T.C.
ISTANBUL SABAHATTIN ZAIM UNIVERSITY
GRADUATE EDUCATION INSTITUTE
DEPARTMENT OF COMPUTER ENGINEERING

DESIGN AND DEVELOPMENT OF AN OVERCURRENT PROTECTION RELAY

MASTER THESIS

Hammad KHALID

Istanbul
January-2022

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THESIS APPROVAL

Upon being assessed in line with the relevant provisions of the Computer Engineering Department of the Sabahattin Zaim University Graduate Education Institute, the study titled "**Design and Development of an Overcurrent Protection Relay**" and submitted by **Hammad Khalid**, as a Master's Dissertation was deemed complete. After being defended before the committee on **31/01/2022**, the dissertation is approved by unanimous vote/a large majority.

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DECLARATION OF SCIENTIFIC ETHICS AND ORIGINALITY

This is to certify that this Master thesis titled “Design and Development of an Overcurrent Protection Relay” is my own work and I have acted according to scientific ethics and academic rules while producing it. I have collected and used all information and data according to scientific ethics and guidelines on thesis writing of Sabahattin Zaim University. I have fully referenced, in both the text and bibliography, all direct and indirect quotations and all sources I have used in this work.

Hammad KHALID

Istanbul, January 2022

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ABSTRACT

DESIGN AND DEVELOPMENT OF AN OVERCURRENT PROTECTION RELAY

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January-2022, Page: 63

Electrical power systems are frequently vulnerable to different types of fault, which, if not handled rapidly, can end up damaging expensive equipment and in the worst case, even cause harm to someone. Some fault types, which can be problematic for power systems, are e.g. overvoltage, overcurrent, and undervoltage. The overcurrent situation is typically more difficult to manage since the fault needs to be detected and circuit breakers need to be opened immediately after the occurrence of the fault in order to prevent equipment damage. Overcurrent protection relays are used for this purpose. In this thesis, the firmware development and simulation for a three-phase digital directional overcurrent relay are presented. The designed overcurrent relay meets the requirements for American National Standards Institute (ANSI) codes 27, 49, 50/51, 50N/51N, 59, 67, and 67N. This research work covers all the designs and simulation work for the firmware development of the overcurrent protection relay. Additionally, it also covers a novel design of coordination automation of directional overcurrent protection relays, which is simulated and demonstrated on an IEEE 9 Bus System designed on MATLAB-Simulink. The results and findings show proper coordination between the relays.

Keywords: Overcurrent Relay, Protection Relay, Design, Microcontroller, Power System Protection, Coordination

ÖZET

AŞIRI AKIM KORUMA RÖLESİNİN TASARIMI VE GELİŞTİRİLMESİ

Hammad KHALID
Yüksek Lisans, Bilgisayar Bilimi ve Mühendisliği
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Elektrik güç sistemleri, hızlı bir şekilde ele alınmazsa, pahalı ekipmana zarar verebilecek ve en kötü durumda birine bile zarar verebilecek farklı arıza türlerine karşı sıklıkla savunmasızdır. Güç sistemleri için sorun yaratabilecek bazı arıza türleri örn. aşırı gerilim, aşırı akım ve düşük gerilim. Aşırı akım durumunun yönetilmesi tipik olarak daha zordur çünkü arızanın tespit edilmesi ve ekipman hasarını önlemek için arıza meydana geldikten hemen sonra devre kesicilerin açılması gerekir. Bunun için aşırı akım koruma röleleri kullanılmaktadır. Bu yazıda, üç fazlı bir dijital yönlü aşırı akım rölesi için yazılım geliştirme ve simülasyon sunulmaktadır. Tasarlanan aşırı akım rölesi, Amerikan Ulusal Standartlar Enstitüsü (ANSI) 27, 49, 50/51, 50N/51N, 59, 67 ve 67N kodlarının gereksinimlerini karşılar. Bu araştırma çalışması, aşırı akım koruma rölesinin yazılım geliştirmesi için tüm tasarımları ve simülasyon çalışmalarını kapsamaktadır. Ek olarak, bu araştırma çalışması, MATLAB-Simulink üzerinde tasarlanmış bir IEEE 9 Bus Sisteminde simüle edilen ve gösterilen yönlü aşırı akım koruma rölelerinin koordinasyon otomasyonunun yeni bir tasarımını da kapsar. Sonuçlar ve bulgular, röleler arasında uygun koordinasyonu göstermektedir.

Anahtar Kelimeler: Aşırı Akım Rölesi, Koruma Rölesi, Tasarım, Mikrodenetleyici, Güç Sistemi Koruması, Koordinasyon

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANSI:	American National Standards Institute
ADC:	Analog to Digital Converter
DG:	Distributed Generation
HMI:	Human-Machine Interface
RTOS:	Real-Time Operating System
DBMS:	Database Management System
DSP:	Digital Signal Processing
IEC:	International Electrotechnical Commission
GFP:	Ground Fault Protection
OVP:	Overvoltage Protection
CB:	Circuit Breaker
A:	Amperes
V:	Volts
LCD:	Liquid Crystal Display
NI:	Normal Inverse
VI:	Very Inverse
EI:	Extremely Inverse
UD:	User-Defined
FPGA:	Field Programmable Gate Array
DG:	Distributed Generation
IED:	Intelligent Electronic Devices
ML:	Machine Learning
DL:	Deep Learning
API:	Application Programming Interface

CHAPTER I

INTRODUCTION

1.1 Purpose of the Study

The aim of this research work is to design and develop an overcurrent protection relay. It will be a bi-directional overcurrent relay. The target is to add functions in this protection relay which will make it a much more unique and advanced as compared to the only other protection relay developed in Turkey. The specific goals of this research work are to assess the technical challenges of designing and developing a protection relay through exhaustive literature review. Secondly, to specify the protection requirements of the overcurrent relay and the utilities, to design and develop the softwares of the proposed overcurrent relay. Finally, the designed overcurrent protection relay is to be simulated on a simulation software, after which, the coordination of several such relays is to be discussed and simulated on a simulation software.

1.2 Statement of the Problem

Power systems are the system of electricity supply networks and distribution networks that make electricity available to the end-users. These networks can be very complex, spanning thousands of kilometers, with tens and hundreds of thousands of kilometers of underground cables and above ground power lines and millions of connected meters. A power system includes a grid with several sub-grids or networks. Each sub-grid or network is usually formed of electrical power generation systems that together produce a defined amount of power and that are connected by power lines to a common grid. It consists of generators, transformers, power lines and other types of switch-gear. An end-user is connected to a generator through a transformer, and that network of buses, transformers, wires and switches that make up the physical system is the power system. It is not possible to avoid faults in the power system, but rather react to the fault in a sensitive, selective, speedy, and reliable manner. Power system protection includes performing very complicated tasks in a reliable, fast, cost-effective manner in order to achieve this. Recently the most popular and developing power system protection method is adaptive protection (Khalid and Shobole, 2021, p. 194; Shobole et al., 2020, p. 48). Current power system protection technologies can be divided into primary protection, secondary protection, backup protection, and real-time protection. For power system protection, fault signals are a critical resource. The power system protection methods use the fault signals to detect and recover the faults. These fault signals are sent using fault detection devices. A fault detection device is called a protection relay. It detects various faults in the power system, and continuously monitors the operation state of the power system is referred to as a protection relay. To achieve this goal, protection relays perform several different kinds of protection, which includes overcurrent protection, overvoltage protection, undervoltage protection, distance protection, differential protection, etc. (Ghafari, 2017, pp. 50-55. 22; Ozturk, 1998, pp. 32-35; Ramarao et al., 2014, p. 2). Additionally, when protection relays are introduced into a power system, they need to be coordinated in order for the power system to be protected. This coordination is necessary to minimize unnecessary tripping of the protection relays and to prevent the protection relays from reacting to an "internal" fault condition. Thus, for example, if a protection relay detects an internal fault, it must not turn on a switch that would cause power to be supplied to a power system component that is known to be operating properly. A protection relay design has been presented in this thesis for power system protection, and a coordination method is presented for relays in an IEEE 9 Bus System.

1.3 Research Questions

This study aims to focus upon finding the answers to the following questions:

1. What technical challenges are faced in the design of a microcontroller-based overcurrent relay?
2. What are the protection requirements and settings needed to be calculated and set in an industrial level overcurrent relay?
3. What are the functions and capablities needed to be included in an overcurrent relay so that it is much more advanced than a basic overcurrent relay?

1.4 Significance of the Study

The field of this thesis is Electric Power System Protection. While power systems is inside just the field of Power Engineering, power system “protection” is a combination of both Power Engineering and Computer Science. An electric power system ought to guarantee the accessibility of electrical energy without interference to each load associated with the system when the electric power supply is stretched out to far off town in the power system would comprise of a few thousand of kilometers of transmission line. The transmission lines attempting to interface the power station with load, when a fault happens on the transmission line, it is important to identify and isolate the issue on power station. Protection relays transfers are utilized for this reason. There are not many research works presented in journals and conferences that have focused solely on developing just a relay device specifically for industrial purposes. Most works focus on adjusting and modifying an existing relay model according to the researcher’s preferences. In the reviewed literatures, the approaches to the practical application of the proposed protection ideas are unavailable or very limited. Some of the algorithms proposed in the literature are too complex to be applied to the industry. The majority of the papers reviewed discussed theoretical applications and did not intend to produce an industrial product. The significance of this thesis focusing on the development of an overcurrent protection relay is that it can be used as a guideline to design a practical model for future development. So the result of this thesis can be used to aid researchers to build a different type of relay and modify it for their own needs. It can be used for industrial applications, as the overcurrent protection relay developed in this study is very compact and cost-effective.

1.5 Limitations of the Study

The limitations of this study include the lack of communication protocol libraries used for the communication of industrial level protection relays. These communication protocol libraries are expensive and have to be purchased directly from only a few companies in the world that have developed these libraries as well as protection relays. Very advanced level international industrial protection relays have significantly more number of functionalities in their protection relays. Developing and including them in this research work is also a limitation of this study.

1.6 Organization of Chapters

This research work provides a systematic approach of the design, development, and verification of the protection relay firmware. As compared to the similar works reviewed, the designed protection relay is for a three-phase power system, covers a wide range of protection functionalities, and has a superior firmware design, which includes a real-time operating system, as well as an embedded database. Several different softwares, namely, Microsoft Visual Studio Code, STM32CubeIDE, Proteus, and MATLAB-Simulink, have been used for this research work. The parts of the project where they have been used is shown in Table 1. In this thesis, the firmware design of an overcurrent protection relay is presented. Chapter I provides a summary of the purpose, significance, and the limitations of the study involved in this thesis. It discusses the problem statement and the organization of chapters in this thesis. Chapter II covers all the literature review done in order to perform this study and compete this thesis. In Chapter III, an introduction to power systems protection and overcurrent relays is given, as well as the components involved in the development of the relay. It also discusses the firmware design in detail of the designed overcurrent protection relay. Different parts and works involved in the firmware development are presented. In Chapter IV, the final simulation and discussion of the microcontroller and firmware operation is presented, as well the simulation of different cases for coordination of relays in an IEEE 9-Bus System. Finally, in Chapter V, the conclusion of this study is provided.

Table 1. Softwares Used In This Research Work.

Part of Research	**Softwares Used**
Firmware Design	Microsoft Visual Studio Code, STM32CubeIDE
Firmware Simulation	Proteus
Coordination Simulation	MATLAB-Simulink

CHAPTER II

LITERATURE REVIEW

Bhattacharya et al. (2017) used the Arduino microcontroller in a circuit with a lamp as a load for overcurrent and overvoltage protection with fixed threshold limits. Agarwal (2016) presented a similar paper with Arduino and single phase source. Kotb et al. (2018) and Kotb et al. (2019) proposed two protection relay systems using Arduino, one that performs overvoltage and undervoltage protection, and the second which performs overcurrent protection. For the under and overvoltage protection circuit, sensors were not used to measure the voltage, but rather a circuit with op-amps. For the overcurrent protection however, hall-effect current sensors were used. Ashwani's (2017) designed protection relay model has a similar design and performs the same functions. Pandhare et al. (2017) performed a similar protection research work, however, they use and only dealt with the temperature rising issue of a transformer. Few research works on developing power/energy meters were also performed, which have similar components and theoretical approach to design of protection relays (Gallo et al., 2010, p. 311; Machado et al., 2017, p. 1; Gunawan et al., 2019, p. 2). Goh et al. (2010) presented a simple overcurrent protection relay in their research work, with the difference that they used MATLAB-Simulink to simulate their model, and used the TMS320F2812 Digital Signal Processing (DSP) module in their model. Abdel-Salam et al. (2017) presented a similar work.

Since recently, Distributed Generations (DGs) have been included in power systems in the way for the development of smart power systems. Due to this, proper coordination maintaining proper coordination of the protection relays is of vital importance. Abbaspour et al. (2019) addressed this issue by proposing a protection mechanism based on a bi-level multi-agent system. The first level is in charge of ensuring good relay coordination by establishing an effective communication infrastructure. This is to make sure that relays which act as backup take as less time as possible to function. The DGs are handled at the second level, with each DG in each dispersed region being overseen by a distinct agent. In this protection strategy, agents are set to act as the relay agents and the generation agents. Chandraratne et al. (2019) proposed a solution that make use of centrally controlled system and is executed in two steps in order to address the coordination challenge. The monitoring of the whole system is involved in the 1st step, which further communicates all and any changes to the centralized monitoring system. In the 2nd stage, settings calculations are done in the monitoring system. The ETAP software was used to implement their suggested approach.

Ibrahim et al. (2016) developed a coordination mechanism for perfect coordination between in the relays in their system, dubbed Artificial Bee Colony algorithm. Their suggested approach was evaluated and was able to create new relay settings in response to changes in the whole system. Shih et al. (2015) used an ant colony optimization approach, which is comparable to ant colony optimization. For effective relay communication and setting updates as the system dynamic changes, a centralized system was set up utilizing a centralized computer technique. The coordination approach is used in this system to ensure that there is perfect coordination between the relays by reducing the operating times of the primary and backup relays. Samuel and Shet (2019) also suggested a fuzzy decision-making tool-based coordination approach. They have also employed instructional learning-based optimization to go along with it. The fundamental purpose of the proposed approach is to figure out the relay pick-up settings to guarantee the proper coordination of the system. On the ETAP program, the proposed approach was simulated. Fani et al. (2018) developed a coordination approach for DGs dominated by solar systems to assure protection system coordination. A two-stage method is employed, with the 1st step using distinct voltage profiles as an index before a fault happens, and the 2nd step is monitoring the short-circuit/load profiles to calculate the correct group protection settings. When the voltage profile is identified in the second stage, the protective devices are adjusted to the appropriate pre-calculated values. Darabi et al. (2020) in their proposed approach focused mainly on optimizing the coordination of the system involving primary and backup relays, in order to have minimum coordination interval time as possible. As a result, they have devised a method for improving the system's dependability. It considers the distance there is between the fault that has occurred and the location of the primary protection relay. Using these, they have proposed a method for classifying relay pairs in various situations.

Fault current limiters and DGs have less of an impact on relays, according to Shih et al. (2019). Overcurrent protection relays which operate in both direction, also known as directional overcurrent protection relays, with restricted bandwidth communication were also used in a system they devised to assure adequate protection coordination. Nikolaidis et al. (2016) discusses a solution that they proposed which makes use of a system where reclosers have been replaced by directional overcurrent protection relays at the system's line. Can et al. (2018) have examined how the since the normal power systems have evolved into DG systems and systems that have micro-grids, has caused most protection techniques to become redundant, and so this study proposes non-standard characteristics to solve the challenges that have developed as a result of the aforementioned changes. Ustun et al. (2011) have presented a protective strategy employing fault current limiters to address the problem of dynamic changes in the DG system in micro-grids. It makes use of a centrally controlled operating point and a communication system for using fault current limiters in order to tackle the problem of dynamic changes in micro-grids. The system employs extensive and extensive contact with fault current limiters in order to identify defects in near-real time. The system's dependability may be considerably improved in this manner. They spoke about using fault current limiters with inverted interfaced DG in a novel communication system with a centrally controlled operational point. Yang and Tang (2018) explain the drawbacks of adding DG and fault current limiters into power systems. To develop a self-adaptive protection approach, a continuous wavelet transform and a developed algorithm called the sensitivity analysis. Gashteroodkhani et al. (2019) have made use of a computational technique for fault detection using a time-time matrix z-score vector. This vector is used to categorize fault patterns. For various fault circumstances and scenarios, different thresholds were calculated, and tripping signals were created appropriately.

In power systems, phasor measurement units are the primary method of determining the frequency of the current values in a signal and the frequency of the voltage values in a signal. Mirsaeidi et al. (2016) presented that their approach is comparable to earlier proposed techniques to handle protection difficulties in micro-grids owing to a considerable reduction in fault current when shifted to islanded mode. Phasor measurement units and a central protection unit are used, and the central protection units is in charge of interpreting the phasor measurement units' data. The central protection unit then sends appropriate tripping signals based on the problem locations and phases it has detected. Habib et al. (2018) have suggested a technique in which communication is with the relays and isolation of a fault takes place because of the consistent communication between the several control centers. To help the relays attain their proper settings, a supercapacitor bank is also utilized. The approach was tested on numerous distinct fault areas and yielded the expected results. Pathirana et al. (2017) developed a hybrid of existing protection techniques in their presented work to address probable time delays involving overcurrent protection relays and distance protection relays. A mixture of phasor-based protection and transient-based protection can be observed in this technique. The transient-based approach compares the polarities of transients caused by system faults, while the phasor-based technique compares the polarities of transients caused by non-faults.

Manditereza and Bansalb (2020) proposed a protection algorithm that uses synchronized phasor values from phasor measurement units. A voltage relay model was used to build the suggested technique. A research on protective strategies employed in North American micro-grids was conducted by Piesciorovsky et al. (2020). This research focused on overvoltage and undervoltage protection strategies. The authors offered this work as a reference for protection engineers to design protection approaches based on distinct micro-grid operational situations. Sari et al. (2020)have highlighted the issue that overcurrent protection in a power system is not always possible. They have presented a protective system that employs undervoltage and reverse power relays as backup relays to address this issue. The IEEE 242-2001 standard is used to coordinate relay communication. Nahas et al. (2020) developed a protection strategy employing a power-voltage relay model. They used the dP-dV profile in their model to create three operational zones and to characterize fault sites and kinds. By identifying a defect in about 0.2 seconds, the suggested relay model proven to be effective in fault detection. Yu et al. (2019) have just used the data from the phasor measurement unit as input in order to develop a scheme that creates a hybrid without using any other schemes. The backup protection system consisted of three steps: locating the feeder linked to the faulty region, identifying the location where the fault occurred, and lastly applying the backup protection. One of the key focuses of the ever-evolving power system technology is power system automation. The system design incorporates technologies such as Intelligent Electronic Devices (IEDs) for this automation purpose. Because there are so many different devices from so many different suppliers, the IEC-61850 standard is now widely utilized to ensure flawless compatibility between them. For the medium voltage level, Sotomayor et al. (2018)

have proposed a protection technique and system. The medium voltage distribution grid uses the same protective functions as normal substations, such as overcurrent protection functions, directional overcurrent protection function, thermal protection functions, undervoltage protection functions, and overvoltage protection function. Sotomayor et al. defines and explains a specific data model offered by the IEC-61850 standard, which is subsequently applied in a practical operational environment in Brescia, Italy. Noce et al. (2019) offered a method based on IEC-61850, a standard that governs the interoperability of various control and protection devices. Apart from that, they communicated at rapid speeds via LTE. Using this method, they have essentially digitized a high voltage/medium voltage distribution substation. The writers are employees of the Enel GI and N business. The components utilized in their method were given specifications by Enel GI and N. In this method, they have included a unique voltage management system as well as smart fault selection.

Fani et al. offer a method for analyzing different photovoltaic penetration sites, levels, and protection efficacy in certain circumstances. To assure coordination, the relays' characteristic curves are altered such that even in the worst-case scenario, there is strong coordination among the ones investigated. The internal circuit of the relay is constantly monitored by a service called Watchdog. The method was put to the test on a real-world power distribution network using photovoltaic units. Due to the fact that the system circumstances change fast in response to consumer demands, and system components are unable to coordinate well in these instances, multi-agent based protection strategies in a power system are increasingly frequently deployed. In their research, Fani et al. (2018) have focused on the fact that multi-agent systems now have worse dependability due to DG units, which exerts a large strain on the system. As a result, communication is less effective and, in some cases, fails. As a result, they suggest an auxiliary algorithm that separates the multi-agent system into two control units. Sekhavatmanesh and Cherkaoui (2017) suggested a self-healing protection strategy that splits the feeders and assigns an agent to each one, according to the authors. These are known as feeder agents, and they interact with the sectionalized agents known as zone-agents in the event of a problem. In the event of a fault, all conceivable combinations of switches with each feeder linked to the agents are considered throughout the restoration process. Based on Thevenin's theory, it is an analytical model of the idea of clustering. MATLAB and the Gurobi solver were used to evaluate the analytical model.

Hussain et al. (2016) provided three types of protection techniques: conventional over-current-based, clark's transformation-based, and positive sequence phase differential-based protection schemes. The authors employed MATLAB to implement a N programming-based technique, in which the software determines which of the three protection schemes to apply by assigning the number N=1, 2 or 3. The system has numerous agents, each of whom is equipped with one of the three protective strategies given. Each protection software runs fault information through it, and the results are generated using polling logic derived from a function based on a truth table. This method allows the system to detect all forms of problems, hence boosting the system's dependability. Shirazi and Jadid (2019) emphasis on feeder switching activities in order to clear a malfunction in a power system. They have presented a hybrid multi-agent system and artificial neural network technique, including switch, zone, DG, and feeder agents as the agents. The neural network component of the DG agent. The location of the fault and the system's circumstances are taken into account while creating the self-healing strategy. Several various loading situations were used, and the simulation produced the expected results. Mosaad et al. (2018) proposed a proportional integral control system using an artificial neural network. This controller is used to regulate power injection into the network, preventing overcurrent relay mis-coordination during grid outages. This solution employs interconnected wind turbine-based distributed switched reluctance generation, with the artificial neural network-proportional integral control scheme controller adapting the switch-off angle of the switched reluctance generation. As parameters are updated on a regular basis, the neural network is continually trained, making the technique more trustworthy after each update. MATLAB-Simulink was used for the simulation. Tian et al. (2016) introduced a new defect diagnostic approach based on multi-agent systems. The system is programmed with a specialized fault diagnostic agent. An analytical model is also provided to describe the link between the agent and their effects on the system. The communication architecture described in this research paper is critical to the suggested fault diagnosis method's effectiveness. A 32-bus active distribution system was used to test the approach.

Intelligent multi-agent systems have been established recently, that consider artificial intelligence, and Lin et al. (2018) have used them to propose a solution that both locates and isolates a defect in a distributed network with DGs. Control and protection intelligent agents are used in intelligent multi-agent systems. It chooses control techniques to enable the system to adapt to various changes in the system. On DigSILENT PowerFactory, the approach was tried and simulated. The approach for locating, isolating, and restoring service is the result of advancements in power system protection technology. Eriksson et al. (2015) suggested a multi-agent system-based distribution automation method. The fault location, isolation, and service restoration approach is used by the authors to focus on the service restoration aspect of it, employing Prim's minimal spanning tree algorithm. This strategy employs three different types of agents: load control agents, restoration control agents, and substation control agents. On a testbed with Arduino microcontrollers and Raspberry-Pi processors, the suggested approach is implemented on a DC-grid model. In their paper, Elmitwally et al. (2015) present a fuzzy multi-agent control system method for smart power systems. Several load agents and just one feeder agent make up this multi-agent system. There is one regulator agent at each substation in the system. Each load agent on their own load bus keeps an eye on the bus and informs the feeder agent of any changes. The suggested solution has the advantage of reducing feeder congestion in the system and voltage violation concerns through distribution network reconfiguration. This design was tested and simulated using the IEEE bus test feeder and MATLAB-JADE.

In the works by Mingyu (2004) and Bhattarai (2015), a multi-agent approach for power system in smart grid protection environment is presented. In these literatures, the method of applying multi-agent system-based protection to IEDs is not specified. In the work presented by Xyngi (2011), centralized and decentralized adaptive protection schemes were proposed. According to this method, the direction of the fault is determined by central relaying unit based on the data received from each relays in the network. The central relaying unit runs the setting algorithm and sends the time dial and pickup values to the relays. The disadvantages of this method are communication dependency and taking of longer time for the relay to operate and clear the fault. Furthermore, for decentralized adaptive protection multi-agent is proposed. Their proposed multi-agent system contains a relay-agent and a DG-agent. Relay-agent contains data-measurement, protection, execution and communication sub-agents. In the work presented by Oudalov (2009), a centralized micro-grid protection system by using a micro-grid central controller and communication system in addition to primary switching equipment is discussed.

According to the method used by Oudalov (2009), micro-grid central controller collects the CBs status and identify the micro-grid configuration. For each configuration offline, short circuit analysis is performed for each relay location or CB points and corresponding protection settings are calculated and stored in the lookup table. These settings are updated to the relay for any change in the configuration of the micro-grid by searching the corresponding setting from the database. This method requires high-speed computation capability of IEDs. Another problem of this method is the possibility of communication disconnection with central controller. A multifunctional digital overcurrent relay was proposed and developed in one more research work. To the best of the researcher’s knowledge, this will be the second work in Turkey to develop an overcurrent relay as a product. The first time, a company called “Pavotek” did it.

CHAPTER III

RESEARCH METHODOLOGY

There are different types of relays available in the market, namely, processor-based digital relays, solid-state relays, and electro-mechanical relays. The electromechanical type of overcurrent relays use a spring for sensing an overcurrent condition and mechanically actuating an opening and closing mechanism. Whereas, the solid-state type of overcurrent relays do not use a spring, but instead, use semiconductor components to detect the overcurrent condition. The digital overcurrent relays have a processor for processing the input current signals. The digital overcurrent relays use a microprocessor or a microcontroller to provide the current monitoring. This relay may also include additional functions such as a voltage monitoring, power monitoring, temperature monitoring, etc. The different types of overcurrent relays have their advantages and disadvantages. In the market, the most popular industrial overcurrent relay manufacturers include ABB, Schneider Electric, and SIEMENS.

The microcontroller-based relays consist of many modules including both hardware as well as software, as shown in Figure 1. These include an independent power supply, filters, Analog to Digital Converters (ADCs), digital input and output systems, Local Human-Machine Interface (HMI) systems, communication modules, memories, and microcontrollers (Mahfoud et al., 2016, pp. 397-399). The architecture of the microcontroller-based relay can be split into three categories. The first category is concerned with accurate measurement of currents and voltages starting from CTs and VTs, and ending to the ADC, which generates discrete samples. The discrete samples go through digital signal processing techniques to compute the voltage and current phasors. Then, the set of programs called firmware performs the protection decisions. The last category includes, the digital inputs and outputs, the local HMI, and the communication protocols implemented in the protection relay (see Figure 1).

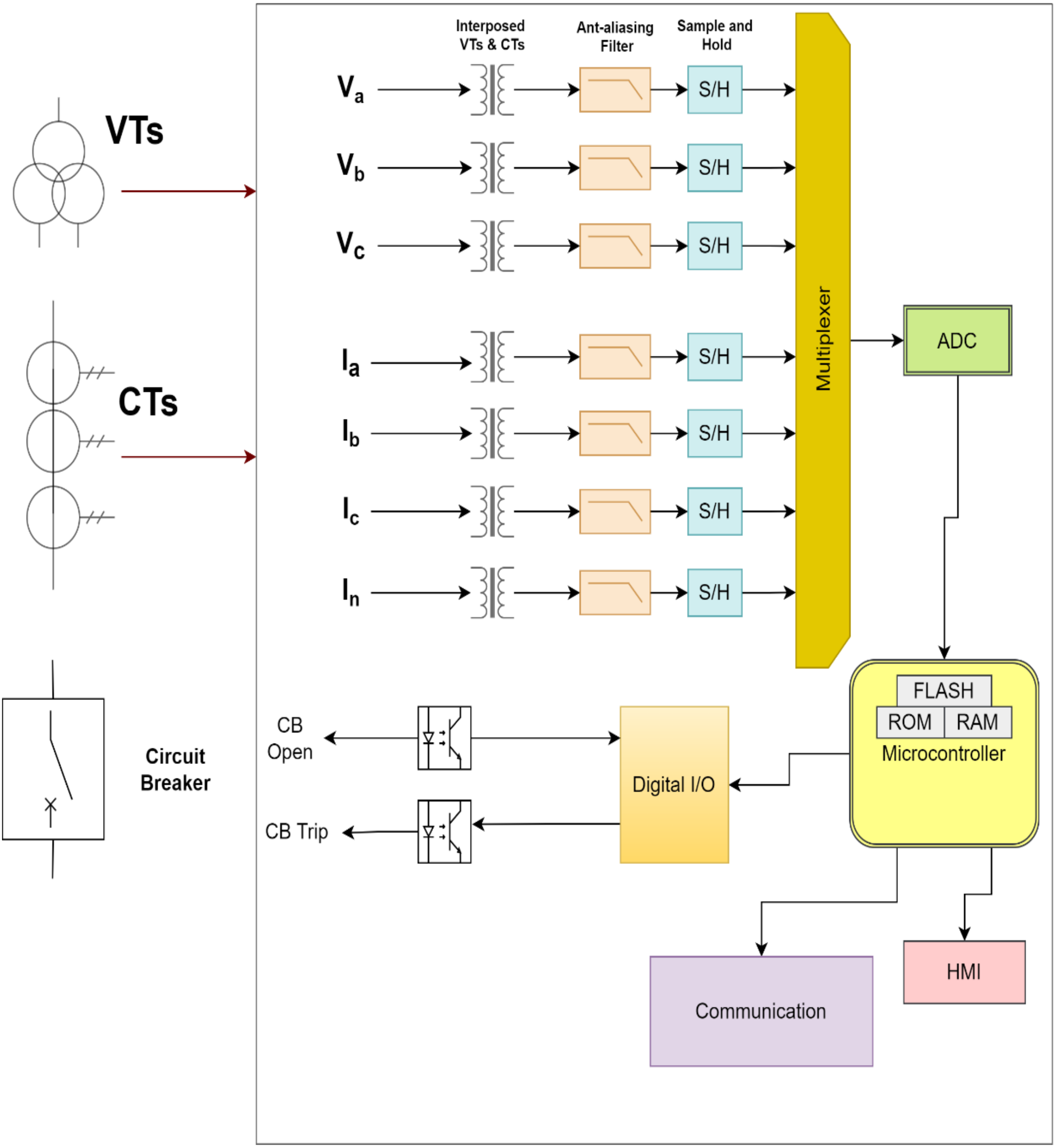

Figure. 1: The Main Components of Protection Relay.

The software of the protection relay can be divided into two parts: the embedded software, and the application configuration software. The embedded software is usually stored on the protected component. In contrast, the application configuration software is usually stored in a configuration database that is accessible by the software of the protection relay. In a traditional protection relay, the software for controlling, operating, and monitoring the protection relay is always stored in the embedded software. The main parts of the embedded software code include the protection algorithms, the local HMI programming, memory programming, embedded database, Real-Time Operating System (RTOS) programming, and the communication protocols (See Figure 2).

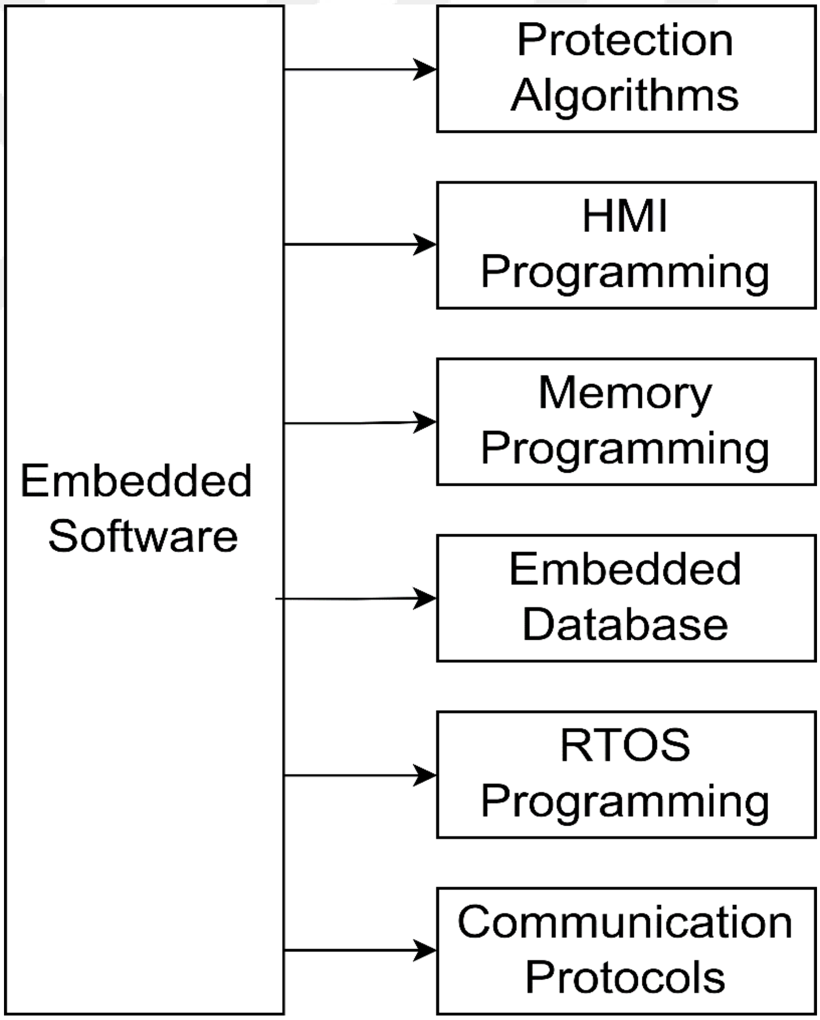

Figure. 2: Overcurrent Relay Firmware.

The protection algorithms consist of code for all the ANSI codes that the protection relay is capable of applying. The local HMI includes the LCD for displaying outputs on the screen and the keypad needed for inputting data from the user. The memory programming is basically setting up data to be stored into the Flash memory area of the microcontroller. The advantage of storing data into the Flash memory area is that data will be kept there even after power off, so it is quite useful if some data logging or storing configuration parameters is being done which are needed to remain even after power off. Any system that deals with storing information needs a database, and to deal with a database it needs a Database Management System (DBMS). The Embedded database provides the base services required for database management. They are divided into three components; storage of data, retrieval of data and data management. Using the Embedded database the data stored will remain available even after a power failure or system restart. This feature makes the Embedded database ideal in embedded software. RTOS are operating systems that utilize real-time computing to ensure that tasks are performed without exceeding their deadlines. This is important for applications where time is crucial and tasks should be done in their specified time periods. A communication protocol helps in the exchange of messages between two overcurrent relays in the power system, without which, communication between these relays cannot be achieved. Ethernet is a common medium for data transfer in the industry because of its reliability and low cost. Information such as current values, voltage values, and relay operating times and much more can be communicated between the relays using this, which would in-turn increase the efficiency of the overall protection system (Midence, 2013, pp. 26-30). Some of the most popular ones are Modbus, DNP3, and IEC-61850 (Sparks, 2018, p. 160).

The hardware of the protection relay consists of mainly the microcontroller, the power supply, the analog input module, the local HMI, and the digital input-output connections. This has also been depicted in Figure 1. The microcontroller has the functions of collecting the operating data from the analog input module, running the protection algorithms, interacting as an input and output with the local HMI, and transmitting trip signals through the digital I/O ports. The hardware interacting directly with the microcontroller is depicted in Figure 3. Some of the very popular microcontroller manufacturers include STMicroelectronics, NXP Semiconductors, and Xilinx. The analog input module includes the anti-aliasing filters, sample and hold circuits, and the ADC. The anti-aliasing filter is essential to minimize the sampling noise and the aliasing signal for a reliable signal measurement. The sample and hold circuits hold a precise reference level during the analog-to-digital conversion process. The digital I/O connections allow the relay to communicate with the circuit breaker, in order to know its open or closed statuses, and to send it tripping signals.

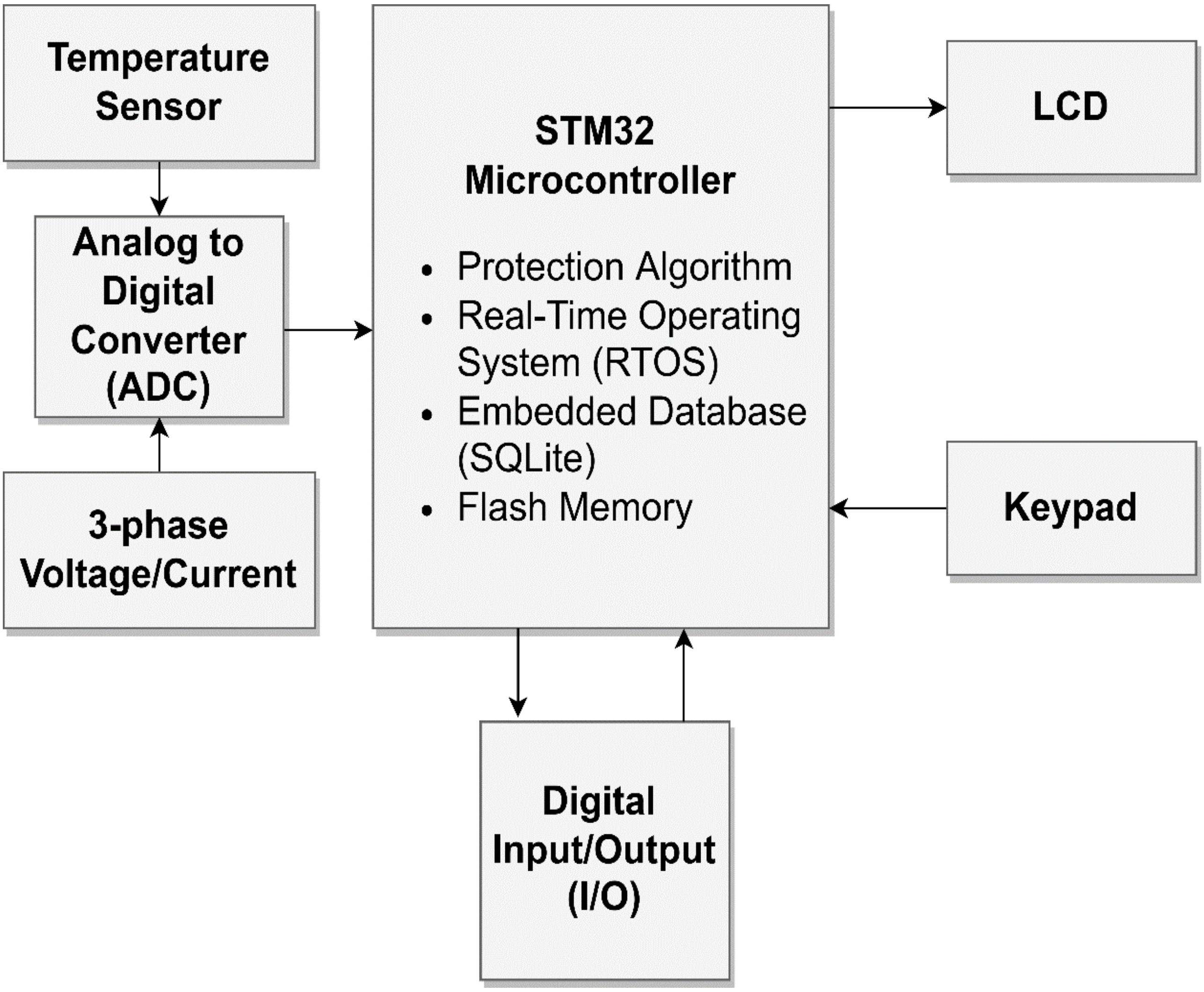

Figure. 3: Microcontroller Hardware Interface

The main firmware tasks are as shown in Figure 2. The code written for the firmware is efficient in terms of the time and memory complexity. The microcontroller used here is the STM32 Bluepill (STM32F103C8) microcontroller.

2.1. Protection Algorithm

One of the main functions that are implemented inside the firmware of the relay is the protection algorithm function. Due to the characteristics of these applications, overcurrent relays are required for both current and voltage protection.

The developed digital overcurrent relay design integrates overcurrent, undervoltage, and residual current protection within a compact housing. A single device can monitor and protect many different applications, eliminating the need for multiple protective devices on a same load that the relay is connected to.

According to the International Electrotechnical Commission (IEC) set standard, the commonly used formula for the inverse time characteristics can defined as in Equation. 1. By changing the values of k and α, as per defined constant values of each characteristic curve, the relay operating time can be calculated for each curve implemented.

$$t = TMS * \frac{\beta}{(\frac{I}{Iset})^{\alpha} - 1} \qquad (1)$$

Where:

t = Relay operating time.

TMS = Time Multiplier Setting.

I = Value of measured relay current.

I_{set} = Current set value.

α = Index characterizing the algebraic function.

β = Scaling term.

In the firmware/software part of the relay design, the code is written in C language for implementing several ANSI standards: (ANSI 27) Undervoltage Protection, (ANSI 49) Thermal Protection, (ANSI 50/51) Phase Overcurrent Protection, (ANSI 50N/51N) Residual Overcurrent Protection, (ANSI 59) Overvoltage Protection, (ANSI 67) Directional Overcurrent Protection, (ANSI 67N) Directional Ground Fault Protection, (ANSI BF) Circuit Breaker Failure, (ANSI 74CT) CT Supervision, (ANSI 74VT) VT Supervision, and (ANSI 74TCS) Trip Circuit Supervision. The goal was to have an ANSI-compliant overcurrent relay.

The purpose of Phase Overcurrent Protection (ANSI 50/51) is to protect a load (in the form of a load resistance) from the excessive voltage across the phase, due to a power failure or malfunction in the grid (in the form of a load impedance). It prevents a load to be damaged by excessive current. The phase overcurrent protection compares the phase voltage to a reference voltage for comparing to a phase trip threshold. If the phase voltage is higher than the phase trip threshold, the digital relay outputs a fault signal, which shuts off the load. A typical range of the phase trip threshold is 20% to 80%. The purpose of Residual Overcurrent Protection (ANSI 50N/51N) is to protect a load from a residual voltage after a phase voltage exceeds the threshold. The residual overcurrent protection can be performed via phase and phase-to-neutral residual currents. Phase and phase-to-neutral residual currents can be measured with current transformers and current sense resistors. If the residual current is higher than the residual current limit, a fault signal is outputted, which shuts off the load. A typical residual voltage limit is 6% to 12% of the phase voltage. The standard ANSI 67/67N specifies the functions of Directional Overcurrent Protection and Directional Ground Fault Protection (GFP). Directional overcurrent protection functions to limit the total fault current flowing in the protected circuit such that the fault current does not exceed the predetermined threshold. It operates for both forward direction and backwards direction. Directional GFP, on the other hand, functions to identify and protect a circuit that has become ground faulted. Ground fault means that the circuit is connected to ground or earth and the flow of current in the circuit is greater than the predetermined threshold. Directional GFP functions to cut off the power supply to the circuit once a ground fault is detected.

There are several ways and algorithms to determine directionality in the protection relay, which is needed to implement the directional protection mentioned. The directional element is the key component to achieve directional overcurrent protection. The directional element allows the operation (tripping) of the overcurrent relay within the directional overcurrent relay only when the measured current flows in the selected direction (forward or reverse) of current flow. Two ways have been used in this research work for this purpose, namely, the cross-polarisation method and the zero sequence elements method, as shown in Figure 4.

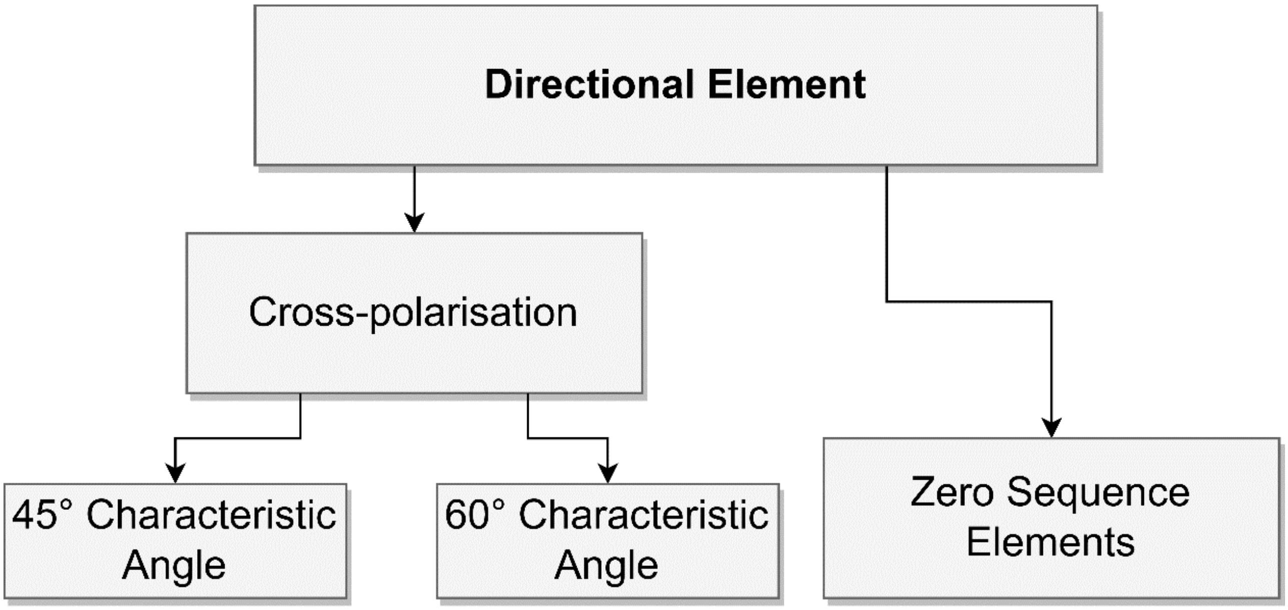

Figure. 4: Directionality Methods Used.

Cross-polarisation method is to extract the phase voltage of the faulty phase, and use the subtraction of the other two phase voltages as the polarizing (reference) voltage. The reason why the faulty phase's own phase voltage is not used is because of cases where it can be zero, such as in phase-to-ground faults, rendering it unusable as a reference vector. A characteristic angle, which can be 45 or 60 degrees, is applied to the reference voltage then. If the polarizing current vector falls inside the 180 degrees range of the reference voltage, it is considered to be in forward direction, otherwise it's in reverse direction. This method is depicted in Figure 5.

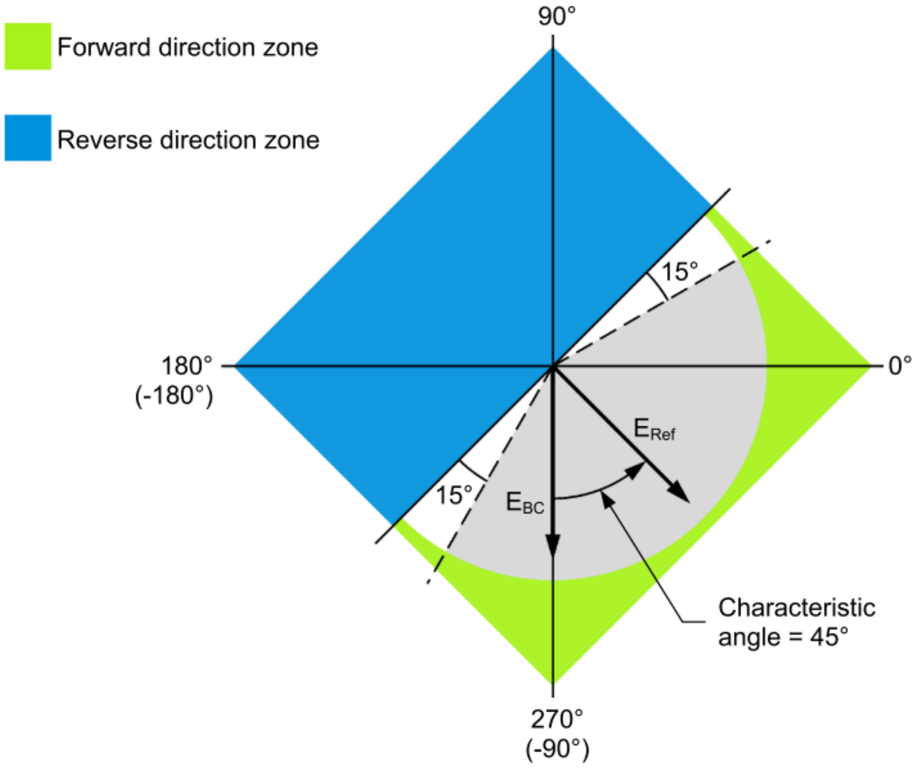

Figure. 5: Determining Direction using Reference Voltage and 45 Degree Characteristic Angle (Festo, 2016, p. 15).

The zero sequence elements method is to use the cross-polarization method, and then filters out the reference vector to be the zero sequence elements. The zero sequence voltage angle is 180 degrees out of phase (is a negative value) with the normal condition positive sequence. Zero sequence current is caused by an unbalanced fault involving ground. Zero sequence overcurrent elements can be set very sensitive (i.e. low threshold setting) because the zero sequence current generated under load conditions is typically very low. Also, the unbalanced phase with the fault is typically very high magnitude in comparison with the ground, therefore the fault can be detected easily (Mooney and Peer, 1998, pp. 6-8).

Undervoltage protection (ANSI 27) is provided in the event of a power supply fault. It is a critical function in any system that provides power. Without undervoltage protection, power would be applied when the system is not in a condition to receive and handle it. Undervoltage protection is also required for the protection of any electrical equipment from damage due to power supply faults, as well as the protection of other electrical equipment from overcurrent conditions. The standard ANSI 59 Overvoltage Protection has been written to specify the function of Overvoltage Protection (OVP). The OVP relays can use the protection methods, e.g., the current protection method, the time-current protection method, and the voltage protection method. The input voltage signal (or current) is measured when the relay detects an overvoltage event, and if the input voltage is greater than a limit value, the relay contacts will be closed. If the input voltage is within the limits, then the contacts are not closed. This protection method has certain advantages. However, this method can only protect the contact switch and it cannot prevent the damage caused by other components, such as the inductor, transformer, and capacitor.

Thermal protection (ANSI 49) is provided in the event of overcurrent or excess heat conditions in the system. In the firmware, the temperature limit for the relay was defined. If the relay's temperature reaches beyond its specified limit, the relay trips. The LM35 temperature sensor has been interfaced with the microcontroller for this purpose. The LM35 temperature sensor is a thermistor-based sensor. It responds directly to the actual temperature of the environment. It measures the temperature of its surrounding and converts it to a digital value (typically a number between 0-1, 0 being "coldest" and 1 being "warmest"). It is designed to read thermistor temperature values up to 120°C (248°F) and provide a digital reading of up to 8bits. For the Protection of Circuit Breaker (CB) (ANSI BF), if the residual current limit and/or phase current limit is exceeded, an internal controller will start to operate one of the CBs to shut off the load. The purpose of CT, VT, and TC Supervision (ANSI 74) is to control the operation of the circuit breakers under certain fault conditions. If one of the CT, VT, or TC supervision limits is exceeded, the internal controller will start to operate one of the circuit breakers to shut off the load.

Eight analog inputs are given to the microcontroller, four CT inputs, three VT inputs, and one temperature sensor input. There is a separate function inside the written code for inputting, scaling, and finally putting each value in its respected variable. Upon getting all the necessary variables, the protection functions codes are called, and their codes are run if the necessary fault condition is met. Inside the overcurrent protection function, depending on non-directionality or directionality chosen, and the inverse time overcurrent characteristic curve chosen, the algorithm runs with an overcurrent limit of 10 Amperes (A). A separate fault function code is written, which is just directly called inside every protection function in case of fault, which trips the CBs. The input for the system is 220 Volts (V); the condition inside the undervoltage protection function is set such that the phases' voltage should not become less than 176V. Similarly, should not go over 250V in the overvoltage protection function.

2.2. Local Human Machine Interface (HMI) Programming

Examples of HMI physical aspects could be a machine with a display, a push button, or a keypad. There exist a few different ways for interfacing such a keypad matrix to a microcontroller. While some of them are interrupt-driven, others work by polling the pins and scanning through all the keys one by one. On the keypad that has been interfaced with the STM32 microcontroller, 8 GPIO pins were configured. Four of which are inputs and the other 4 are output pins. The column pins are hooked to either the input or output pins. Lastly, the 4-row pins are connected to the 4 input pins of the microcontroller, as seen in Figure 7. There is a whole separate function for the keypad interfacing. The function is called to the main function of the whole code, in order to enter the inputs at the start menu of the relay during startup. For the Liquid Crystal Display (LCD), the 16×4 LCD is interfaced with the microcontroller, which is very similar to the more commonly used 16x2 LCD.

2.3. Flash Memory Interfacing

In the reference manual of the STM32 microcontroller that has been used, the memory map is shown after navigating to the embedded flash memory section. Usually, data can be stored in the first few sectors of the flash memory. The flash consists of 12 sectors. For the storage of variables, it is highly recommended to store them into the latest sectors, so sector 11 was chosen in this case. In order to use the Flash library in the STM32, a function needs to be called to specify the sector in which to read or write data. As mentioned before, sector 11 was chosen, and the start address of the sector was entered in the function as the index. The flash memory interfacing allowed the options chosen at the start-up menu of the Relay and the values calculated according to the IDMT curve chosen to be stored inside the Flash memory.

2.4. Real-Time Operating System

There are two types of real-time systems, depending on how they react when a task doesn't meet its deadline: hard real-time and soft real-time. Hard real-time causes the system to fail if a task doesn't produce a response before the deadline, while soft real-time tolerates responses after the deadline but the quality of the process degrades. This is illustrated in Figure 6.

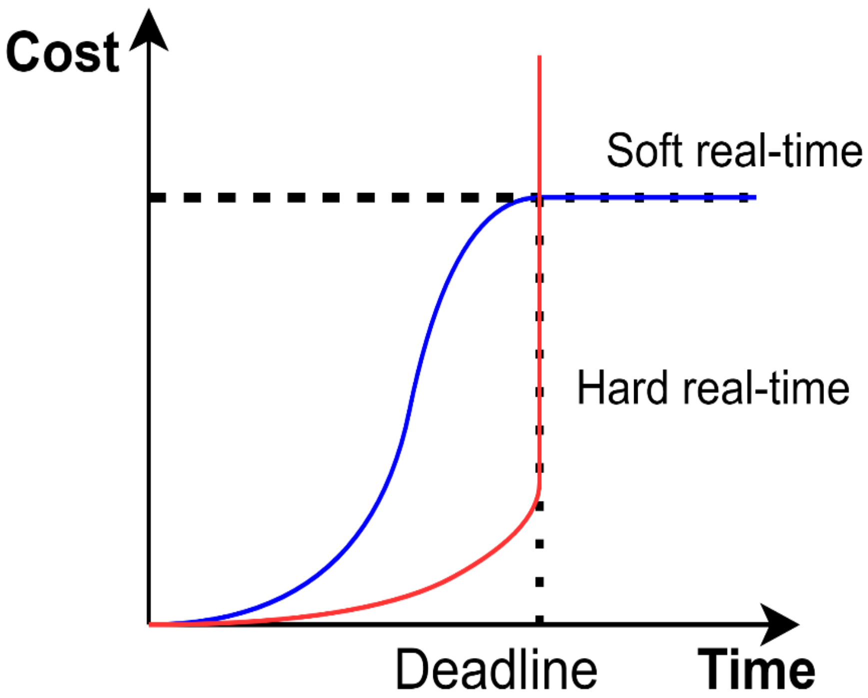

Figure. 6: Relation Between Time Taken By Task to Generate a Response and its Consequence.

Real-time systems need a scheduler to help with making the tasks meet their deadlines and have sufficient resources allocated to them. For most cases, schedulers getting the job done at the lowest cost is more important than maximizing the efficiency of allocation. Thus, each task is assigned its own priority level with which time and resource allocation that is provided to it is determined (Oshana and Kraeling, 2013, pp. 224-234). There are many real-time operating systems in the market to choose from. The most prominent amongst them are TR-Thread, FreeRTOS, Zephyr, and ThreadX (also known as Azure RTOS). The STM32 microcontroller generally has FreeRTOS and Zephyr included in its products, so it is convenient to choose FreeRTOS in this research work.

To test FreeRTOS's speed to see whether or not it is appropriate for this overcurrent relay design, the execution time of several mathematical operations was measured in the microcontroller. Each measured operation was executed with and without RTOS to compare their time. The RTOS application included eight tasks including the one to be measured, each having varying mathematical operations and for-loops. The code observed that how much time it took for the tasks to run with RTOS and without RTOS. This comparison between tasks operating times with and without RTOS is shown in Table 2.

Table 2. Real-Time Operating System (RTOS) Tasks.

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**	**Task 8**
With RTOS	2.138	2.43	2.156	1.516	1.516	1.3	5.99	2.76
Without RTOS	1.172	3.02	2.234	2.28	2.69	0.9	1.71	1.68

As can be seen from the comparison, there is not much significant difference between the operating times of the tasks whether we are using or not using RTOS in our firmware design. The main purpose of an RTOS is not to reduce operating times of functions, but to enable concurrent execution of multiple tasks. This is the main motivation to use RTOS, specifically, FreeRTOS in this firmware design. FreeRTOS is a time-driven RTOS that implements real-time computing by implementing a priority system and the Round-robin Scheduling algorithm. Following that module, it implements multi-threading by calling a thread tick at regular short time intervals. the interval is usually from 1ms to 10ms. If a task has not finished before the thread-tick is called, the task is put on pause status, and the process switches to the task in ready status on the top of the list.

2.5. Embedded Database

A category of databases includes what is called an embedded database system. As not all embedded database systems are used for real-time embedded systems like in this research work. Only a small subset of embedded database systems can be used for this purpose, called mobile databases. Mobile database, as its name indicates, is used for mobile devices which have low memory specs. However, since it's designed for small-footprint databases it's suitable for embedded devices, and thus also for this research work. The most popular amongst them is SQLite. SQLite is a very widely used database, especially used in smartphones, it also supports many programming languages, from C/C++ to python and PHP. It also has a C programming library. SQLite is a database engine that, unlike database management systems, does not have a client-server scheme, and is embedded in the end program. This makes it fit for this research work, as the information can be stored inside the embedded device in the relay without the need for an outside server. It's also known for its portability and speed, being much faster than traditional file storage. All of this makes it an appealing database engine and is why SQLite database engine is used in this work. A database table was created, data inserted into it and retrieved, and modified. A table is created, data is inputted, and data is retrieved from it.

CHAPTER IV

FINDINGS & DISCUSSION

3.1. Microcontroller Simulation

STM32CubeIDE was used to develop the firmware of the proposed protection relay. STM32CubeIDE is a free IDE for STM32 microcontrollers and is developed by STMicroelectronics. This tool enables the developer to edit the source code, compile the source code, and upload the generated binary file into the targeted microcontroller. The programming languages for the firmware are C/C++ and assembly. The main difference between the digital and traditional analog protective relay is that the digital protective relay is implemented by software, which is executed by the instruction set architecture. The digital protective relay features such as protection, auto-monitoring, and local HMI are implemented by software. The software is menu driven and interacts with the user. The embedded software and how the software will be programmed do all functions like checking the relay input after few milliseconds, printing something on the display of the relay, and processing of the relaying algorithms in case of a fault. The microcontroller and the operation of the firmware were simulated in the Proteus software. As shown in Figure 7, a three-phase system has been simulated, which includes four current inputs, three voltage inputs, a temperature input, keypad (which has been used in the form of buttons for the sake of simulation) connections, and LCD connections to the microcontroller. As can be seen in the simulation, the LM35 temperature sensor is used to detect the temperature changes of the relay, while ACS712 current sensors have been used to detect the power supply current. The specific pin configuration and interfaces are shown in Table 3.

Table 3. Pin Configuration of the Microcontroller.

Role	**Pin Configured**
Current Input-1	PA0
Current Input-2	PA2
Current Input-3	PA4
Current Input-4	PA7
Voltage Input-1	PA1
Voltage Input-2	PA3
Voltage Input-3	PA5
Temperature Sensor Input	PA6
LCD Interface	PB7, PB8, PB9, PB10, PB11, PB12
Keypad Interface	PB3, PB4, PB5, PB6

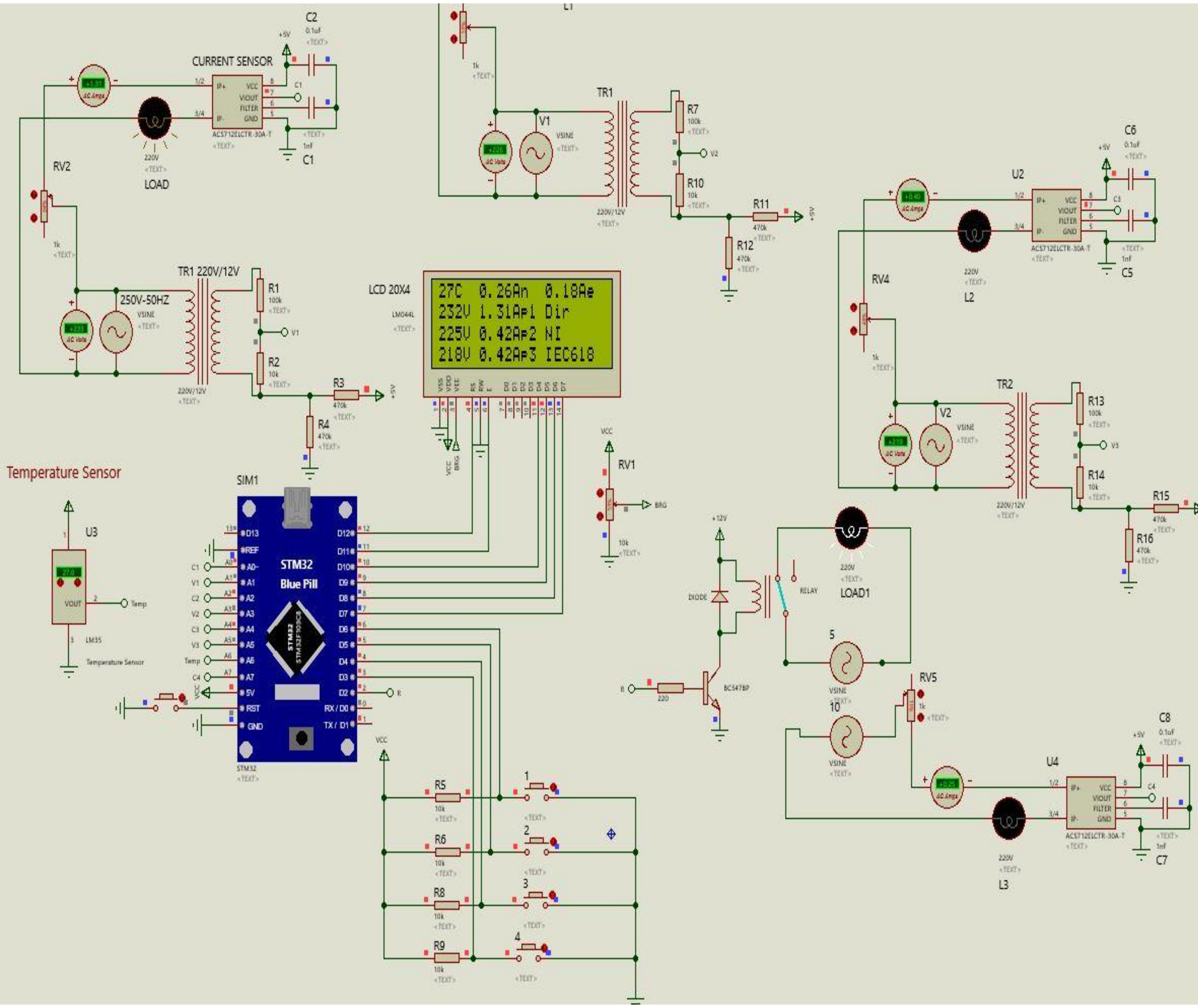

Figure. 7: Microcontroller Simulation.

The developed protection relay operation is as such: Upon starting the relay, after the initial booting and data acquisition, the relay will check if the CB is closed or not. Relay operation starts if CB is closed. The relay immediately starts its operations after taking pre-set protection settings from the embedded database, which includes the inverse time overcurrent curve to be used for relay operating time calculation, directionality method, the current limit setting, the voltage upper and lower limits setting, and the temperature limit setting. During the relay operation, if the settings need to be changed, a menu can be opened by the user using the keypad. An option to see the protection ANSI codes supported by the protection relay is available at the top. Another option available is to select the method of directionality to be applied. The options of implementing directionality include cross-polarisation method and zero sequence element method. The cross-polarisation method includes the option to select 45 degrees and 60 degrees characteristic angle. The next option is to select the inverse time overcurrent curve, which includes the Normal Inverse (NI) curve, Very Inverse (VI) curve, Extremely Inverse (EI) curve, and the User Defined (UD) curve. In case of any kind of fault relating to the ANSI codes applied, the correct fault message according to the ANSI code will be shown on LCD. For the sake of testing the firmware, the ADC inside the microcontroller has been utilized.

The operating system of the protection relay and the flow of operation is depicted in Figure 8. It shows that the embedded software of the protection relay is split into tasks. The connection and vital data exchange between these scheduled tasks are also shown. FreeRTOS here is used to schedule the processing of these tasks to ensure that they are processed in the time available and according to the priority that the tasks have been given. The flowchart in Figure 8 shows an overview of the relay operation, including the RTOS main scheduled tasks labeled "RTOS-1", "RTOS-2", "RTOS-3", and "RTOS-4". Flow diagram at the top of the figure is the start-up flow, which includes the power-up and booting of the relay, the CB checking, and the initial data acquisitions. The scheduled tasks include the local HMI, protection algorithms, fault handling, and communication protocols. The fault-handling task has been given the highest priority, whereas the other three tasks have been given the same priority, as they need to constantly work with the minimal delay. The fault-handling task has been given the highest priority because in case of a fault, the tripping of CB should carry the maximum priority, therefore the switch to this task would be an interrupt-based switch. On the other hand, the remaining three tasks needs to switch from one another with event-based switching. As can be seen in the figure, all the tasks are connected to the embedded database, in order to exchange protection settings, measurements, and fault records. Further works on the development of an overcurrent relay could be the communication capabilities of the relay. The communication protocols commonly supported by industrial relays include IEC-61850, Modbus, and DNP3. These are industrial protocol standards used in industrial networks to build industrial automation systems. These three protocols are commonly supported in industrial communication protocols for the control of process automation equipment in factories. IEC-61850, Modbus, and DNP3 are all international standards and it is of course very important that they are supported by a protection relay. They are vital for the protection relay to be able to receive and transmit status messages in the presence of a control unit, as well as communicate with other protection relays connected in the system. These messages may include measurement data, fault records, protection and control settings, and instances of relay failure and signals for backup protection.

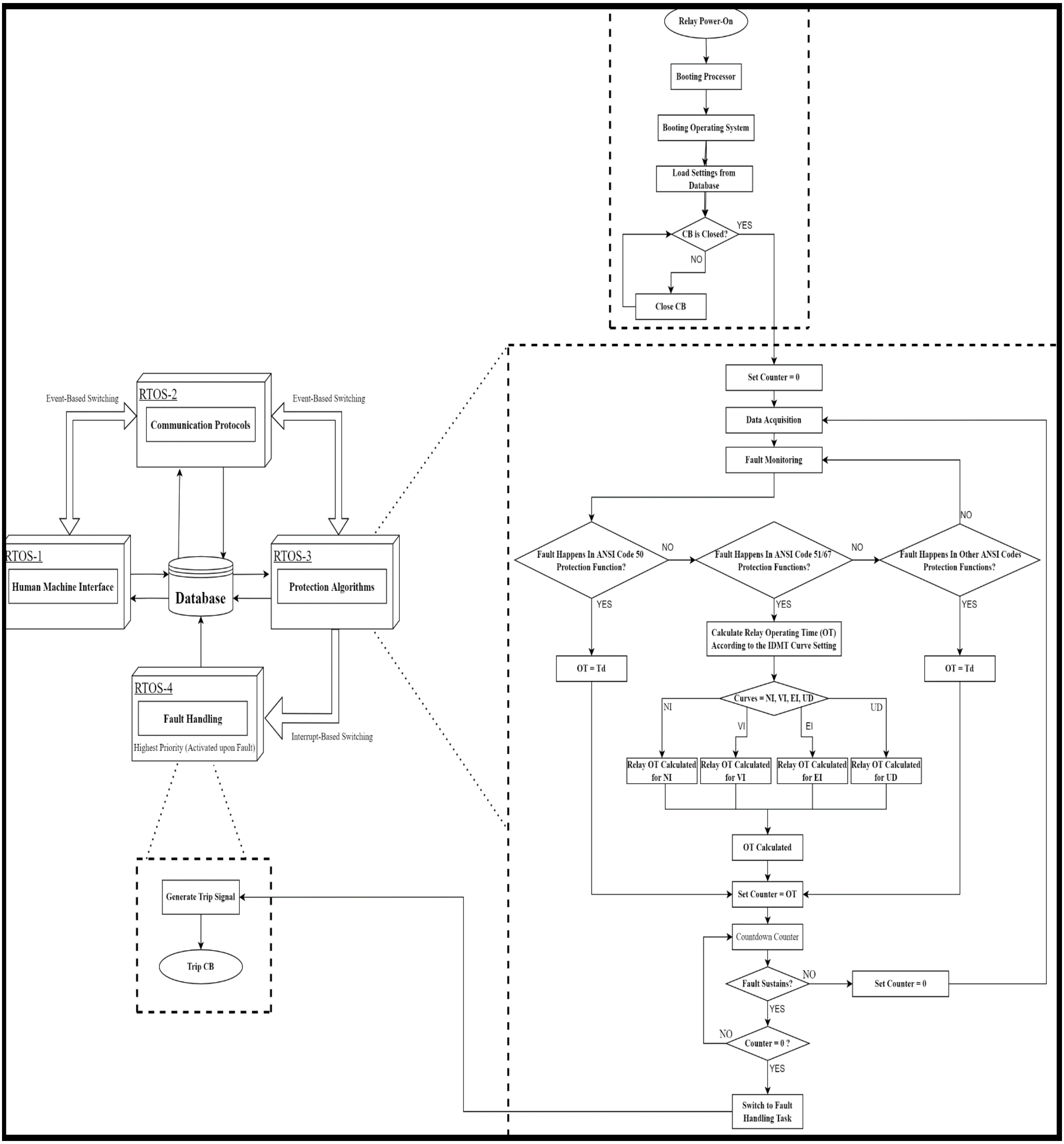

Figure. 8: Relay Real-time Operating System (FreeRTOS) & Flowchart.

3.2. Coordination Automation on IEEE 9-Bus System

The IEEE 9-bus system is a very useful benchmark system for power flow simulations in power systems. The 9-bus system is used in many power flow studies; it is relatively simple, yet very detailed and realistic. It consists of three generation units and three loads. There are a total of six transmission lines and nine buses in the system. The generation units are generators on the system that supply power. The loads are consumers of power on the system. In order for all the relays to be coordinated, data needs to be exchanged between them in order to do the coordination calculations of each relay.

Three cases of coordination using the developed IEEE 9-Bus system are proposed. In Case 1, coordination automation is done, in which the protection settings of all the relays present on the IEEE 9-Bus system are calculated, and the fault simulation is done in order to prove the correctness of the developed model and its calculations. In the Case 2, a communication-based coordination system is presented. In this case, there are communication links between relay primary and backup pairs. Case 3 is a consequence of the second case, which is a prediction-based coordination system, in which values extracted from Case 2 are used to train machine learning and deep learning models to predict coordination values.

In the coordination techniques proposed, the 9-bus system is designed in MATLAB-Simulink. One relay is connected with each of the three generation buses, and two relays are connected with each of the remaining buses. The resulting system is as shown in Figure 9.

In Case 1, the coordination of all the relays is done by applying a fault near to each relay in the system and do the calculation for the primary operating time and backup operating time of all the relays. The three generations are considered as the coordination starting points during the simulation, so the TMS of the three relays is initially set as 0.1. The coordination time interval for all relays is set as 0.2. To calculate the primary operating time of each relay, Equation. 1 is used, where $\alpha = 0.2$ and $\beta = 0.14$. For the relay that will act as a backup for a primary relay, coordination time interval is added to the primary operating time of the primary relay.

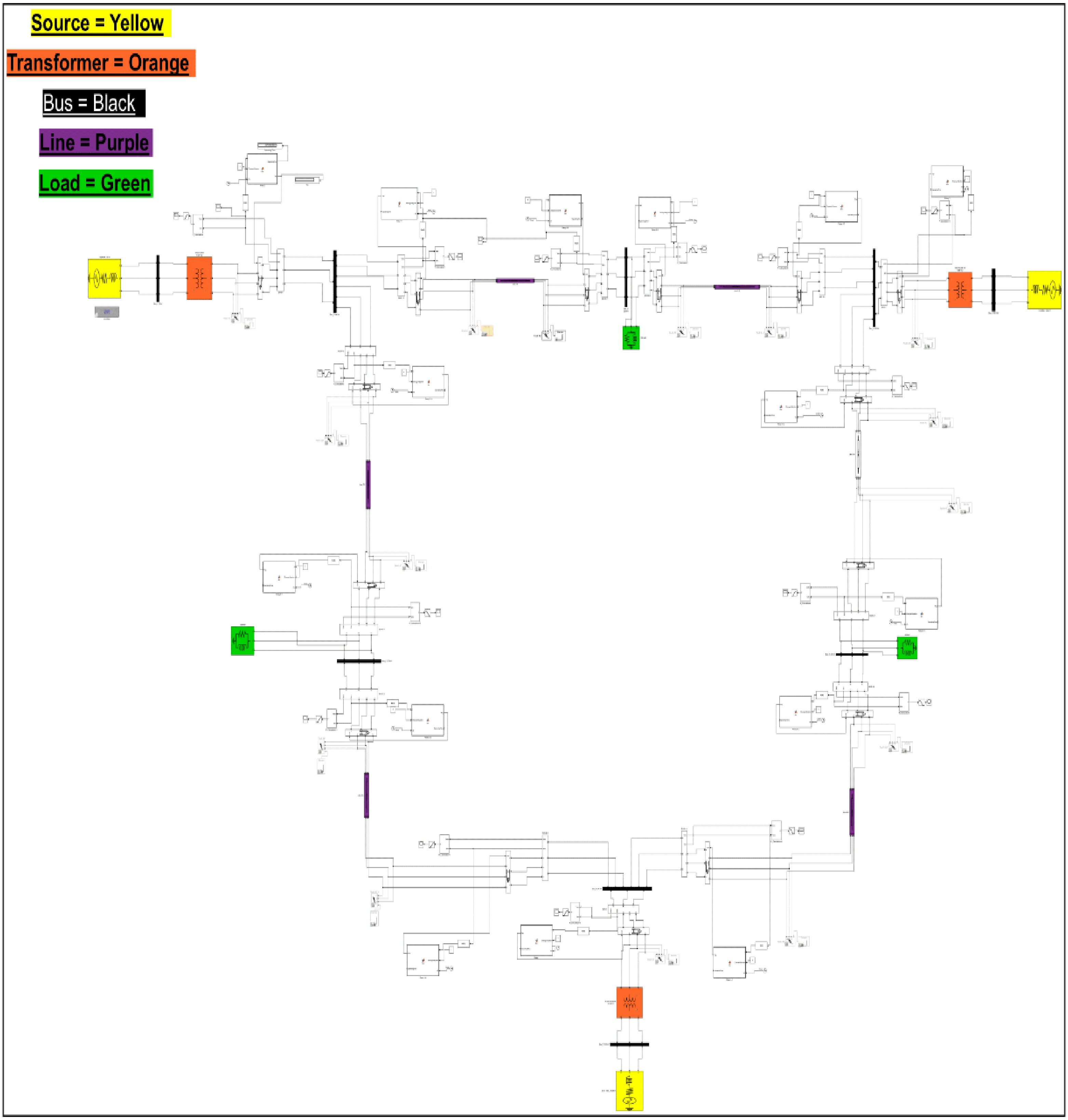

Figure. 9: Coordination on IEEE 9-Bus System.

With this, we would get the backup operating time of the backup relay, which is used to calculate the TMS of this relay. To be clear, as shown in Figure 10, when coordination starts from the two generations shown, when fault is applied near R2, the primary operating time for it is calculated using the initially set TMS = 0.1. The backup operating time of R8-1 will be calculated by adding the coordination time interval of 0.2 to the primary operating time of R2. Using this backup operating time, the TMS of R8-1 will be calculated. Using this calculated TMS, the primary operating time of R8-1 is calculated. The same procedure is followed for R9-1, using R8-1's primary operating time, and then same for R8-2 using R3's primary operating time, whose TMS is also 0.1.

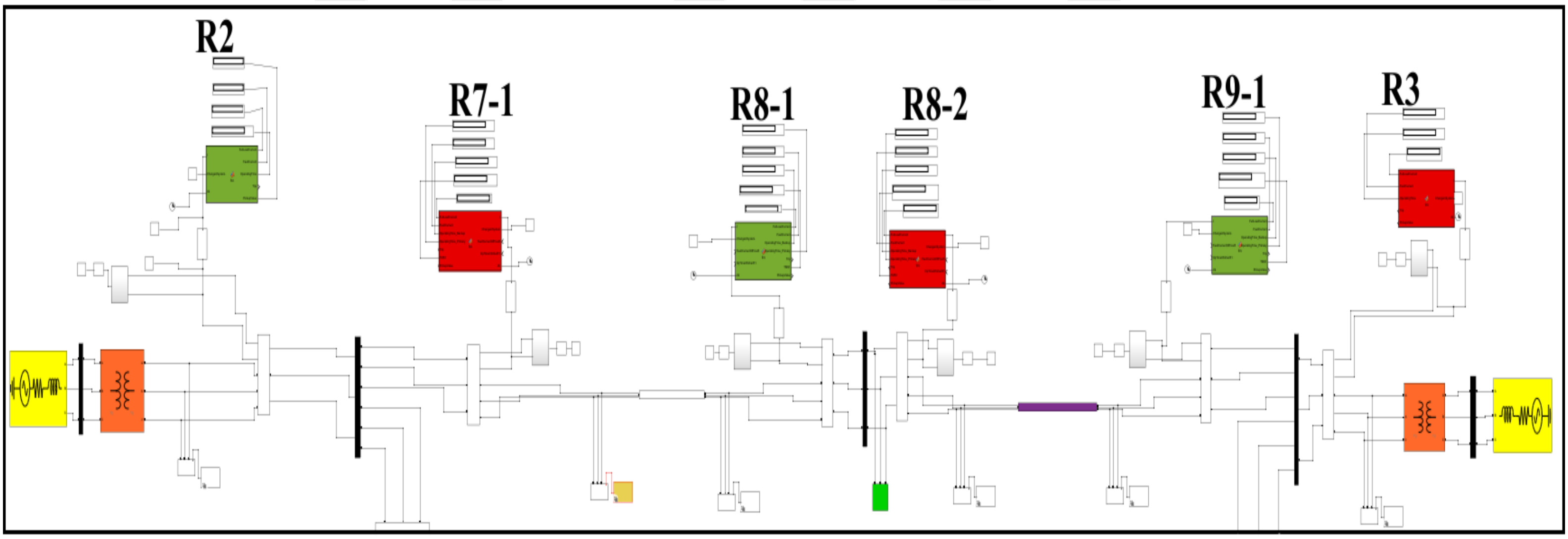

Figure. 10: Primary and Backup Relays.

The coordination is verified by simulating faults in the system, and see the operation of the relays and their operating times. As seen in Figure 11, faults are applied at several places in the system, to see the operation of the relays. The faults are applied on the bus 7, bus 9, line 7-8, and line 8-9.

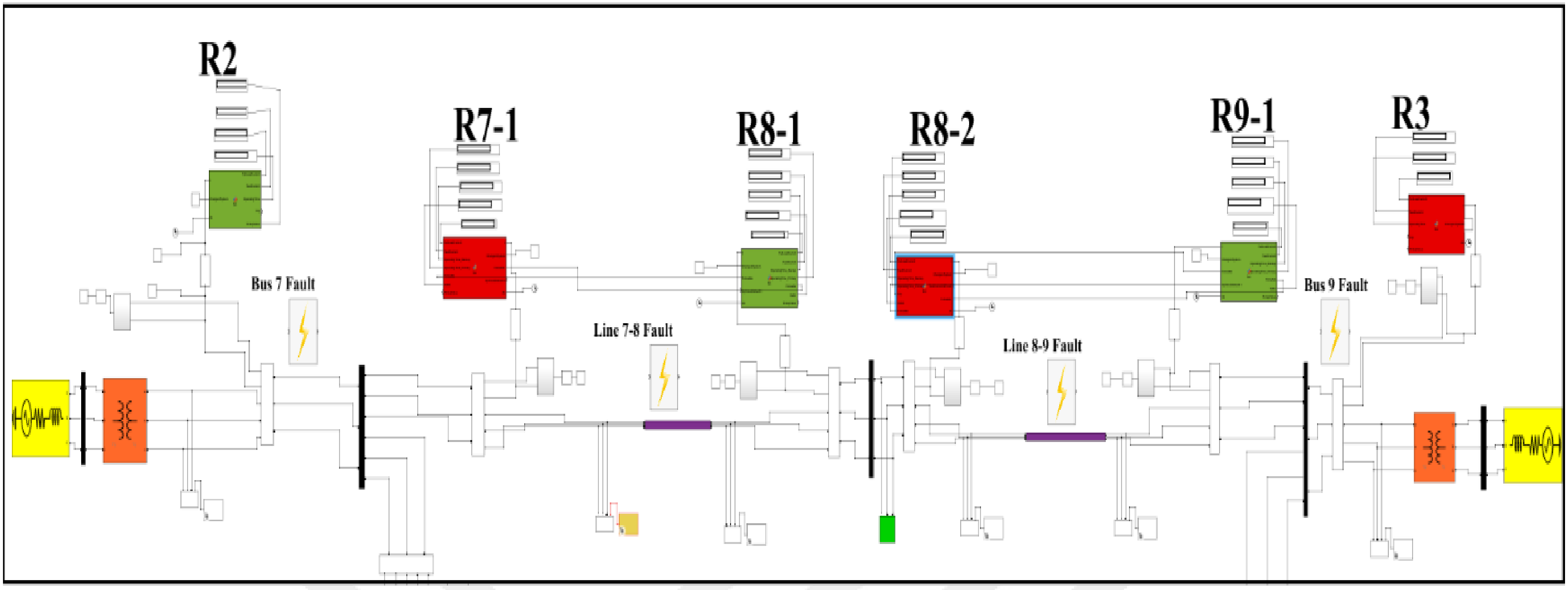

Figure. 11: Fault Simulation.

The values and results acquired prove that the coordination was accurately done. For the fault applied at bus 7, R2 should and does have the smallest operating time, as the fault is nearer to it. The largest operating time is for R9-1 in this case, as it is the farthest relay from the fault area. Block signals are applied for R7-1, R8-2, as the fault is in opposite direction for these two relays. For the fault applied at bus 9, R3 should and does have the smallest operating time, as the fault is nearer to it. The largest operating time is for R7-1 in this case, as it is the farthest relay from the fault area. Block signals are applied for R9-1, R8-1, as the fault is in opposite direction for these two relays. For the fault applied on line 7-8, it can be seen that both relays R7-1 and R8-1 have the fault in forward direction, which means that both of them would react. The relay that has the smaller operating time of the two would trip first, and send a follow-me signal to its pair, making sure that the other relay also does not trip. In case of fault on a line, the relays with the generations always detect in the opposite direction, which is why the block signals are applied here also. The calculated operating times of each fault case are shown in Table 4. The faults and the respective operating times of the relays show that the coordination was successful. This can be observed by seeing that when the fault current is high, the operating time will be low, and the operating time of the backup relay will always be higher than the operating time of the primary relay, as can be seen in the results. The presented operating times are considerably higher than a proper protection relay's operating times, however these values are calculated using the standard settings and values of a IEEE 9-Bus System, and the fault current was comparatively very low. Since the operating times depend on the fault current and Equation 1, the presented operating times also have high values.

Table 4: Fault Simulation Results.

Relays / Fault Position	**R2**	**R7-1**	**R8-1**	**R8-2**	**R9-1**	**R3**
Operating Times (seconds)						
Bus 7	1.04194	X	1.24048	X	1.38071	2.9893
Bus 9	3.81948	1.09669	X	0.72532	X	0.52971
Line 7-8	X	0.99642	1.24186	X	1.38104	X
Line 8-9	X	1.09683	X	0.72547	1.15806	X

3.3. Communication-Based Relay Pairs Coordination

In Case 2, modifications are made to the same developed IEEE 9-Bus system as in Case 1, and communication links are established between primary and backup relay pairs. The communication link makes sure that the operating time calculated by the primary relay in any case is communicated to its respective backup relay. The coordination is done by applying a fault on the transmission line near to the primary relay in that situation and the TMS of that relay is set as 0.1, making it the primary and first relay in that case. As shown in Figure 12, the transmission line near the respective primary relay is divided into 20 different sections, due to which the simulation is performed by applying a fault on each of these sections. With this, the reaction and calculations of the relays are observed in several different cases, and a general trend can be seen.

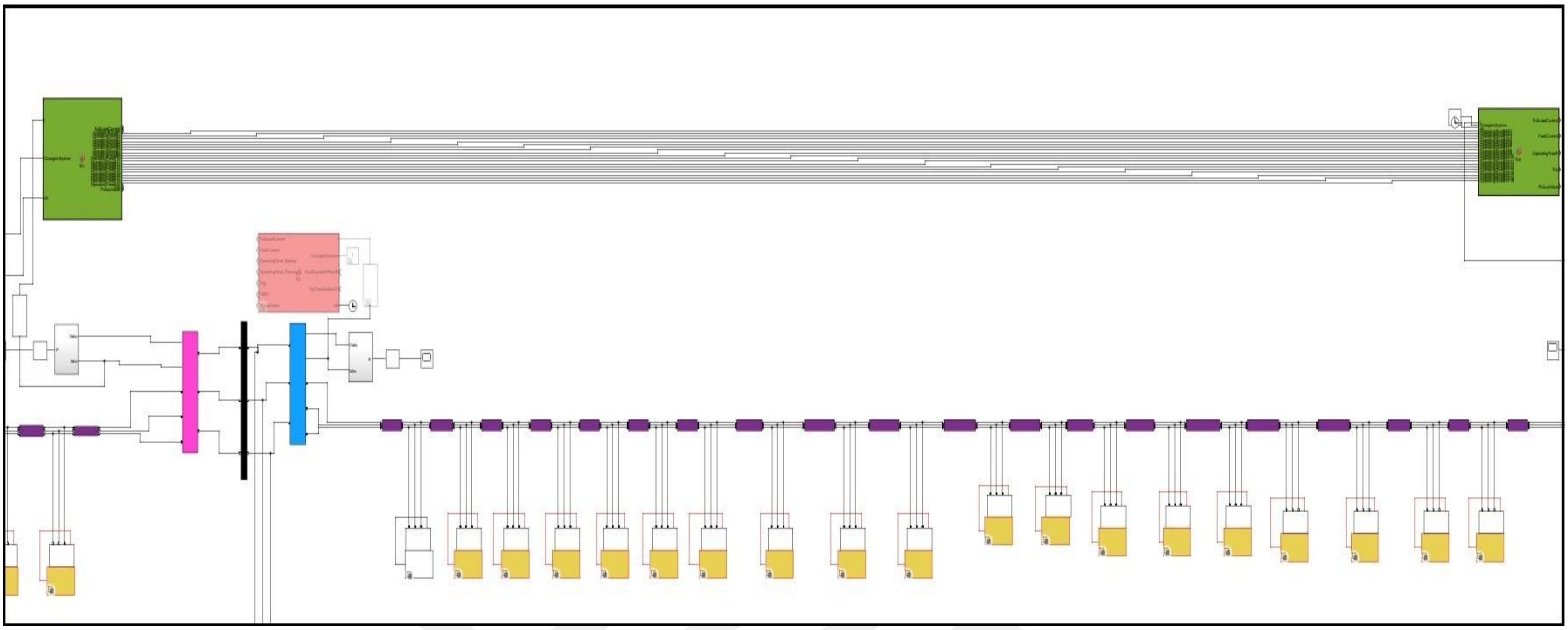

Figure. 12: Communication-Based Relay Pairs Coordination

The length of the complete transmission line in this system is 100 kilometers. The transmission line is divided into 20 sections; therefore, a fault is applied after every 5 kilometers increment. Using the fault current produced after applying fault at these sections, the primary operating time of the primary relay is calculated using Equation 1. After calculating the operating time of the primary relay, the CTI value of 0.2 is added to this value to get the backup operating time of the backup relay. Using this backup operating time, the TMS of the backup relay is calculated. The values calculated with a fault at each point on the divided transmission can be seen in Table 5. As can be seen in the values, as the distance of the fault from the primary relay on the transmission increases, the fault current decreases. When the fault is closest (distance is lowest) to the primary relay, then the fault current is the highest. When the fault current is high, then the relay needs to operate faster, therefore its operating time should be minimum. As seen in the table, as the fault current becomes lower, the operating time becomes larger. In every case, the backup operating time is larger than its respective primary operating time. These prove that the calculations done were correct and the relay would operate as desired.

Table 5: Relay Pairs Coordination Results.

Distance From Fault(km)	**Full Load Current (A)**	**Pickup Current (A)**	**Fault Current (A)**	**Primary Relay TMS**	**Primary Operating Time (sec)**	**Backup Operating Time (sec)**	**Backup Relay TMS**
5	162.921	181.975	272.385	0.1	1.728	1.928	0.341
10	162.921	181.975	247.919	0.1	2.256	2.456	0.428
15	162.921	181.975	238.855	0.1	2.566	2.766	0.482
20	162.921	181.975	225.249	0.1	3.274	3.474	0.612
25	162.921	181.975	219.079	0.1	3.765	3.965	0.698
30	162.921	181.975	216.508	0.1	4.0216	4.221	0.742
35	162.921	181.975	216.197	0.1	4.055	4.255	0.746
40	162.921	181.975	216.873	0.1	3.982	4.182	0.730
45	162.921	181.975	217.908	0.1	3.877	4.07	0.709
50	162.921	181.975	218.989	0.1	3.773	3.973	0.687
55	162.921	181.975	219.959	0.1	3.685	3.885	0.668
60	162.921	181.975	220.749	0.1	3.617	3.817	0.652
65	162.921	181.975	221.325	0.1	3.568	3.768	0.640
70	162.921	181.975	221.689	0.1	3.539	3.739	0.630
75	162.921	181.975	221.841	0.1	3.526	3.726	0.624
80	162.921	181.975	221.794	0.1	3.530	3.730	0.619
85	162.921	181.975	221.561	0.1	3.549	3.749	0.618
90	162.921	181.975	221.158	0.1	3.582	3.782	0.618
95	162.921	181.975	220.600	0.1	3.629	3.829	0.620

As shown in Figure 13, when the values of the primary relay and the backup relay are plotted on a graph, it proves that the primary relay and the backup relay are coordinated perfectly.

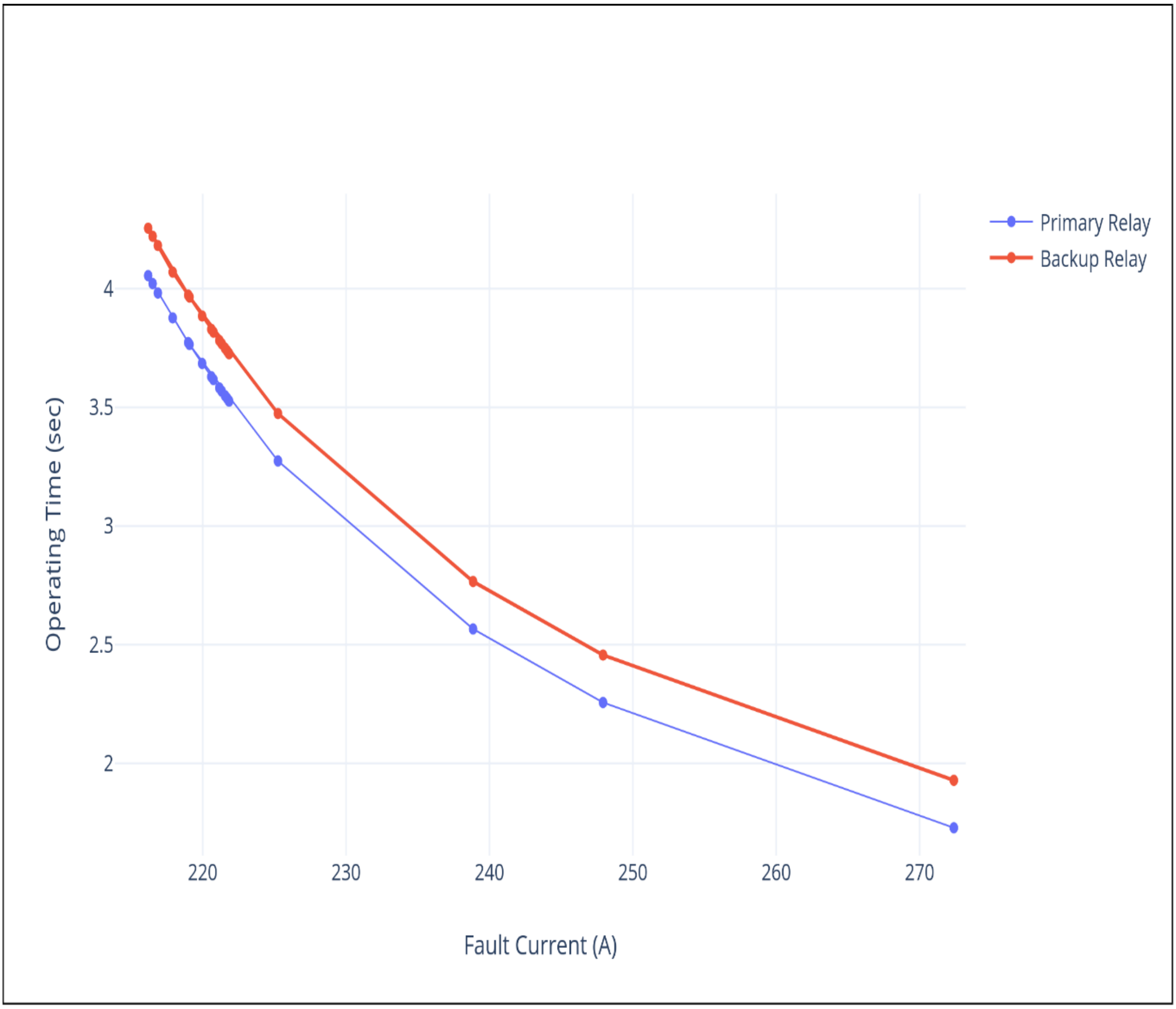

Figure. 13: Coordination Curves of Primary and Backup Relays.

3.4. Prediction-Based Coordination Using Artificial Intelligence

As discussed in Case 2, the primary and backup relay pairs have communication links between them; however, cases can arise when the communication between the relay pairs fail. In light of this issue, a ML and DL based coordination is proposed. Using the coordination method discussed in Case 2, the system was changed continuously and coordination was done to collect the data of the relays according to those changes. The changes that were considered were: 1) the location of faults on the transmission line next to the Primary relay, 2) changes in the power level of the generators in the system, 3) and the type of fault occurring. A large number of data was collected in order to train the ML and DL models. A small sample of the data collected is shown in Table 6, so a clear idea of the format of data generated can be presented.

Table 6: Sample of Data-set for training ML & DL Models.

Distance From Fault(km)	Full Load Current (A)	Pickup Current (A)	Fault Current (A)	Primary Relay TMS	Primary Operating Time (sec)	Backup Operating Time (sec)	Backup Relay TMS
5	162.921	181.975	272.385	0.1	1.728	1.928	0.341
10	162.921	181.975	247.919	0.1	2.256	2.456	0.428
15	162.921	181.975	238.855	0.1	2.566	2.766	0.482
20	162.921	181.975	225.249	0.1	3.274	3.474	0.612
25	162.921	181.975	219.079	0.1	3.765	3.965	0.698
30	162.921	181.975	216.508	0.1	4.0216	4.221	0.742
35	162.921	181.975	216.197	0.1	4.055	4.255	0.746
40	162.921	181.975	216.873	0.1	3.982	4.182	0.730
45	162.921	181.975	217.908	0.1	3.877	4.07	0.709
50	162.921	181.975	218.989	0.1	3.773	3.973	0.687
55	162.921	181.975	219.959	0.1	3.685	3.885	0.668
60	162.921	181.975	220.749	0.1	3.617	3.817	0.652

65	162.921	181.975	221.325	0.1	3.568	3.768	0.640
70	162.921	181.975	221.689	0.1	3.539	3.739	0.630
75	162.921	181.975	221.841	0.1	3.526	3.726	0.624
80	162.921	181.975	221.794	0.1	3.530	3.730	0.619
85	162.921	181.975	221.561	0.1	3.549	3.749	0.618
90	162.921	181.975	221.158	0.1	3.582	3.782	0.618
95	162.921	181.975	220.600	0.1	3.629	3.829	0.620

In this case, artificial intelligence techniques are utilized in order to predict the future protection settings of the primary and backup relays according to system changes and the respective values. ML and DL techniques are used for this purpose. Different methods and their results are compared. Using the artificial neural network technique of DL, a neural network is trained in the course of data preparation, in order to recognize future protection settings of the relays according to parameters, and their changes. In addition, this process is utilized to evaluate the reliability of different data sources and parameters. In order to get a better prediction of the future protection settings of the relays, it is necessary to have reliable information about their current settings. Hence, a training process in which the existing protection settings of the relays are used as inputs is necessary. At the end of the training process, the network knows the protection settings of the relays and also the relationships between them. Therefore, when the network is applied to new data, the network knows how to predict the protection settings of the relays according to the training information and the current data. Since there are different sets of protection settings and the changes between them, a data preparation stage is needed to prepare data. In this stage, we first select data with the same protection setting from the data. Then, we split it into training data and test data. The sample of the data is shown in Table 7, as mentioned before.

Since it is hard for a machine to understand how big the different values in the data are, it is necessary to normalize them. To normalize the values, the normalization process needs to be performed, and the mean and the standard deviation values are used to normalize the data. We apply normalization to both training data and test data. Therefore, the network learns how to normalize the values of data and thus can handle any data better in the future.

In the training of the Neural Network, there are two Application Programming Interfaces (APIs) for designing a model: Sequential and Functional API. The architectures are shown in Figure 14 and Figure 15.

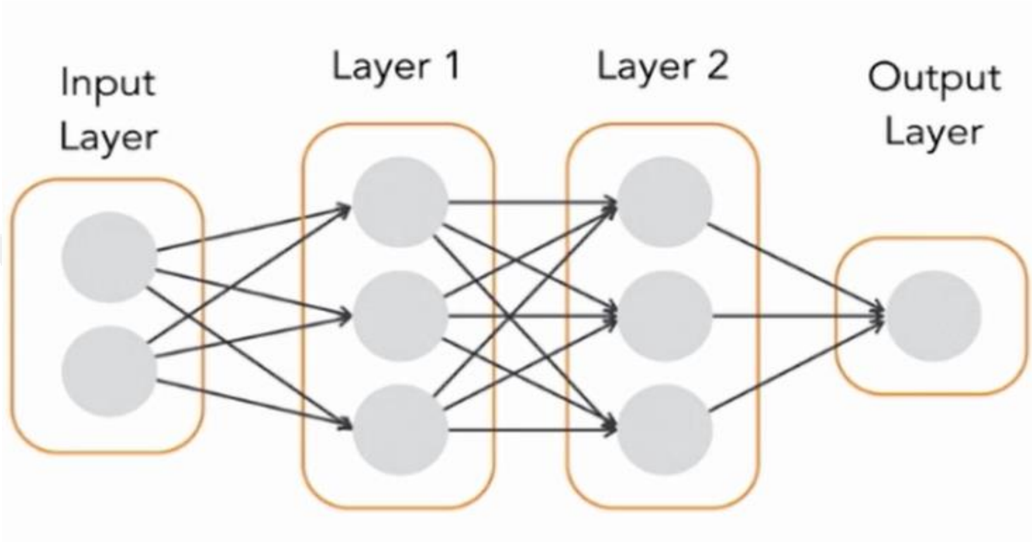

Figure. 14: Sequential API Model.

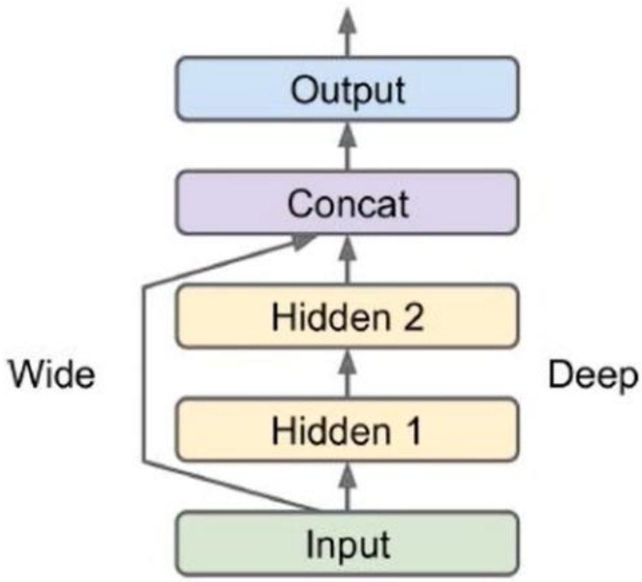

Figure. 15: Functional API Model.

Sequential API model is a straightforward model with an input layer, dense layers, and an output layer. The functional API model however has an additional layer knowns as the "concat" layer. This layer has a direct link from the input layer to the output layer, and all data from the input layer are concatenated together, and the network then runs through this layer to get to the output layer. The two API's have some inherent advantages and disadvantages. In a Sequential API, each layer is a fully connected neural network, and thus the number of trainable parameters that the model has is directly correlated to the size of the dataset. Thus, training a Sequential API will take a lot longer than a Functional API. The functional API can be run on extremely large data sets and may still be able to be trained fairly quickly. However, there are certain restrictions on the way data may be input into and output out of the network that are needed to be careful about. Our problem is a regression problem, for which, the sequential API model is the ideal one. The model made using the dataset was as shown in Figure 16.

```
Model: "sequential"
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
dense (Dense)                (None, 20)                180
_________________________________________________________________
dense_1 (Dense)              (None, 20)                420
_________________________________________________________________
dense_2 (Dense)              (None, 1)                 21
=================================================================
Total params: 621
Trainable params: 621
Non-trainable params: 0
_________________________________________________________________
```

Figure. 16: Sequential Model Used.

The training of the model was close to perfect as shown in Figure 17, and the losses were minimal. The training loss is the function that measures the difference between the predictions and the actual values. The validation loss is a metric that measure the ability of the model to generalize to new data by measuring the difference between the predictions and the actual data, on a new set of unseen data, usually called a validation set. This metric is useful when you want to see how your model changes with data. If the accuracy of the predictions are to be checked, we can see in the Table 7 that the difference between the actual values of the data-set, and the predicted values is minimal.

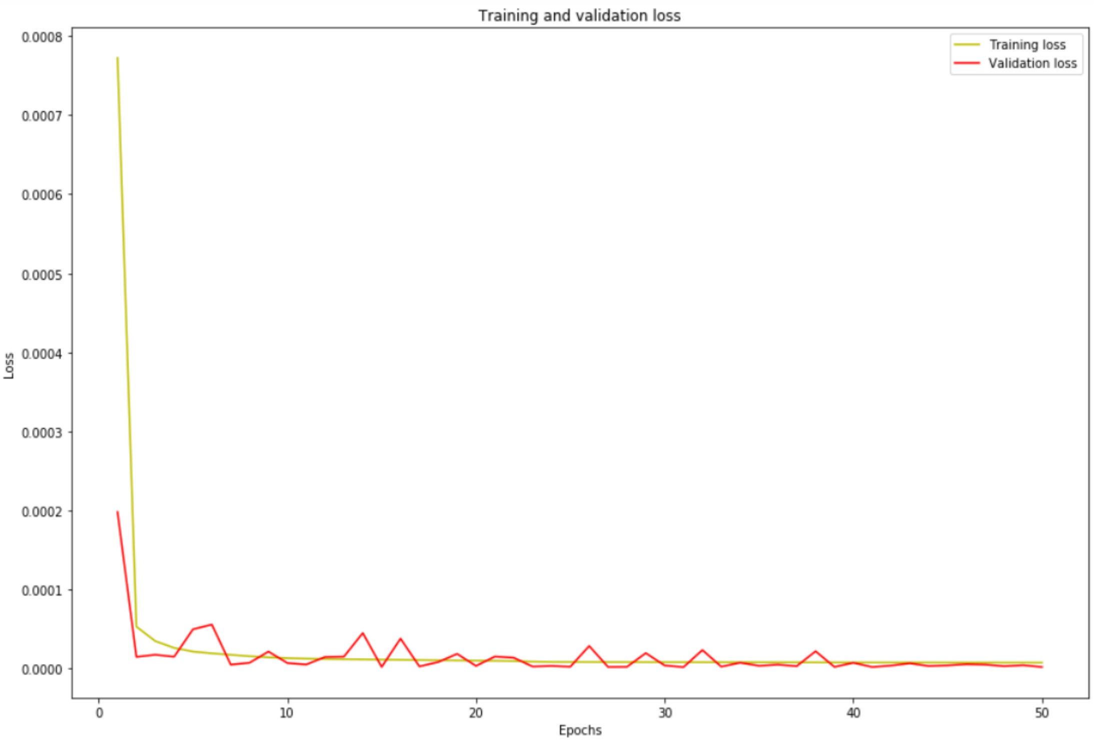

Figure. 17: Training and Validation Losses.

Table 7. Accuracy of Predictions.

Actual Values	**Predicted Values**
0.8542503	0.85427433
0.3007908	0.30145928
0.5308602	0.53067213
1.343198	1.3423052
0.6113721	0.6119192
1.126132	1.125289
0.7612928	0.7613499

The overall flow of the protection using the coordination done in the cases discussed is as depicted in Figure 18. The fault monitoring is performed as normal, and on detection of a fault, the fault zone is determined; that is it in primary relay operation zone or backup relay operation zone. According to this, the relays' operating time is calculated. As discussed, if the communication between relays does not take place and data is not exchanged, then the values predicted using ML or DL will be utilized to determine the operating times.

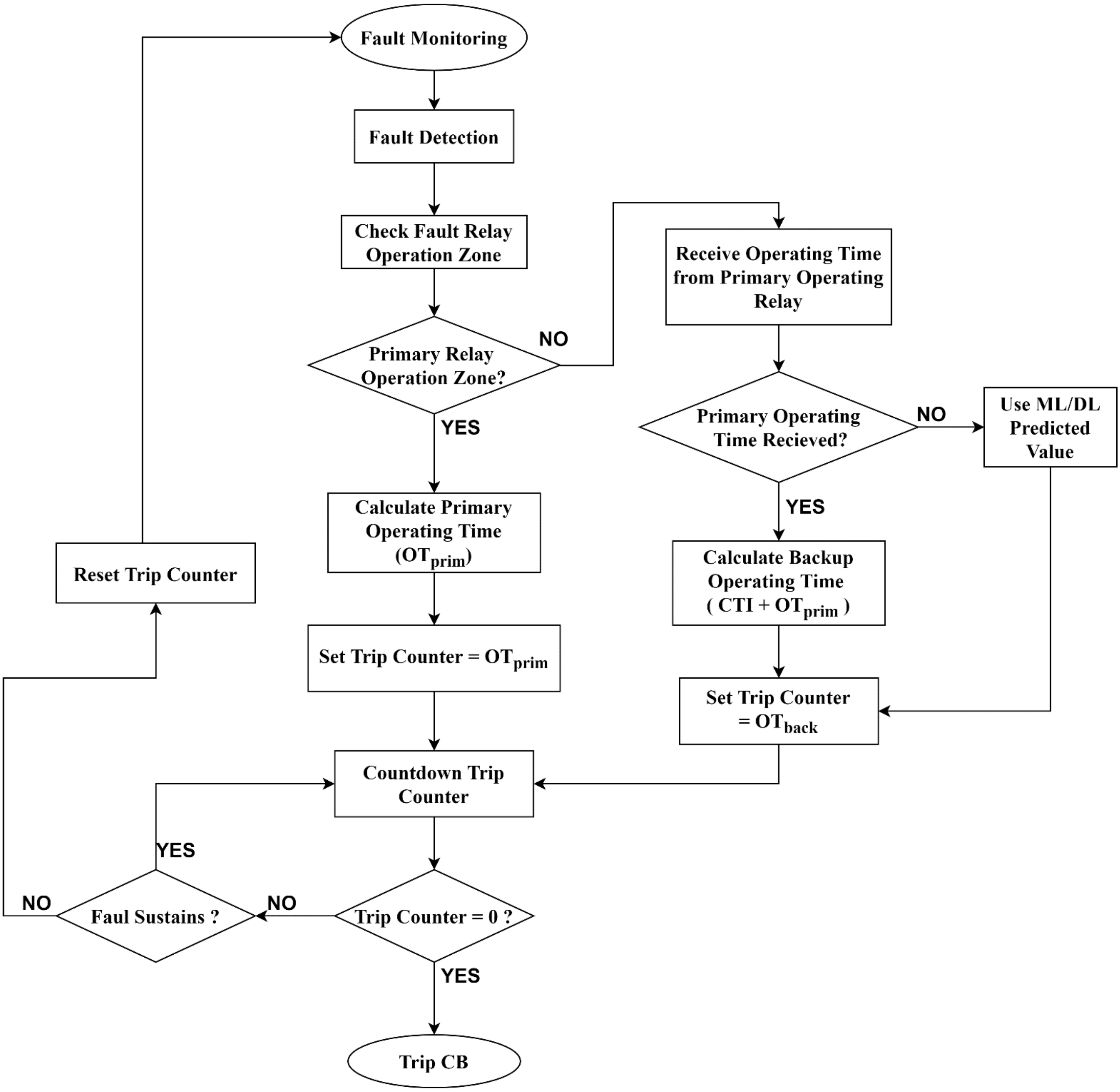

Figure. 18: Overall Protection Flowchart.

CHAPTER V

CONCLUSION

This research work presented the research work done on the development of a digital directional overcurrent protection relay. The firmware of the proposed overcurrent protection relay was designed and simulated in this thesis. Additionally, a coordination system was designed on MATLAB-Simulink as well, using an IEEE 9-bus system. The coordination system considered three cases in which the designed IEEE 9-bus system was involved. The results of each case were presented and they proved to be the desired results. The consequence and opportunity from the second in the coordination system presented was artificial intelligence. Even though the third case, which is reliance on the artificial intelligence, is only a fail-safe, still the results acquired were close to perfect and very accurate and desirable. The accuracy of the value predictions can be seen with the minimal difference between the actual simulated values and the artificial intelligence predicted values. The coordination results were also given in table forms. The overall protection flow using the coordination methods provided was depicted in figure form. A review of several other similar research works was done as well. The overall operation of the designed protection relay was also depicted with a detailed flowchart. The design proves to have more functionalities and practical applications as compared to the similar works reviewed. Further upgrades can also be made to this design of the relay firmware, such as using a Field Programmable Gate Array (FPGA) microcontroller, adding adaptive protection capabilities to the relay, etc. Regarding the coordination, systems that are more complicated can be designed, such as the IEEE 14-bus system, in which the coordination algorithms would need more work.

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C. PUBLICATIONS

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