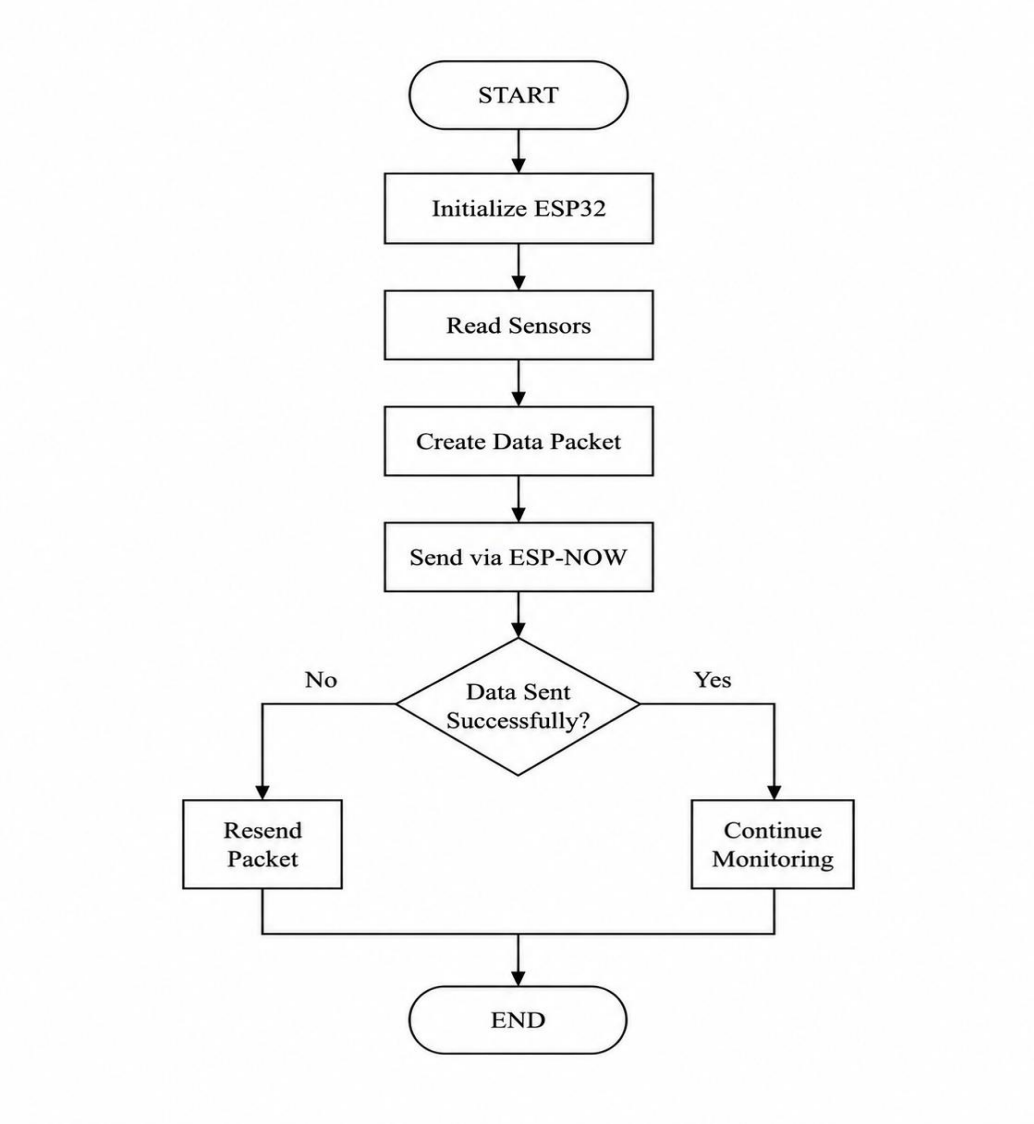


Figure III.16: Secondary Unit Algorithm

III.8 Application Developer:

A mobile application was developed to provide real-time monitoring and control of the S-PROTECTION system. The application allows users to visualize electrical parameters, receive fault notifications, and remotely manage protection functions through a user-friendly interface.

III.8.1 Login Interface:

The login interface provides secure access to the S-PROTECTION application. Each installed system is assigned a unique username and password during deployment. These credentials are provided to the customer and are required to access monitoring data, system settings, and remote-

control functions. This mechanism ensures that only authorized users can access and manage their electrical protection system.

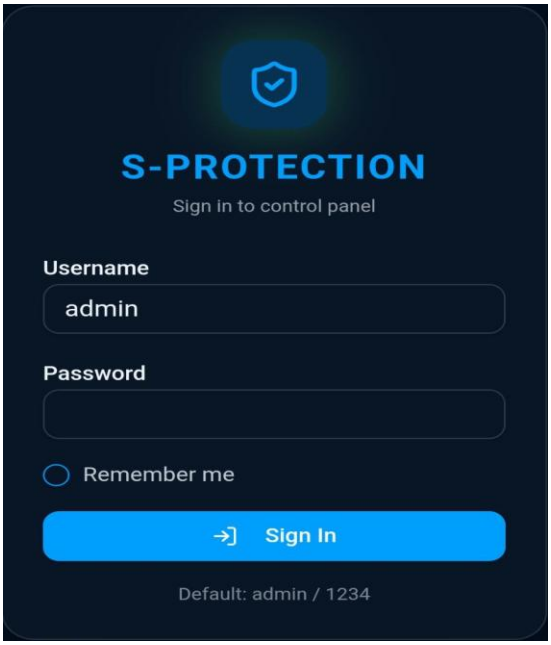


Figure III.17: Login Interface

III.8.2 Monitoring and Notification Interfac:

The monitoring and notification interface represents the main dashboard of the S-PROTECTION application. It provides real-time information about electrical measurements, communication status, operating conditions, and detected faults. This interface enables users to continuously supervise the protected electrical installation and receive alerts when abnormal situations occur.

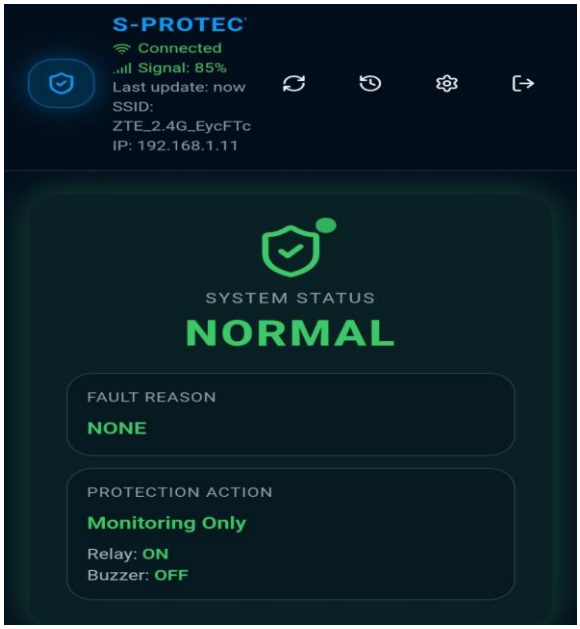


Figure III.18 : Communication and System Status Interface



Figure III.19 : Main and Secondary Unit Monitoring Interface

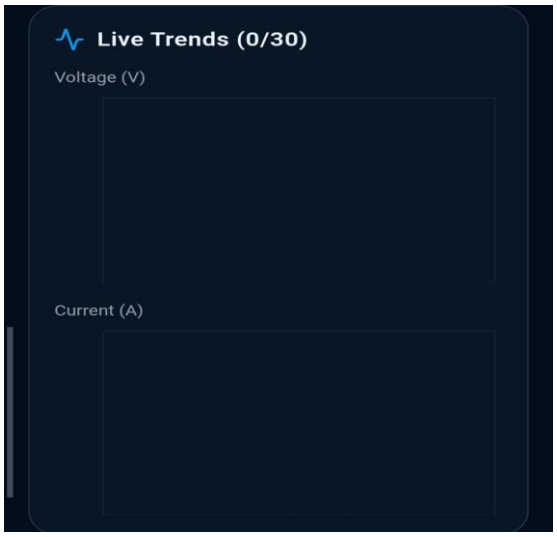


Figure III.20 : Real-Time Trends Interface

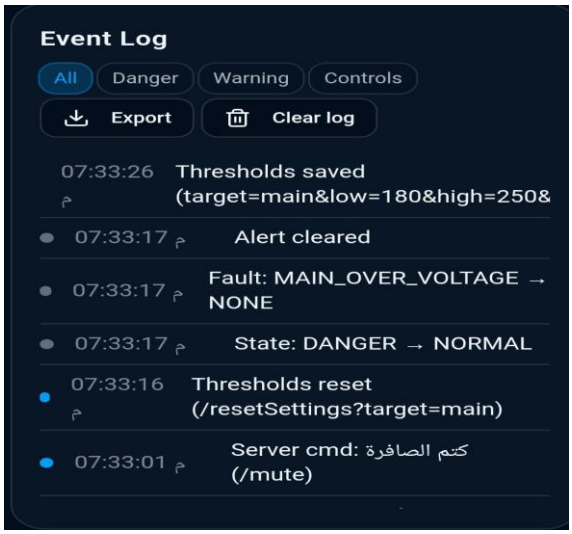


Figure III.21 : Event Log Interface

III.8.3 Configuration Interface:

The configuration interface allows users to customize the operating parameters of the S-PROTECTION system. It provides access to protection thresholds, communication settings, cloud synchronization options, and application preferences.

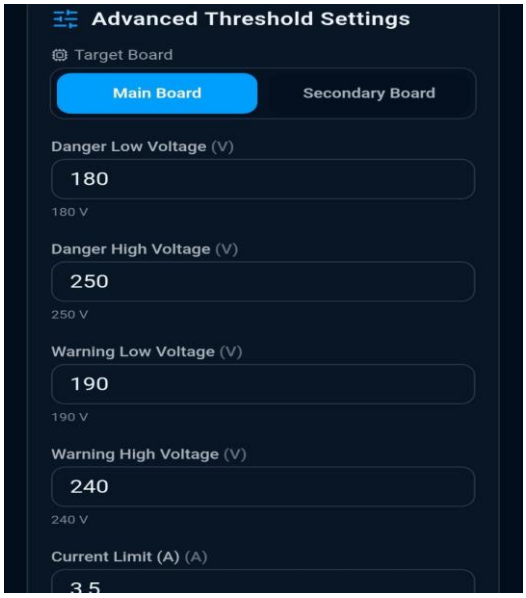


Figure III.22 : Threshold Configuration Interface

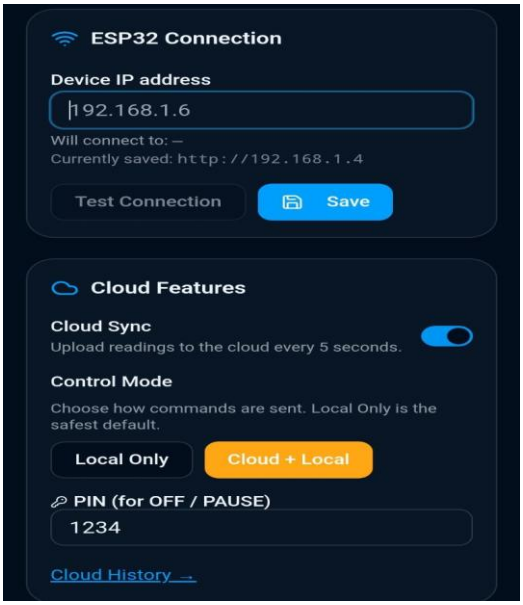


Figure III.23 : Communication and Cloud Configuration Interface

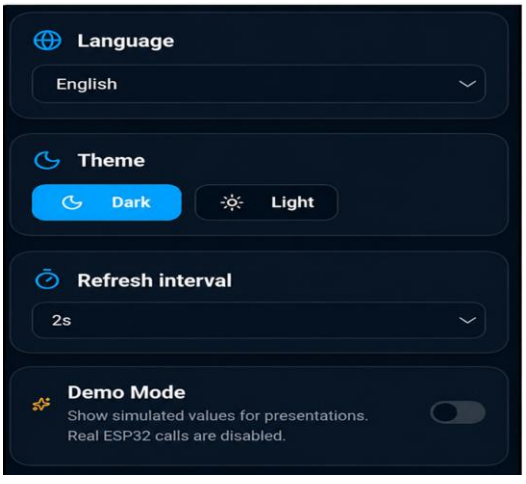


Figure III.24 : Application Preferences Interface

III.8.4 Control Interface:

The control interface enables users to remotely manage the protection system. It provides direct access to protection functions and relay control operations.

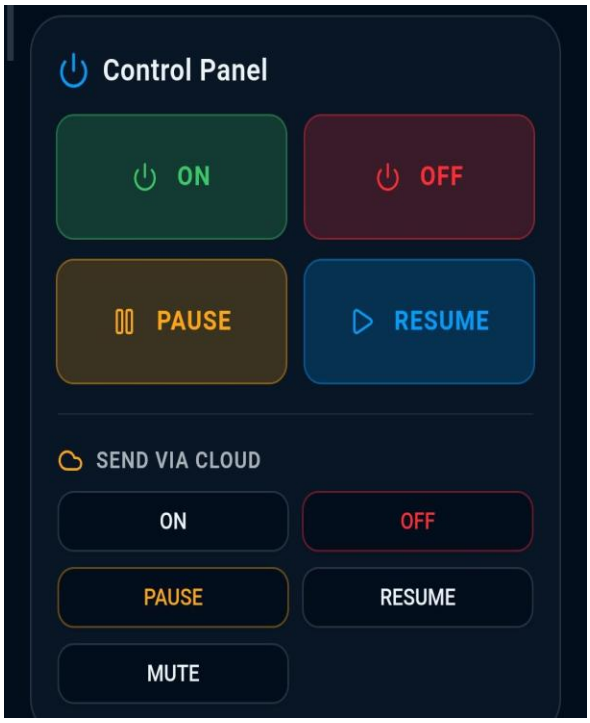


Figure III.25 : Protection Control Panel

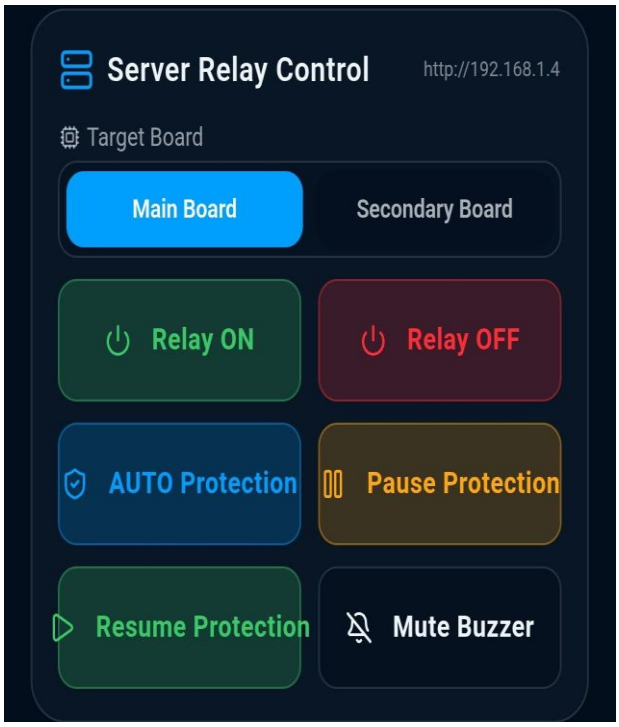


Figure III.26 : Relay Management Interface

III.9 Conclusion:

This chapter presented the hardware and software implementation of the S-PROTECTION system. The different components of the central and secondary units were described, including sensing, communication, protection, and user interaction modules. In addition, the developed mobile application was presented, highlighting its monitoring, configuration, and control functionalities. The integration of these elements provides a complete intelligent electrical protection solution for smart home environments.

Chapter IV:

Tests, Results and Perspectives

Chapter IV: Tests, Results and Perspectives

IV.1 Introduction:

This chapter presents the testing and evaluation of the proposed S-PROTECTION system. It describes the methodology used to verify the main protection functions, communication performance, relay response, and system reliability. The obtained results are then analyzed in order to evaluate the effectiveness of the developed prototype and identify possible improvements.

IV.2 Test Methodology:

Several experimental tests were performed to verify the proper operation of the S-PROTECTION system, including fault detection, protection response, and wireless communication.

IV.2.1 Overvoltage Test:

The overvoltage test was conducted to verify the capability of the S-PROTECTION system to detect voltage values exceeding the predefined safety threshold. During the test, the danger voltage threshold was adjusted through the mobile application until the measured voltage exceeded the configured limit. The response of the protection system, including alarm activation and relay disconnection, was then observed.



Figure IV.1 : Central Unit During Overvoltage Fault



IV.2 : Overvoltage Fault Detection in the Mobile Application

IV.2.2 Undervoltage Test:

The undervoltage test was conducted to verify the ability of the S-PROTECTION system to detect voltage values below the predefined safety threshold. During the test, the low-voltage threshold was adjusted through the mobile application until the measured voltage fell below the configured limit. The system response, including alarm activation and relay disconnection, was then evaluated.



Figure IV.3 : Central Unit During Undervoltage Fault



IV.4 : Undervoltage Fault Detection in the Mobile Application

IV.2.3 Warning Condition Test:

The warning condition test was conducted to verify the ability of the S-PROTECTION system to provide an early alert before reaching a dangerous state. During the test, the warning thresholds were adjusted through the mobile application until the measured values exceeded the warning limits without reaching the danger thresholds. In this case, the system displayed a warning state while keeping the relay connected.



Figure IV.5 : Central Unit During Warning Condition



Figure IV.6 : Mobile Application During Warning Condition

IV.2.4 Overcurrent Test:

The overheating test was conducted to evaluate the ability of the S-PROTECTION system to detect overheating risks caused by excessive current consumption over a prolonged period of time. During the test, the current level and its duration were monitored continuously. When the measured current remained above the predefined threshold for a specified period, the system generated the corresponding warning or danger state and activated the appropriate protection mechanisms.



Figure IV.7 : Mobile Application During Overheating Warning Condition



IV.8 : Mobile Application During Overheating Danger Condition

IV.2.5 Short-Circuit Test:

The short-circuit test was conducted to evaluate the ability of the S-PROTECTION system to detect severe fault conditions and immediately activate the protection mechanisms. During the test, an abnormal current increase was simulated to represent a short-circuit condition. The system successfully detected the fault and immediately disconnected the relay to protect the electrical installation and connected equipment.



Figure IV.9 : Mobile Application During Short-Circuit Condition

IV.2.6 Wireless Communication Test:

The wireless communication test was carried out to evaluate the reliability of data exchange between the main unit and the secondary unit. Communication between the two ESP32 modules was established using ESP-NOW technology, while the mobile application communicated with the main unit through Wi-Fi. During the test, voltage, current, power, and system status information were transmitted continuously. The results confirmed stable communication and successful real-time monitoring of the electrical parameters.



Figure IV.10 : Communication Between Main and Secondary Units



Figure IV.11 : Real-Time Monitoring Through the Mobile Application

IV.3 Experimental Results:

This section presents the experimental results obtained during the testing phase of the S-PROTECTION system. Several tests were performed under different operating conditions to evaluate the effectiveness of the monitoring, fault detection, communication, and protection functions. The obtained results were analyzed in order to assess the overall performance and reliability of the proposed system.

IV.3.1 Reaction Time:

The reaction time of the S-PROTECTION system was evaluated during the different experimental tests carried out under abnormal operating conditions. The obtained results showed that the system was able to detect electrical faults and activate the corresponding protection mechanisms in less than one second. Once a fault was detected, the system immediately generated the appropriate warning or danger state, activated the alarm indicators, and controlled the relay according to the predefined protection strategy. This fast response significantly improves the safety of the electrical installation and reduces the risk of damage to electrical equipment.

IV.3.2 Detection Reliability:

The reliability of the S-PROTECTION system was evaluated through repeated tests performed under different operating conditions. The system successfully detected abnormal voltage and

current values while maintaining stable operation during normal conditions. The obtained results confirmed the effectiveness of the monitoring and fault detection algorithms in identifying overvoltage, undervoltage, short-circuit, and overheating conditions. The system consistently generated the appropriate warning and protection actions, demonstrating a reliable performance throughout the testing phase.

The experimental tests showed a high detection reliability, with all tested fault conditions successfully identified by the system.

IV.3.3 Relay Performance:

The performance of the relay was evaluated during the different fault tests carried out on the S-PROTECTION system. The relay operated correctly according to the protection strategy implemented in the system. Under normal operating conditions, the relay remained energized, ensuring continuous power supply to the protected circuit. When a dangerous fault condition was detected, such as overvoltage, undervoltage, short-circuit, or overheating, the relay successfully disconnected the affected circuit to prevent potential damage. The experimental results confirmed the reliability and effectiveness of the relay control mechanism.

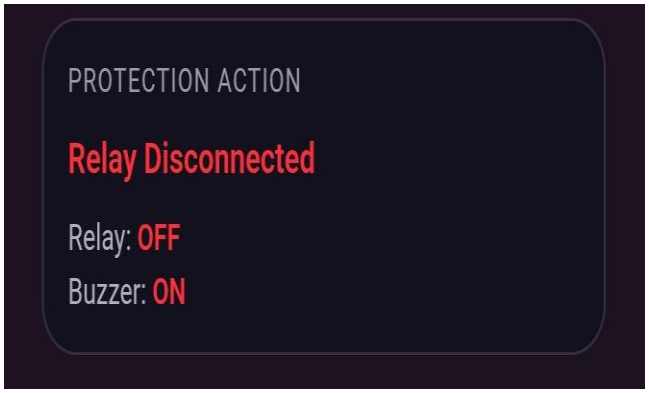


Figure IV.12 : Relay Operation During Fault Conditions

IV.3.4 Energy Consumption:

The energy consumption of the S-PROTECTION system was evaluated based on the typical electrical characteristics provided in the manufacturers' datasheets. The proposed system is

composed of low-power electronic components, including the ESP32 microcontrollers, sensing modules, OLED display, LEDs, buzzer, and relay modules. The obtained estimations indicate that the system operates with relatively low power requirements while ensuring continuous monitoring, communication, and protection functions. This low energy consumption makes the system suitable for permanent operation in residential electrical installations.

Component	Operating Voltage (V)	Typical Current (mA)	Estimated Power (W)
ESP32 Main Unit	3.3	240	0.79
ESP32 Secondary Unit	3.3	240	0.79
OLED Display	3.3	30	0.10
ACS712 Current Sensor	5	10	0.05
ZMPT101B Voltage Sensor	5	5	0.03
Relay Module	5	70	0.35
Green LED	3.3	20	0.07
Orange LED	3.3	20	0.07
Red LED	3.3	20	0.07
Active Buzzer	5	30	0.15
Total Estimated Power Consumption			**2.47 W**

IV.4 Analysis and Discussion of Results:

The experimental results obtained during the testing phase demonstrate the effectiveness of the proposed S-PROTECTION system in monitoring electrical parameters and detecting abnormal operating conditions. The performed tests confirmed the proper operation of the monitoring,

communication, and protection functions. The system successfully detected fault conditions, generated the corresponding warning and danger states, and activated the appropriate protection mechanisms when required.

IV.4.1 Analysis of Protection Performance:

The protection mechanisms implemented in the S-PROTECTION system showed reliable performance during all experimental tests. The system was able to identify overvoltage, undervoltage, short-circuit, and overheating conditions and react accordingly. The use of configurable protection thresholds allowed flexible adaptation to different operating conditions, while the relay control strategy ensured effective isolation of dangerous faults. The obtained results confirm the capability of the proposed system to improve the safety of residential electrical installations.

IV.4.2 Analysis of Communication Performance:

The communication architecture of the S-PROTECTION system demonstrated stable and reliable performance throughout the experimental tests. The ESP-NOW protocol ensured efficient data exchange between the central unit and the secondary unit, while the Wi-Fi connection enabled real-time communication between the mobile application and the central controller. The obtained results confirmed successful transmission of measurements, status information, and control commands, allowing effective monitoring and management of the electrical installation.

IV.4.3 Analysis of System Reliability:

The reliability of the proposed system was confirmed through repeated experimental tests under different operating conditions. The monitoring algorithms consistently detected abnormal electrical conditions and generated the appropriate protection actions. The distributed architecture improved fault localization and contributed to the overall stability of the system. The obtained results indicate that the S-PROTECTION system provides a dependable solution for intelligent residential electrical protection.

IV.5 Improvement Perspectives:

Although the developed S-PROTECTION system achieved satisfactory results, several improvements can be considered in future developments. Additional sensors may be integrated to enhance fault detection capabilities, particularly for direct earth leakage monitoring. The system can also be extended by increasing the number of secondary units in order to cover larger electrical installations. Furthermore, cloud-based monitoring services and artificial intelligence techniques could be incorporated to provide advanced fault prediction, energy management, and intelligent decision-making functions. These improvements would further increase the performance, reliability, and functionality of the proposed system.

IV.6 Conclusion:

This chapter presented the experimental tests and performance evaluation of the proposed S-PROTECTION system. The obtained results demonstrated the effectiveness of the monitoring, communication, and protection functions under different operating conditions. The system successfully detected abnormal electrical situations, generated appropriate warning and danger states, and activated the required protection mechanisms. The experimental evaluation confirmed the reliability and practical applicability of the proposed solution for intelligent residential electrical protection.

General Conclusion

General Conclusion

This thesis presented the design and development of S-PROTECTION, a distributed intelligent electrical protection system dedicated to residential applications. The proposed solution combines monitoring, communication, and protection functions to ensure continuous supervision of electrical installations and rapid response to abnormal operating conditions.

The developed system is based on a distributed architecture composed of a central unit and secondary units communicating through wireless technologies. By continuously monitoring voltage and current values, the system is able to detect faults such as overvoltage, undervoltage, short-circuit, and overheating conditions, while automatically activating the appropriate protection mechanisms.

A mobile application was also developed to provide real-time monitoring, fault notifications, and configuration capabilities. This interface improves user interaction and facilitates the management of the protection system.

The experimental tests carried out on the prototype confirmed the effectiveness of the proposed solution. The obtained results demonstrated reliable fault detection, stable wireless communication, proper relay operation, and a reaction time of less than one second under the tested conditions. These results highlight the potential of the S-PROTECTION system as an effective solution for improving electrical safety in residential environments.

Future improvements may include the integration of dedicated earth leakage detection sensors, cloud-based monitoring services, and artificial intelligence techniques for predictive fault analysis. Such developments would further enhance the performance and intelligence of the proposed system.

In conclusion, the S-PROTECTION system successfully achieved the main objectives of the project and demonstrated the practical advantages of combining embedded systems, wireless communication, and intelligent protection technologies in modern electrical installations.

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