GRADUATE SCHOOL OF ENGINEERING AND SCIENCE 2018

MASTER'S THESIS

Development of Module-Based Educational Platform for Digital Differential Relays using LabVIEW Program

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science

in the

Graduate School of Engineering and Science
(Master's Program)
Electrical Engineering and Computer Science

Spring 2019

Declaration of Authorship

I, Lodu Moses Gabriel
Student ID No. MA17131, declare that this thesis titled, "Development of Module-Based Educational Platform for Digital Differential Relays using LabVIEW Program" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a masters degree at this university.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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Abstract

Graduate School of Engineering and Science
Electrical Engineering and Computer Science

Master of Science

Development of Module-Based Educational Platform for Digital Differential Relays using LabVIEW Program

by Lodu Moses Gabriel
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Protection relays are some of the necessary and fascinating components in power system. Protection relays play major role in maintaining normal operation, prevention of electrical failure, and mitigation of the effects of electrical failure [1]. Many of the major blackouts recorded in the world are caused, intensified, or prolonged due to issues related to failure of protection system.

The Technical Analysis of the August 14, 2003, Blackout reported an inconsistency in the application of the available system protection technologies to optimize the ability to slow or stop an uncontrolled cascading failure of the power system [6]. It has also lamented on poor operators training.

Therefore, it is very essential for every power engineer to have a hands-on experience on power system protection right from the academic institutions and early days at the utility companies. However, the education of power system protection in universities and technical institutions has not been in pace with the current trend of power system advancement. In power system protection class, laboratory sessions involving relays and relays' design, software handling and hands-on experience are highly recommended [7].

In another development, microgrid, as a key component of smart grid and a great player in the penetration of renewable distribution energy resources suffers a great challenge in fault protection. Differential relay has been identified as one of the better alternative to overcome those challenges because its principle of operation does not concern much about the magnitude of current as it only depends on the difference between primary (input) current and secondary (out) currents [27].

Based on the above overview, the main purpose of this research is to develop a module-based educational platform for studies and conducting experiments on differential relays using LabVIEW programs for control. First a mathematical formulation of a digital relay control algorithms for differential relays were researched on. The algorithms are then validated by simulations in a Simulink environment. Finally the LabVIEW program is coded with a special consideration on a novel and understandable Human Machine Interface (HMI) also known as Graphical User Interface (GUI). The thesis focused on two types of differential relay: transformer differential relay for protecting power transformers and line differential relay that protects transmission lines.

In the second part of the study, a simulation studies to verify the effectiveness of line differential relay in islanding phenomenon on a micro grid system was carried out. A microgrid short circuit currents level in both main grid connected mode, and in islanding modes were investigated using SKM power tool software. The simulation results for the transformer differential relay from both Simulink and LabVIEW were successful. The short circuit currents in main grid connected mode is higher than when it is in islanding mode in all the nodes. However, the Line differential relay program was able to respond in both cases effectively without changing the settings.

For the Laboratory scale hardware setup, Data Acquisition (DAQ) module was designed and built by assembling transducers and data acquisition instruments into 300mm cube module. a short circuit module which is just a set of switches wired in a way that it can create the main types of faults (line to ground (L-G) and line to line (L-L)) was also made. A circuit breaker (contactor relay) was also designed and its hardware was built.

Lastly, a new combined hardware-software approach that reflects the nature of a real system is developed and tested in real time based on a laboratory setup using module concept in Power System Laboratory, Shibaura Institute of Technology. This experimental platform is readily set up for conducting the hands- on experiments.

Several trial experiments conducted were able to detect faults and respond positively to different faults conditions within the protected zone in both the transformer and line differential relay. It can also send the tripping signals to the contactor relay that acts as the circuit breaker. This platform is cheap, easy to store and safe. The modules can also be used for other experiments

Acknowledgements

This journey for earning of master's degree was intense and hectic though it was a journey of "no return and no retrieve" right from the start. However, it was because of the mercy of the heavenly GOD, and material, advisory, encouragement, and supervisory support from many actors that led to the successful completion of this two and half years' program.

First and foremost, I would like to thank the Japanese taxpayers(people), and their government for granting such a precious scholarship(Africa Business Education Initiative) to over one thousand young Africans of which I am one. Without this chance, my dreams for masters especially in overseas and Japan in particular could remain a nightmare. Japan International Cooperation Agency/Center - JICA/JICE, thank you so much for your tremendous effort in implementing the scholarship. Your guidance especially socially and organizationally not only let to the successful completion of this program but also boosted my integrity for the rest of my life.

My profound gratitude goes to my supervisor Prof. Dr. Goro FUJITA, Power System Laboratory at Shibaura Institute of Technology, for his constant academic guidance and encouragement. He allowed me explore the best of my ability in this research, and showed me direction whenever I was stuck. Prof. Fujita provided me with all the necessary resources for this thesis, through his enthusiastic support, I wrote some papers and was able to traveled to overseas for data collections and participated in academic conferences. I am deeply inspired and motivated by his professionalism: academical, Organizational, and intellectual mentor-ship.

I would also like to acknowledge the contribution of the staff of Shibaura Institute of Technology and my lively lab mates. I am gratefully indebted to their collaboration, assistance and communication. They have helped me not only in my study but also in my daily life in Japan. Wish all of you a brilliant future.

Finally, I must express my ultimate gratitude to my family for providing me with unvarying support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. I would have never attained this academic heights without them. Thanks for your LOVE.

Your Sincerely,

Lodu Moses Gabriel

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List of Abbreviations

A/D	**A**nalog- to- **D**igital
AC	**A**lternating **C**urrent
ANSI	**A**merican **N**ational **S**tandard **I**nstitute
BD	**B**lock **D**iagram
CAD	**C**omputer **A**ided **D**esign
CAPTOR	**C**omputer **A**ided **P**lotting for **T**ime **O**vercurrent
CB	**C**ircuit **B**reaker
CT	**C**urrent **T**ransformer
DAQ	**D**ata **A**cquisition
DC	**D**irect **C**urrent
DFT	**D**iscret **F**ourier **T**ransform
DG	**D**istributed **G**eneration
DOCR	**D**irectional **O**ver **C**urrent **R**elay
FP	**F**ront **P**anel
GUI	**G**raphical **U**ser **I**nterface
(HMI)	**H**uman **M**achine **I**nterface
HV	**H**igh **V**oltage
IEC	**I**nternational **E**lectrotechnical **C**ommission
IEEE	**I**nstitute of **E**lectrical and **E**lectronic **E**ngineers
LabVIEW	**Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench
LV	**L**ow **V**oltage
MV	**M**edium **V**oltage
NI	**N**ational **I**nstrument
N/A	**N**on **A**pplicable
OCR	**O**ver **C**urrent **R**elay
PBL	**P**roject **B**ased **L**earning
PC	**P**ersonal **C**omputer

PSRC	**P**ower **S**ystem **R**elaying **C**ommittee
PTW	**P**ower **T**ools for **W**indows
PV	**P**hoto **V**oltaic
SLD	**S**ingle **L**ine **D**iagram
SLG	**S**ingle **L**ine- to- **G**round
SC	**S**hort **C**ircuit
TL	**T**ransmission **L**ine
USB	**U**niversal **S**erial **B**us
VT	**V**oltage **T**ransformer
4PDT	**Four P**ole **D**ouble **T**hrow
PCC	**P**oint of **C**ommon **C**oupling

List of Symbols

I_1	Input (primary) current
I_2	Output (secondary) current
I_{OC}	Current through an operating coil
I_D, I_{Diff}	Differential current
I_R, I_{Res}	Restraining current
n	Number of conductor at a node
i_1	Differential relay input primary current in one line diagram
i_2	Differential relay input secondary current in one line diagram
I_A, I_B, I_C	Phase A, Phase B and Phase C Differential relay primary input current
I_a, I_b, I_c	Phase A, Phase B and Phase C Differential relay secondary input current
I_0	Zero sequence current
I_A^*, I_B^*, I_C^*	Relay primary input current processed of Zero sequence current
I_a^*, I_b^*, I_c^*	Normalized relay secondary input current
$I_A^{**}, I_B^{**}, I_C^{**}$	phase shift corrected relay secondary input current
T	Transformation matrix for the zero sequence elimination
k	Vector group number
K	Slope of characteristic curve group number
Tx	Power Transformer

Dedicated to my Late brother E.Eng. Paride Gabriel Tombe

CHAPTER 1

Introduction

1.1 Background

1.1.1 Power system and power system protection

The Electric Utility Industry which is concern with every step in the process of generation, transmission, distribution, utilization of electrical energy, is growing faster in both magnitude and technologies. Due to introduction and increase of electric vehicles and trains, continues industrialization, and improvement of human life characterized by urbanization, power system will probably become the largest and most complex industry in the world [1] [2].

The expansion of power system has couple with introduction of new technologies, which includes: introduction of distributed (disperse) generation, advancement in power electronics and communication technologies and digitalization of many power system components.

This expansion and complexity will boost electrical power supply but in turn, will not only make it vulnerable to natural disasters, human errors and faults but also renders challenging problems to electrical engineers and technicians to easily understand and adopt the new technologies in order to deliver the increasing electrical energy in a safe, clean and economical manner. Reports have already shown that complexity of the power system and protection failures played greater role in most of the blackouts since 1965 [5]. The Technical Analysis of the August 14, 2003, U.S Blackout strongly concluded that there was inadequate training of operators to recognize and respond to system emergencies and inability of system operators to visualize events on the system. It as well recommended provision of reliability tools, visualization tools and training to the personals [6].

In another development, power system industry is facing a challenge of aging workforce and outdated technological experts. The number of retirements, and the technological knocked out from the power system industry outweighs the number of engineering graduates and skilled workers entering the workforce [34]

Therefore, there is need for increase in number of highly professional protection engineers, through quality and attractive education in the technical institutions. Unfortunately, the education of electrical engineers, has not kept pace with the technical developments, meanwhile, students can be attracted and retained in power programs if they are exposed early to the joys of creation through design, discovery through research, and invention through hands-on experimentation using Laboratory experiments (practicals) and computer-based activities in the education and training of power system protection [5], [7]- [9].

One convenient and powerful way for teaching protective relaying design and application is to use modeling and simulation. A number of efforts have been made in this regard, these include the emphasis on the design of full-blown operator training stimulator to powerful graphical interface, and special packages for study of specific power system phenomena or topics. More emphasis was placed on developing either customized packages or adopting conventional solution. However most of the models are very expensive, not digitized (for the current trending digital relays) and simulations cannot interact with real power system [10], [11], [13].

1.1.2 Philosophy and economic considerations of power system protection

The main systems that constitute electric power system includes: power plant systems, transmission systems, distribution systems, supervisory control and data acquisition, power system protection and power system stabilization control. This thesis is under the scope of power system protection specifically, its education and/or training.

Power system protection deals with detection of abnormal and intolerable conditions and initiates appropriate corrective actions. The principal function of protective system is to cause the prompt removal from service of any element of the power system when it starts to operate in an abnormal manner or interferes with the effective operation of the rest of the system [1]-[3]

The following are some of the important aspects/ qualities of protection thoroughly considered while designing a protection system.

- *Reliability:* there are two aspects of reliable operation of protection systems, dependability and security.

  Dependability of protection systems is "The facet of reliability that relates to the degree of certainty that a relay or relay system will operate correctly." Dependability is a concern when a fault occurs within the protected zone. A dependability-related failure raises concerns with the consequence of a failure to operate when required or to operate at the designed speed.

  Security of protection systems is "That facet of reliability that relates to the degree of certainty that a relay or relay system will not operate incorrectly." Security is a concern for external faults and unfaulted operating conditions. A security related failure raises concerns with the consequence of undesired operation, including operating faster than designed.

- *Selectivity (which also is sometimes referred to as timing coordination)*: is maximal continuity of service with minimum disconnection system. it is therefore, refers to analysis to assure that the relays intended to operate for a given condition will operate faster than other relays that may provide backup protection for the condition

- *Sensitivity:* is the ability of the relay system to operate with low value of actuating quantity. This assures that, no matter what the magnitude of the fault, or the location of the fault on the protected power system element, the intended relays will "see" the fault more strongly.

- *The speed of operation (Clearing Time)*: is minimum duration of the fault, damage to equipment and system instability. that is to say, faults must be cleared within a time that minimizes equipment damage and permits recovery of the power system to a stable operating state.

- *Redundancy:* is defined as "the existence of more than one means for performing a given function." Redundancy may be achieved locally through duplication of protection systems or through remote backup protection.

- *Simplicity:* is minimum protective equipment and related circuits to achieve the objectives of protection.

- *Economy:* is maximum protection with minimum cost. The protection system should also be economically viable in respect to the system to be protected.

Apart from Protection System Design consideration, there are more other attributes that support protection system reliability. These other attributes includes:

- *Maintenance:* Protection systems continuously monitor the power system, but may be called upon to operate infrequently. Properly maintained protection systems help to assure both the dependability and security intended within the protection system design and application.

- *Availability:* Protection system continuously monitor the system but occasionally operates, thought such, it should be ever available. During maintenance other protection should be set to include the zone.

- *Settings:* To promote protection system reliability, settings should be developed considering a range of credible operating conditions.

  Coordination; the protection system is set to a manner that, only the protection intended for a specific zone operates in in the given time, before other protections trip.

  Loadability protection system must be set to accommodate all the loading conditions the system can manage and those bearable overload.

  Modeling; modeling in a relay coordination can help to verify proper selectivity and secure operations in stable swings.

- *Performance Verification:* Reliable operation of the protection system is supported by;

  Protection System Monitoring: continuous monitoring of protection systems allows identification of failures and prompt corrective actions to prevent a latent failure from resulting in unreliable operation.

  Analysis of Misoperations: allows corrective measures such as re-setting, design corrections to be performed. It also provides information for the improvement of future design.

  Analysis of Protection System Failure Rates: due to some factors such as age, environmental (natural). Such that where the performance of such protection systems are substantially degraded (high failure rates, reach end-of-life, etc.), appropriate corrective action should be initiated to maintain adequate reliability.

1.1.3 Trends in protection relays

Protective relays existed more than a century ago. The earlies used relays were the analog electromechanical and static type.
The Numerical relays came into used around 1980s and dominated the market through 2000s where digital relays picked up [12]. Figure 1.1 shows the trends of relays over the years.

Digital relays are more superior in fulfilling the aspects of protection system due to their intelligence and ability to easily communicate within themselves and with other elements of power system.

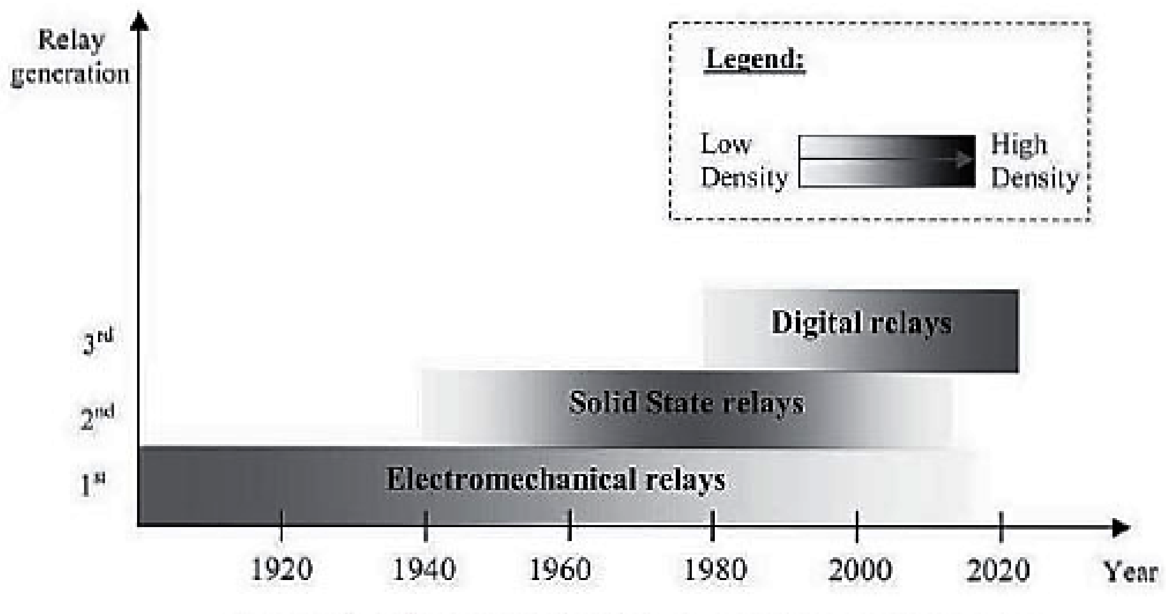

FIGURE 1.1: The different eras of protective relays
Source: [12]

1.2 Research Background and Motivation

Power System Protection is very essential in power system industry. All power system engineers should at least have a basic understanding of the principles, operations and setting of protection relays during power system engineering professional courses in the institutions of learning. In the recent years, power system protection, is hugely shifting from electromechanical relays to solid state relays. Although these relays have the same philosophy, there are many design, functional and setting differences. For example:

1. Design: many correction algorithms and compensation ratios are included in the relay software in the numerical relays unlike in electromechanical counterparts.

2. Connections: in the electromechanical relays, CTs connections follow the transformer connection, for instant a Y-D transformer will have a D-Y connected CTs while in solid state transformers, the CTs are usually connected in Y in both sides.

3. Settings: electromechanical relays have limited range of operations and functional settings, most being industrially specified while the numerical relays have several operator settings.

This educational module will serve as a good fundamental platform for practical experiments during protection lessons for young engineers and even experienced engineers in other types of relays to easily understand the trending digital relays.

1.3 Procedure and Outcome

First a differential digital relay was analyzed, that included the mathematical formulations. Then it was simulated in Simulink environment. The signal waveforms from the current sensors through the input of trip signals into the circuit breaker were visualized. This was not only done to visualize the current waveforms but also to prove the functionality of the mathematical equations.

The relay was then programmed using LabVIEW, and the hardware components were designed and built into modules. The main modules created for digital relays are data acquisition module, short circuit module and a contactor relay. A laboratory-scale educational platform was then developed for experimentation of differential relay in a power system laboratory.

The experiment manual was written in such away that students can conduct experiment with less supervisions. This platform is readily available for use now.

1.4 Limitations

1. It requires the basic power system modules (Voltage regulator module, Metering (POWER HITESTER), Transmission line module, Distribution line module and Load module), it may be expensive if all this modules are built for only this one platform.

2. The experiment involves creating short-circuit using the Short circuit module, this may trip the main main breakers or my cause fire breakout if carelessly handle.

1.5 Thesis Contributions

Power System Protection is as essential as safety measures in power system industry. All power system engineers should at least have a basics understanding of the principles, operations and setting of protection relays. To achieve this, the teaching of power system protection courses in universities and technical institutions need to be boosted by Laboratory sessions [37]. This thesis will contribute in:

1. It enriches laboratory curriculum in power system protection courses in universities and vocational institutions.
2. It can be good platform in the power utility companies for training of un-experience engineers and technicians.
3. It can be used in the industry for the initial testing of digital differential relays.
4. The electromechanical relays oriented engineers/technicians can use this platform as a transition to the digital relays.
5. The software part can be use by researchers to grasp initial understanding of digital relays and consequent development of new advance protective algorithms. The hardware as well can be use for experimenting (testing) the digital relays during its development.

1.6 Organization of the Thesis

This thesis is organized into six chapters in a chronological order of the project to ease understanding and following of the thesis. These chapters are:

Chapter 1. Introduction

In this first chapter, a brief background of power system current development is introduced. The motivation, research background, procedure and expected outcomes are explored in this chapter.

Chapter 2. Fundamentals and Theories for Transformer Differential Relay

In this chapter, fundamentals and theories behind the success of differential relay are scrutinized. More emphasis was put on transformer percentage current differential relays.

Chapter 3. Software modeling of Transformer Differential Relay and the Simulation Results

This chapter discusses the simulations procedures and results. The mathematical equations obtained in Chapter 2 were first verified in Simulink environment and the results for different phenomena were analyzed until the accuracy target was reached. Thereafter, a LabVIEW program was built from the verified parameters. This labVIEW program was later used as the control (brain) of the experimental platform in Chapter 4.

Chapter 4. Laboratory Scale Experimental Setup of Transformer Differential Relay using Modules

The building of the hardware part of this project is discussed in this chapter. It also talk about the complete (combined software and hardware) platform. The results and discussion of this platform are presented in the last subsection of this section.

Chapter 5. Application of Differential Relay in Microgrid Distribution Line Protection

In another development, due to dramatic variation of short circuit currents of a microgrid during islanding conditions, protection system previously set for grid connected mode will malfunction. However, many studies have pointed out the effectiveness of differential relays (line differential relay). This chapter discusses an SKM power tool simulations to justify the short circuit current variation, Simulink simulations to test the tolerance of line differential relay during islanding conditions and finally discusses a hands-on experiment of line differential relay on the platform discribed in Chapter 4 above.

Chapter 6. Conclusion and Future viewpoints for research

A brief summary of the research conducted in this project, important conclusions and potential future works drawn thereof are outlined in Chapter 6. This chapter is followed by appendices and a list of references. In appendix A, is an operation manual for the transformer differential relay. the steps for conducting the experiment using this platform is clearly articulated. In appendix B, the manual for the line differential relay is presented.

1.7 Summary

From the beginning of 21^{st} century, there has been great shift from electro-mechanical , static relays and numerical relays to digital relays in power systems protection due to immense advantages and technological availability for digital relays. It is important to attract, train inexperienced and young electrical engineers how to simulate, design and set different digital relays. In this chapter, the importance of protection system has been briefly discussed as well as the current trends in protection relaying schemes. The motivation and research background of the thesis, followed by the procedures and expected outcomes have been outlined. The organization of the thesis is described and the contributions that this research impacts have been highlighted.

CHAPTER 2

Fundamentals and Theories for Transformer Differential Relay

2.1 Introduction

This chapter is concerned with the algorithms for differential relay with more emphasis on the protection of power transformers. However, a bird's eye into the general overview of protective relaying is first being recapitulated. Then the differential relay is presented. Finally the mathematical formulation in the functional units of the transformer digital differential relay are derived. The chapter will be concluded with end of chapter discussion.

Transformers are considered as protection zones in power system protection, other zones includes: generator, bus, line, and motor zones. Figure 2.1 shows typical power system protection zones.

2.2 Overview of Protective Relaying

The public view of the power system is only based on the eye-catching elements of the power system such as the huge generation plants, the transformers in substations and more passionately the abundant over head transmission line. Until they experience unusual and unexpected occurrences, for example when electrical appliances get ablaze due to a lightening stroke on the transmission system miles away, then they may understand that a lot need to be done to avoid the transmition of dangerous electrical power. There are more fascinating and yet the most functional supportive components of the power system. This includes: the control system, the communication system and the protection system. The protective relays are the main elements of the protection system [1], [3].

Protection relay is a smart device that receives data compares them with reference values, and delivers results. The function of protective relaying is to cause the prompt removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in any

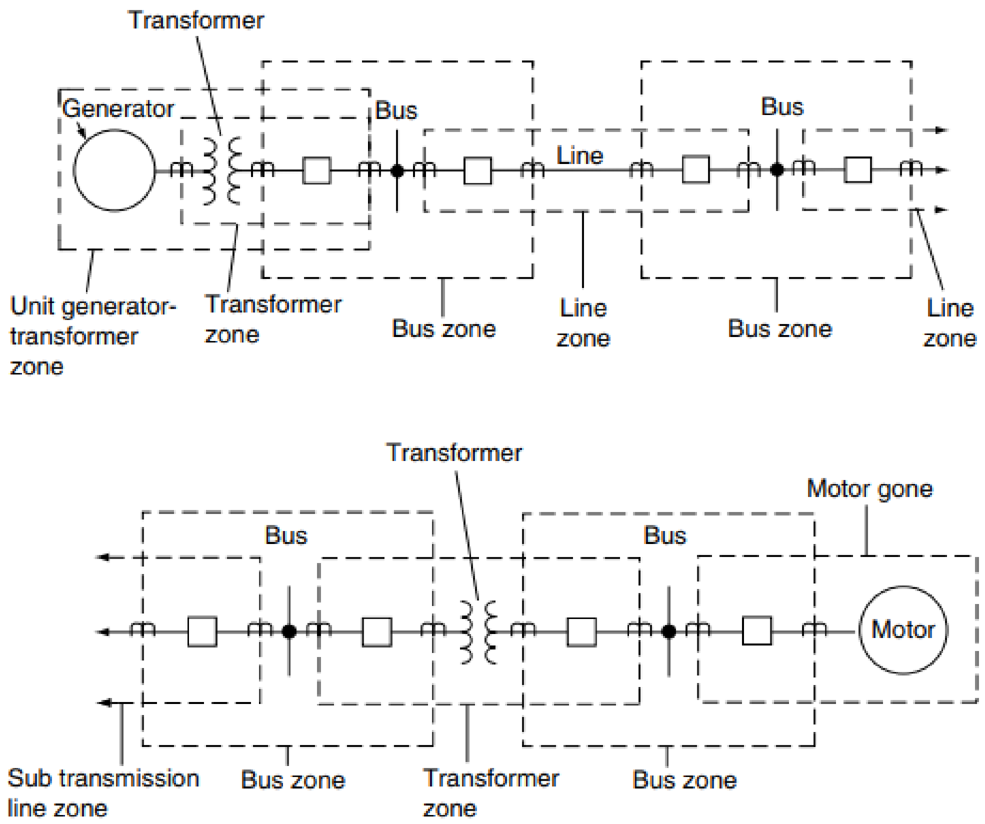

FIGURE 2.1: Typical relay primary protection zones in a power system.
Source: [1]- [3]

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abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system [15].

Protective relays receive actuation quantities and settings as input and send tripping or wanning signals as output quantities. Figure 2.1 shows the input and out put data of a relay. The Protective Relays are aided in this task by a series of equipment . These equipment includes: input devices; such as current transformers, voltage transformers, resistance temperature detectors, gas detectors, pressure detectors and etc. Output devices such as visualization screen, speakers/light indicators, circuit breakers, reclosers and etc.
circuit breakers are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment. The circuit breakers are connected in such away that it can completely isolate the protected device from the system during fault [1].

Figure 2.2. below shows the sequence of protection operation initiated by a fault and the functional elements (blocks) of a protective device. The comparison element, the decision element, and the threshold quantity are all programmed in to the digital relay.

The metered quantities are the inputs in Fig. 2.1 above. They include: current, voltage, phase, harmonics, gases, temperature, and so on, while the compared characteristics of the above quantities can be magnitude, frequency, phase angle, duration, rate of change, direction or order of

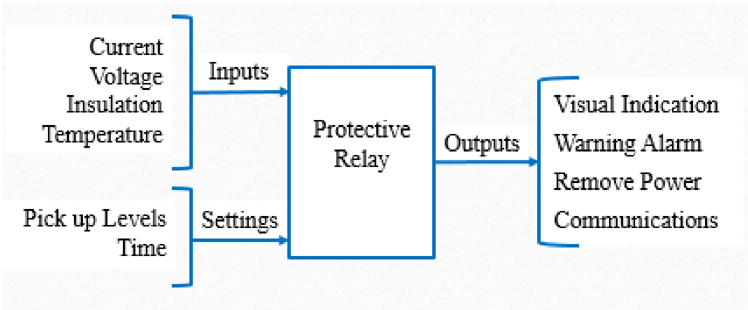


FIGURE 2.2: Input and output quantities of a relay

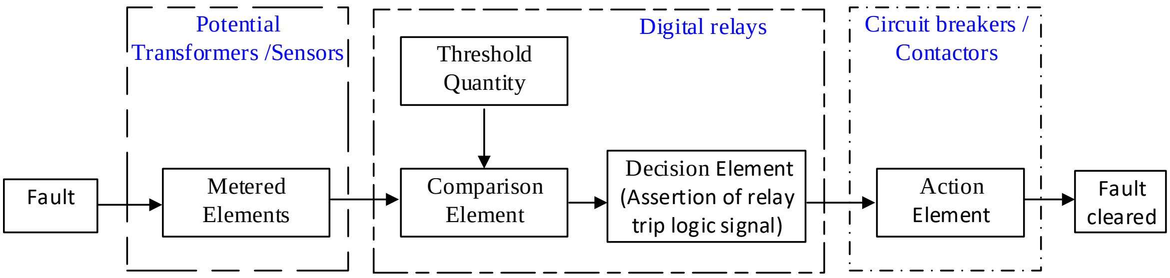


FIGURE 2.3: Protective device functional element

change, and harmonics or wave shape [1] - [3], [14], [40].

2.3 Differential Relay

Differential protective relay (power system device function numbers) is a protective relay that functions on a percentage or phase angle or other quantitative difference of two currents or of some other electrical quantities [15]

All devices such as generators, buses, and motors and even Lines can be protected with algorithm based upon ideas of differential relay, provided measurements at the terminals can be made available to the algorithm. However, each algorithm must deal with effects that tend to distort the signals or confuse the differential characteristic. Figure 2.4 shows the general representation of differential relay.

2.3.1 Transformer and its failures and causes

Transformers are electrical devices used for energy transfer by electromagnetic induction between two or more circuits. Transformers play the greatest role to avoid power loss I^2R in the transmission line, by stepping up the voltage and stepping down the currents during in the transmission line and vice versa at the distribution end. Transformers are one of the most expensive components in this network which makes it another reason for being very important. Any failure

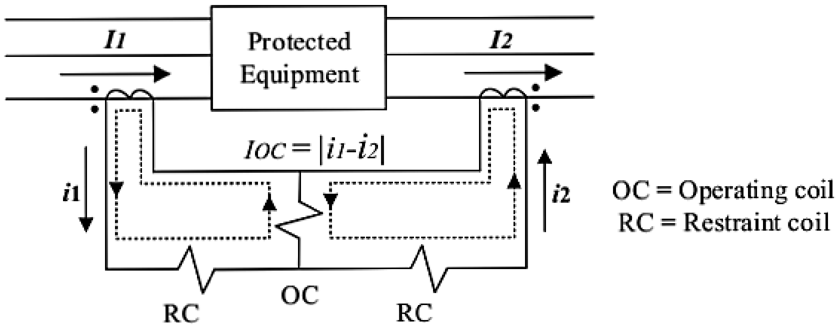


FIGURE 2.4: General representation of differential relay protection

of transformer can cause a wide area blackout. Transformers also pose increased risk of fires and explosions due to failures as it contains large quantity of flammable oil in direct contact with high voltage conductors. This is a threat to the substation and near by infrastructures. Some of the common failures of Transformers includes: Winding failure, windings withstand dielectric, thermal and mechanical stresses. Partial discharges may occur when insulation deteriorate due to the stresses.

Other threatening failures are bushing failure, tap changer failure, core failure, tank failures, protection system failure and cooling system failure. Following this brief introduction, a proper protection of transformer is very essential and economical.

2.3.2 Algorithm for the proposed digital transformer differential relay

Figure 4.5 shows the algorithm proposed in this studies for the differential relay logical action. The algorithm starts by the DAQ constantly measures the system current from both sides of the protected device, say transformer for this matter and delivers the current to the LabVIEW program in the PC/Labtop computer. The LabVIEW program then precesses the current signals, calculate the differential and restraining currents and apply the relay logic in two decision blocks. First, the differential current is compared by the threshold value. If the differential current is less than half of threshold, the system will run normally. If not alarm shows and, or rings. Once again the differential current is compared to the threshold. If the differential current is less than the threshold, the system continue to run with the alarm on, if the differential current is more than the threshold, it will indicate fault and send tripping signals instantaneously to the circuit breaker.

2.4 Mathematical Modeling of Digital Differential Relay

Basically, three characteristics provide means for detecting transformer internal faults. these characteristics include; gas formation, increase in phase currents, and an increase in differential currents. The latter characteristic and Kirchhoff's nodal rule of electric networks as shown in

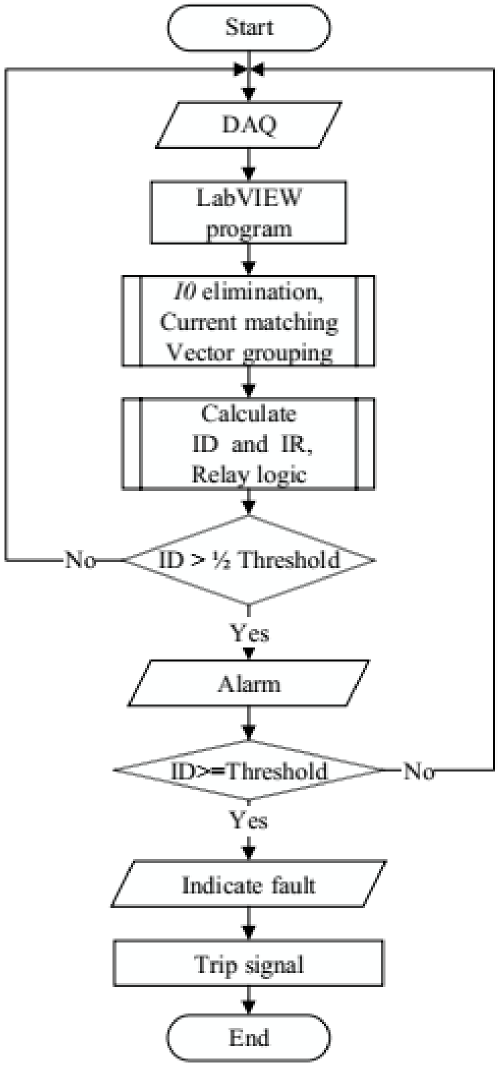


FIGURE 2.5: Algorithm for the proposed digital transformer differential relay

Eq.(2.1) (The algebraic sum of the currents toward any point in a network is zero) are the principles for the operation of the differential relay [3], [14].

$$\sum_{K=1}^{n} I_k = 0 \tag{2.1}$$

where n is the number of conductors at the node.

In transformer differential relay, the transformer itself is considered a node and input currents (I_A,I_B,I_C) is compared with output currents (I_a,I_b,I_c). The differential or operation current (I_D) and the restraining currents (I_R) are then calculated for use in the tripping logic. Before comparison the raw CTs currents first undergo processing and matching.

Figure 2.6. shows basic currents processing, matching and comparison blocks for transformer

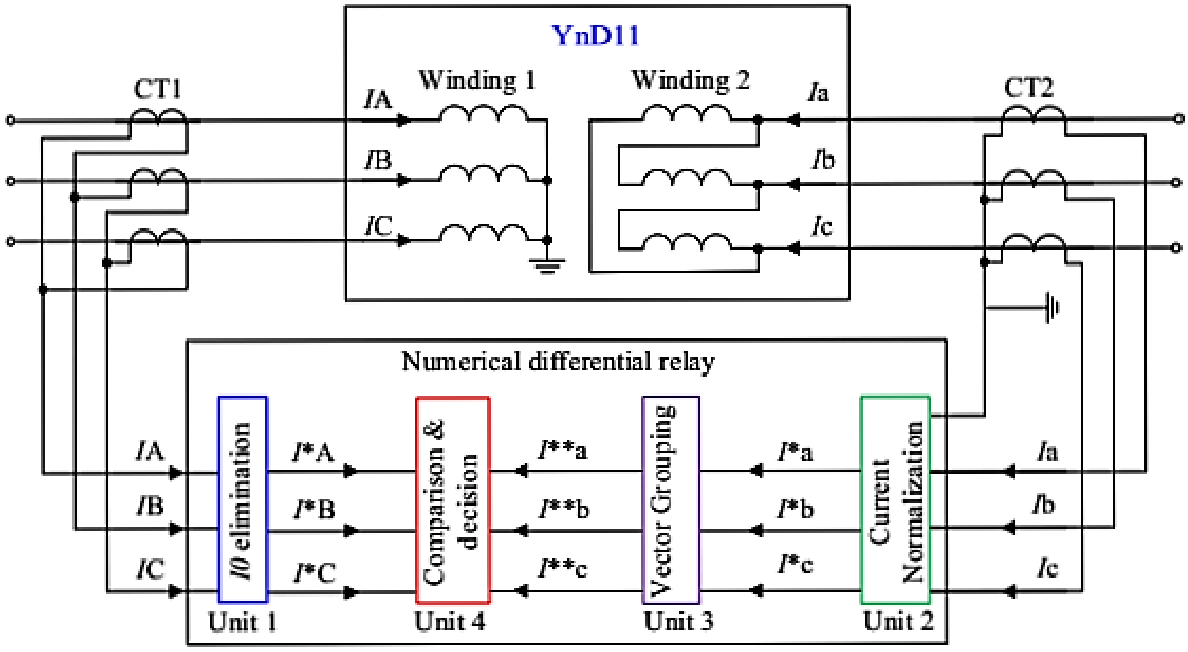


FIGURE 2.6: Processing of current signals in the differential relay; Winding 1 and Winding 2 - protected transformer windings; CT1 and CT2 - current transformers; Unit 1, Unit 2, Unit 3, and Unit 4 - Current processing and matching units

digital relay. The raw currents from current transformers (CT1 and CT2) are first processed in Unit 1, Unit 2, and Unit 3 before feeding into Unit 4 for I_D and I_R calculations, comparison and tripping logic algorithm [16], [17]. In Unit 1; Zero sequence current due to the grounded winding of the transformer may cause differential relay maloperation during an external ground fault[10]. Zero-sequence current symmetrical components I_0 in each phase is eliminated. This is only done on wye connected and solidly grounded side (winding1) of the transformer. Eq.(2.2), Eq.(2.3), Eq.(2.4), and Eq.(2.5) are used in this unit. Zero sequence component I_0 in a three phase system is equal to:

$$I_0 = (I_A + I_B + I_C)/3 \tag{2.2}$$

$$I_A^* = I_A - I_0 = I_A - (I_A + I_B + I_C) = \frac{2}{3} I_A - (I_B + I_C)/3 \tag{2.3}$$

$$I_B^* = I_B - I_0 = I_B - (I_A + I_B + I_C) = \frac{2}{3} I_B - (I_A + I_C)/3 \tag{2.4}$$

$$I_C^* = I_C - I_0 = I_C - (I_A + I_B + I_C) = \frac{2}{3} I_C - (I_A + I_B)/3 \tag{2.5}$$

The matrix form of the Zero sequence component equations above is given by:

$$[I_{A,B,C}^*] = T * [I_{A,B,C}] \tag{2.6}$$

$$T = \frac{1}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \tag{2.7}$$

Therefore,

$$\begin{pmatrix} I_A^* \\ I_B^* \\ I_C^* \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} \tag{2.8}$$

where:
I_0 is zero sequence currents
$I_{A,B,C}$ are measured currents by CT_1
$I^*_{A,B,C}$ are Currents after zero sequence elimination
T is the transformation matrix for the zero sequence elimination

Unit 2 addresses the the input and out put current differences due to the transformer and current transformers ratio. Here the reciprocal of the CTs and power transformer ratios are used for matching the CT_2 current. This will adjust the amplitude of CT_1 current equal to CT_2 currents.

In Unit 3, the phase shift between the power transformer primary and secondary currents due to delta-wye or wye-delta connections is addressed by Vector grouping adaptation. In electrical engineering, a vector group is the International Electrotechnical Commission (IEC) method of categorizing the high voltage (HV) windings and low voltage (LV) winding configurations of three-phase transformers. The vector group designation indicates the windings configurations and the difference in phase angle between them. The common two windings' power transformers vector group notations are Yy0, Dd0, Yd1, Dy1, Yd5, Dy5, Yd11, Dy11.

The phase different is the angle shift in the secondary voltage or current of a three phase transformer. It is measured in units of 30^o and can be grouped into five: group 0. no phase displacement, group 1. -30° phase displacement, group 5. (+150°) phase displacement, group 6. (+ 180°) phase displacement, and group 11. (+30) phase displacement.
The general equation for this adaptation is given in Eq.(2.9) , where k is the vector group number.

$$\begin{pmatrix} I^{**}_A \\ I^{**}_B \\ I^{**}_C \end{pmatrix} = \frac{1}{\sqrt{3}}\left(T_2^{(k)}\right)\begin{pmatrix} I_A^* \\ I_B^* \\ I_C^* \end{pmatrix} \tag{2.9}$$

Where:

$T_2^{(k)}$ is the transformation matrix

k is the vector group number

$I^{*}_{A,B,C}$ is the amplitude of adjusted current (adjustment of current transformer mismatch and tap changer mismatch)

$I^{**}_{A,B,C}$ is the phase angle adjusted current

The general matrix form for $T_2^{(k)}$ is given as in the Eq.(2.10).

$$\left(T_2^{(k)}\right) = \frac{2}{\sqrt{3}} \begin{pmatrix} f(k) & f(k-120^o) & f(k+120^o) \\ f(k+120^o) & f(k) & f(k-120^o) \\ f(k-120^o) & f(k+120^o) & f(k) \end{pmatrix}. \tag{2.10}$$

Where:

f(k) Trigonometric transformation function.

$$\left(T_2^{(k)}\right) = \frac{2}{\sqrt{3}} \begin{pmatrix} cos[k.30^o] & cos[(k+4).30^o] & cos[(k-4).30^o] \\ cos[(k-4).30^o] & cos[k.30^o] & cos[(k+4).30^o] \\ cos[(k+4).30^o] & cos[(k-4).30^o] & cos[k.30^o] \end{pmatrix}. \tag{2.11}$$

$$\begin{pmatrix} I^{**}_A \\ I^{**}_B \\ I^{**}_C \end{pmatrix} = \frac{1}{\sqrt{3}} \left(\frac{2}{\sqrt{3}} . \begin{pmatrix} cos[k.30^o] & cos[(k+4).30^o] & cos[(k-4).30^o] \\ cos[(k-4).30^o] & cos[k.30^o] & cos[(k+4).30^o] \\ cos[(k+4).30^o] & cos[(k-4).30^o] & cos[k.30^o] \end{pmatrix} \right) . \begin{pmatrix} I^{*}_A \\ I^{*}_B \\ I^{*}_C \end{pmatrix} \tag{2.12}$$

For example, substituting k in Eq. 2.12 with the vector group notation, the transformation matrix for the phase shift correction of vector group 5 (Yd5) is given by;

$$\left(T_2^{(k)}\right) = \frac{1}{\sqrt{3}} \begin{pmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{pmatrix}. \tag{2.13}$$

In this study, a transformer of a vector group Yd11 with a phase shift of 30^o on the delta side is used. The transformation matrix for the phase shift correction for this group is:

$$\left(T_2^{(k)}\right) = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{pmatrix}. \tag{2.14}$$

and Eq.(2.15), Eq.(2.16), and Eq.(2.17) are generated and used for the phase shift correction in this unit.

$$I_a^* = \frac{1}{\sqrt{3}}(I_a - I_c) \tag{2.15}$$

$$I_b^* = \frac{1}{\sqrt{3}}(I_b - I_a) \tag{2.16}$$

$$I_c^* = \frac{1}{\sqrt{3}}(I_c - I_b) \tag{2.17}$$

However, in the conventional relay, a phase shift transformer is used.

Unit 4 is the functional unit of the digital relay, here differential/operation and restraint/bias /stabilized currents are computed by Eq.(2.18) and Eq.(2.19).

$$I_D = |I_{A,B,C}^* - I_{a,b,c}^{**}| \tag{2.18}$$

$$I_R = (|I_{A,B,C}^*| + |I_{a,b,c}^{**}|)/2 \tag{2.19}$$

Where I_D and I_R are differential and restraining currents respectively.

Furthermore, relay decision is done in this block according to I_D and I_R. The relay issues the trip command when one of the following conditions given in Eq.(2.20) which is used in a differential relay with a single slope characteristic or in Eq.(2.21) which is used in differential relay with a dual slope characteristic, is satisfied in any one of the phases A, B or C.

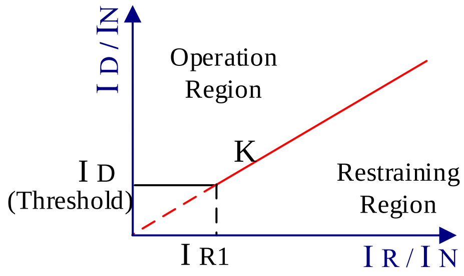
$$|I_R| < I_{R1} \text{ and } |I_D| > K_1 \times |I_R| + I_{D1} \tag{2.20}$$

$$|I_R| \geqslant I_{R1} \text{ and } |I_D| > K_2 \times |I_R| - (K_2 - K_1)I_{R1} + I_{D1} \tag{2.21}$$

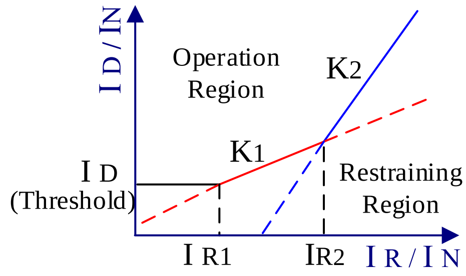
Where $K;$ is the slope of characteristic curve.

$$K = \frac{I_D}{I_R} \tag{2.22}$$

Figure 2.7 (A) shows the operating characteristics of a differential relay with a single slope and Figure 2.7 (B) is for differential relay with double slope characteristic.



(A) Single slope operating characteristics of a differential relay



(B) Double slope operating characteristics of a differential relay

FIGURE 2.7: Characteristic slopes of differential relay

When the transformer is in normal operating conditions, the differential current should be zero. However, in practice it may not be zero due to winding heating, CT saturation, and inaccuracies in CT matching.

The minimum pickup differential current is obtained from the MATLAB/SIMULINK simulation.

2.5 Summary

This section is very fundamental in this research, The theories for differential differential relays were first researched. Then the mathematical and logical equations were formulated. These equations are later used in the software control algorithms. However, before implemented in LabVIEW control program, they should first

CHAPTER 3

Software Modeling of Transformer Differential Relay and the Simulation Results

3.1 Introduction

This chapter discusses the parameters, steps and the outcomes of both the Simulink validation of the mathematical formulations and LabVIEW programing. The LabVIEW program will be used later on in Chapter 4 for conducting the experiment. In addition, the software modeling is also part of the training package. It plays a vital role in improving the learning experience of students and is very useful and long been used by academics, manufacturers, and consultants for designing relays and checking their performance [31]. The IEEE Power System Relaying Committee (PSRC) recommends that PSP courses should consist of standard lectures, laboratory sessions, software sessions, and assignments [18]

3.2 Software Modeling Methodology

3.2.1 Simulations for validation of differential relay parameters and mathematical operations in Simulink

The mathematical formulations described in chapter 2 were modeled in Simulink. Three simulations, two on transformer differential digital relay and the other on line differential digital relay were conducted. In this section, only a digital transformer differential relay is discussed [19].

First, high voltage (transmission line, and a step down transformer) parameters shown in TABLE 3.1 were simulated and studied. Secondly, a series of Laboratory scaled low voltage simulations were done for building up a platform in the power system laboratory, Shibaura Institute of Technology for experimental teaching of differential relay based on modules. Figure 3.1 shows the Simulink simulation layout

TABLE 3.1: Transformer parameters.

Parameters	Value	
Nominal power	47 MVA	
Nominal frequency	50 Hz	
Ratio	4.8 : 1 (Step Down)	
Magnetization resistance (pu)	500	
Magnetization inductance (pu)	500.01	
	Winding1 Value	**Winding2 Value**
Connection	Yn	D11
Voltage Ph-Ph (KVrms)	132	33
Resistance(PU)	0.002	0.002
Inductance (PU)	0.080001	0.080004

In this simulation layout (Fig.3.1), the protection zone is the Power Transformer (PT), in between current transformers (CT1 and CT2). Unit 1 to Unit 4 are the control units of the numerical differential relay as describe in Chapter 2. F_S, F_W1, F_W2 and F_L are only used in this study to represent faults at the source side, faults on winding 1, faults on winding 2, and faults on the line respectively. These faults are simulated in such different locations of the power system to view the characteristics of the faults and respond of the relay. The switching time for all the faults are 0.02 seconds, set to start at 0.04 seconds and end at 0.06 seconds in every 100 milliseconds simulation time. The validity of the numerical equations and faults characteristics are observed systematically in meters M1 for raw waveforms, M2 processed (transformer ratio, phase shift, zero current sequences all fixed) waveforms and M3 to observed the Differential and restraining currents. The triggering signal for the action of the relay trip contact is observed in M4. This triggering signal determine the action and general effectiveness of the relay.

3.2.2 LabVIEW Programing

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a systems engineering software with visual programming language from National Instrument. LabVIEW is commonly used for data acquisition, instrument control, and industrial automation. In this research, LabVEW program is used as the control engine of the digital differential relay. After the validation results of the mathematical and logical computational equations and algorithms were successful in simulink environment, The LabVIEW was programmed using the same equations and algorithms. The programing follows the same sequence of the Simulink simulation [20].

First a program for simulation studies was done. The programming starts with creating a twelve numeric control, six for the transformer primary current and six for secondary, in each case, three for the magnitudes and other three for phase angles. Then the mathematical formulations are programmed according to the current processing units of the simulink simulations. Last, a novel Graphical User Interface (GUI) also known as Human Machine Interface (HMI) was designed. A subVI of relay decision logic (unit 4) with lower threshold value was programmed along side the main program to ignite ar alarm at the earlier stage of the fault. Several simulations using the LabVIEW program were perform to see the genuinity of the program. For connecting LabVIEW to the physical world through NI USB-6210 for the experiment, the program was modified by replacing the numeric control part with data acquisition (DAQ) system and modifying the GUI. Data acquisition system consist of DAQ assistant, Write to Measurement File, Filter and Tone Measurement blocks. Figure 3.2 shows the complete LabVIEW program structure used in the experiment.

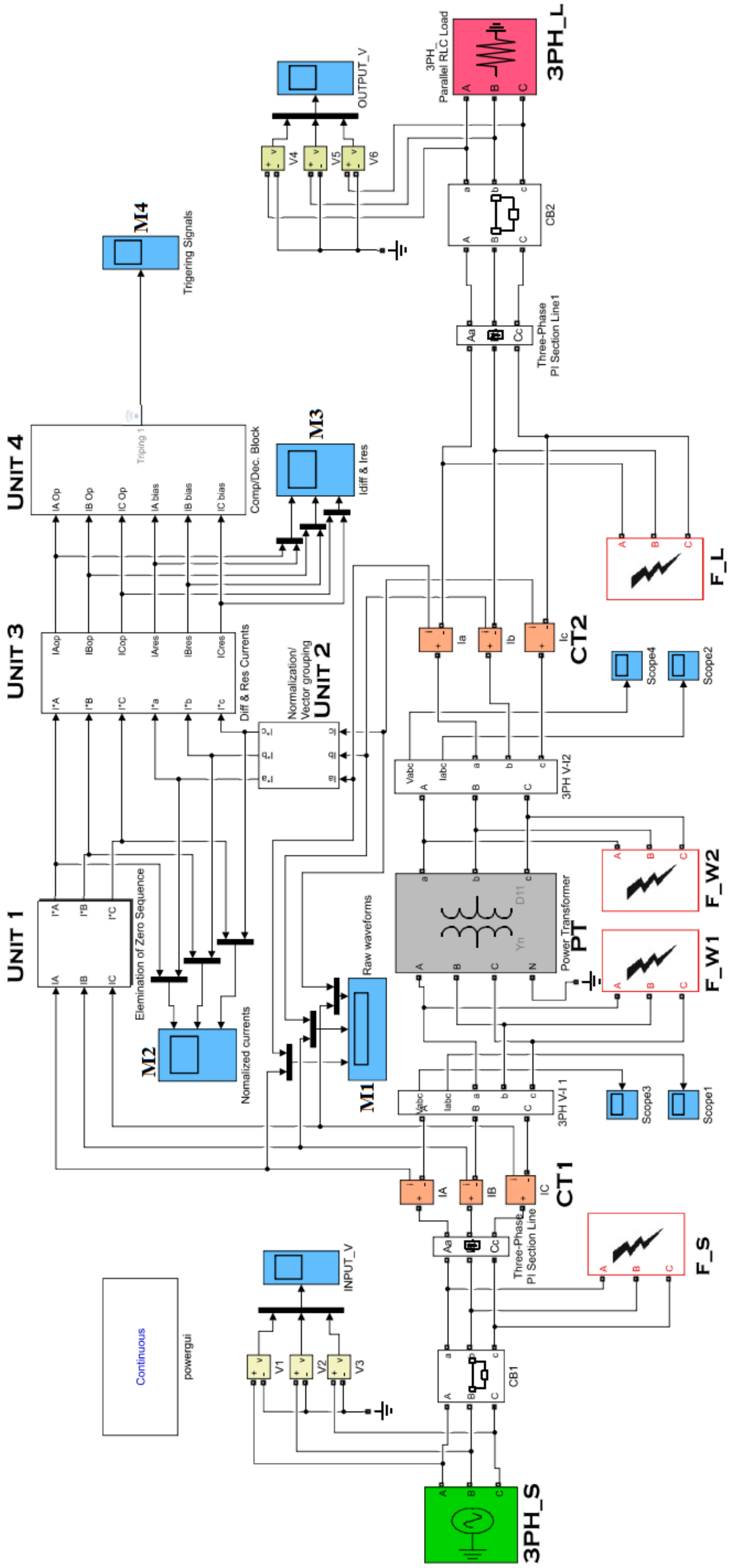


FIGURE 3.1: Arrangement of the simulation layout

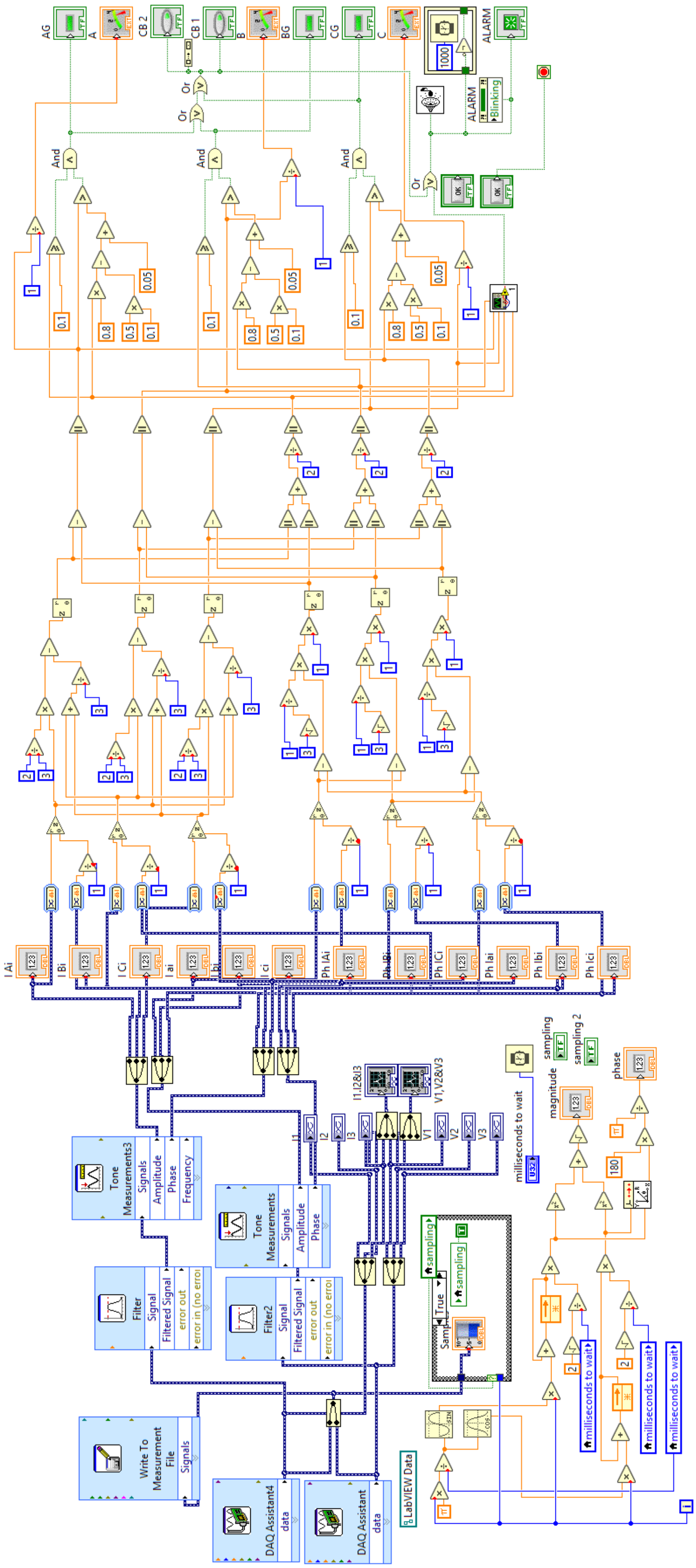


FIGURE 3.2: LabVIEW program for the control of the differential digital relay

3.3 Results and Discussion

3.3.1 Simulink Results

The simulation results give the in dept analysis of the relay theories and the effectiveness of the mathematical equations used in the simulations. It also help unearth new characteristics of the differential relay. The results were noted after every step of the simulation process and of different fault location. Figure 3.2: shows M1 signals, obtained by CT1 and CT2 from the system before any mathematical and computational algorithm application. A differential relay can not use these signals in this form. However, for analysis and system validation reasons, it is visualized Part A of the figure (Figure 3.2) shows the signals when the system is running normally while part B and C is when a (L-L-G) fault between phase A and phase B is applied from 0.04 to 0.06 seconds.

In this figure, Figure 3.2: It can be observed that the transformer is a step down type, because the magnitude of primary current is lower than that of the secondary. Therefore, this called for a factor (the reciprocal of the transformer ratio) to equalize the current amplitudes before feeding into the differential computational algorithm. The fault current due to short circuit between phase A and Phase B, from 0.04 seconds to 0.06 seconds created at the primary side is about 22.5 times the normal primary current.

The primary raw currents is passed through Unit 1 to eliminate any possible zero sequence current and the secondary is processed in Unit 2. There are two mathematical expressions in Unit 2, transformer ratio elimination and Phase shift correction.

Figure 3.3: shows the current waveform after the transformation ratio correction and before the phase shift correction. It indicates clearly the phase shift, the primary current leads the secondary by 30 deg. This is the characteristic of Yd11 vector group.

Unit 2 also contained a vector group adaptation mathematical algorithm which numerically removes the phase shift. After it's applications, both the primary and secondary current follows in the same path. That is to say, have equal magnitude, phase angle and frequency as seen in Fig. 3.4 obtained from M2 meter. On this figure, the current signals appears to be three, however, they are six signals in three sinusoidal wave path.

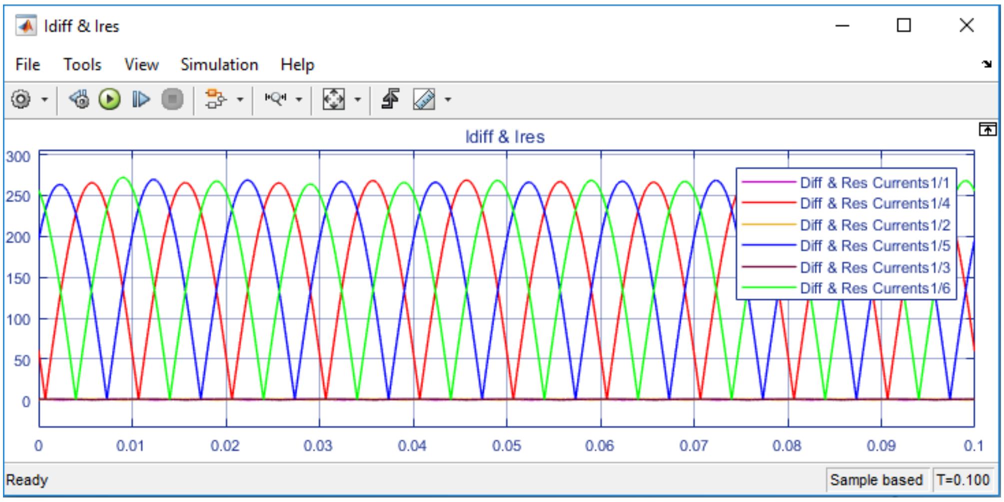
After this stage, the differential and restraining currents can now be calculated. Unit 4, does the calculation of differential and restraining currents and is visualized through meter M3 as shown in Figure 3.5

In Figure 3.5, only the restraining currents (275 A) is clearly visible, but the differential current which theoretically should be 0 A in the normal operating system is around 1 A in this simulation and is seen just as a single line on the horizontal 0 A axis.

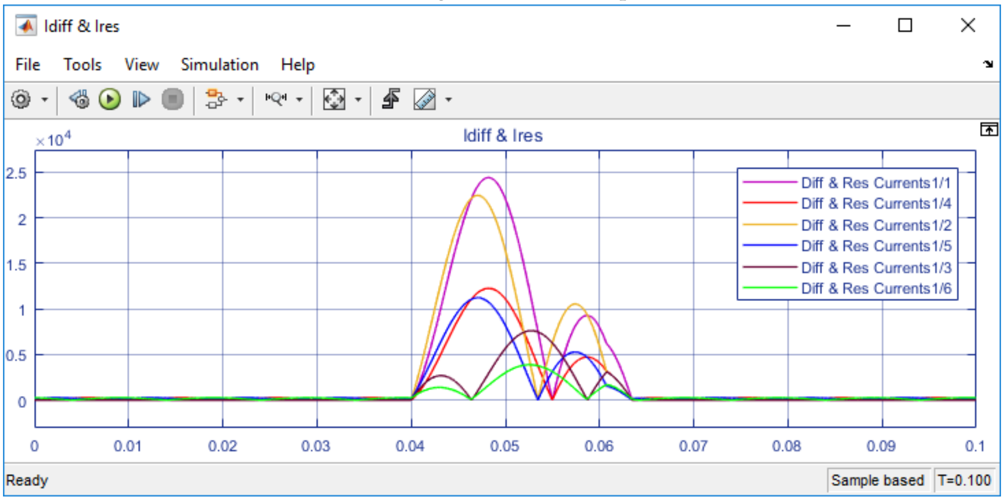
The differential and the restraining currents are then fed into Unit 4 for the computational differential relay logical algorithm for fault identification and subsequent sending of tripped signals to the contactors or circuit breakers for clearance of the fault.

Figure 3.6 shows the trip signal stage. High(1) indicates trip and Low(0) indicates no trip signals and hence the system is running normally.

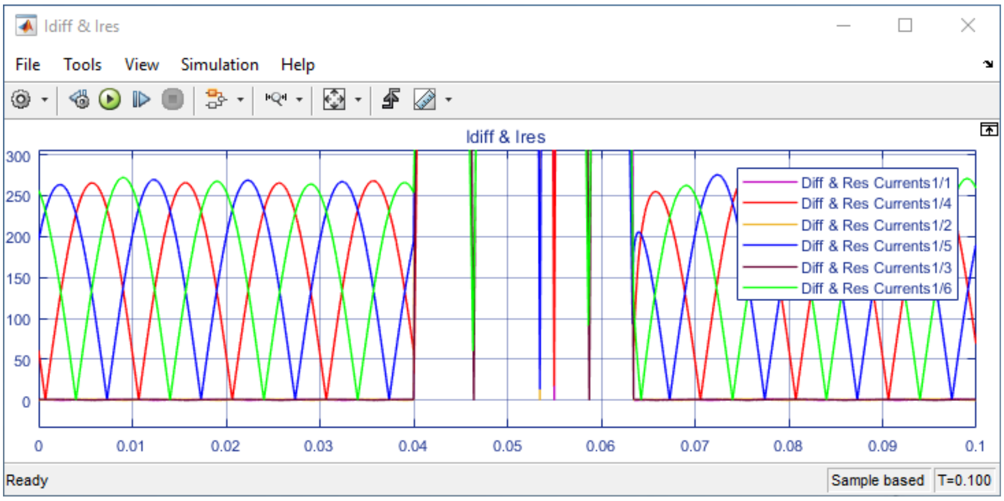
3.3.2 LabVIEW Results



(A) current signals in normal operation

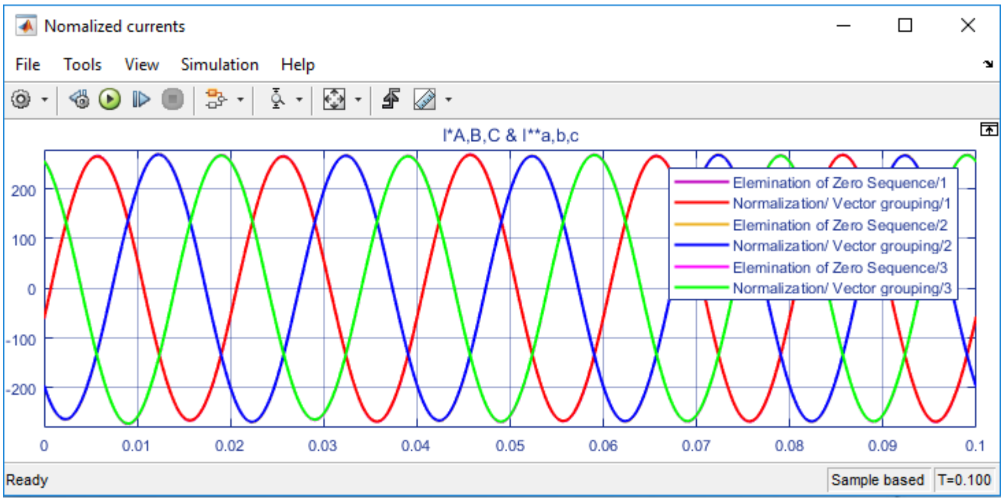


(B) current signal in faulted condition

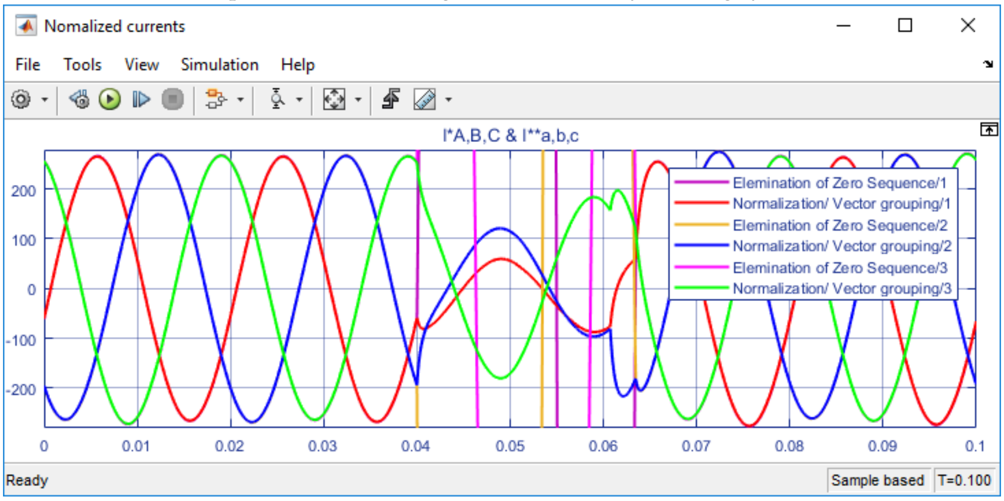


(C) zoomed current signals in faulted conditions

FIGURE 3.3: Differential and restraining waveforms



(A) processed current signals in a normally running system



(B) zoomed processed current signals during a fault

FIGURE 3.4: Processed current signals

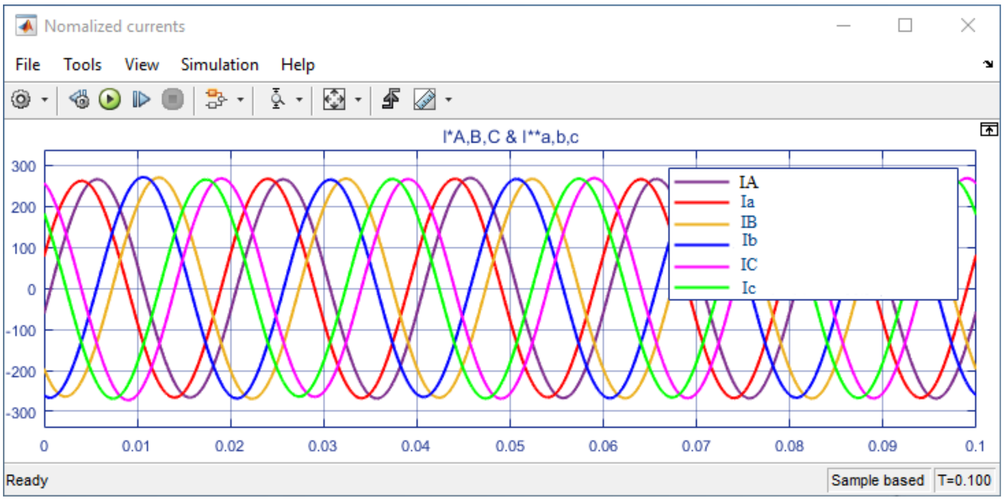
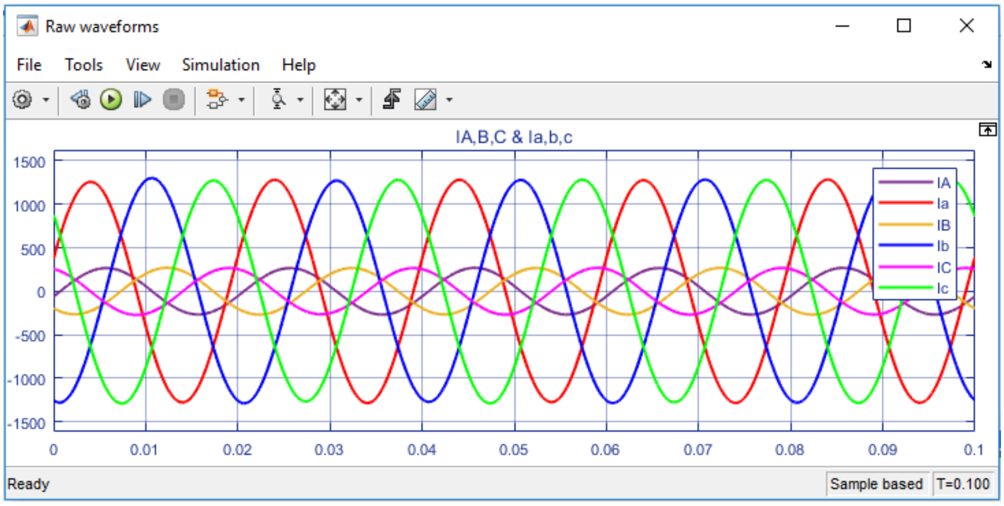
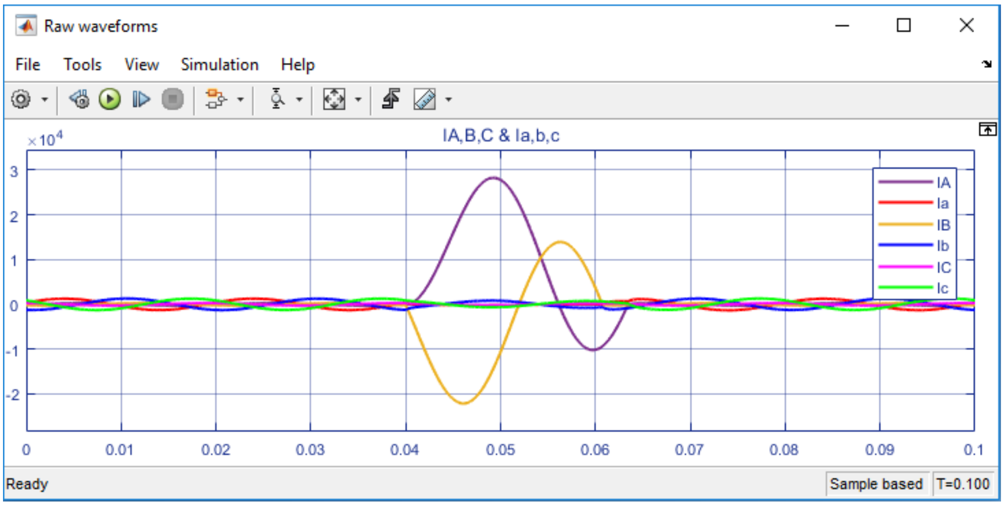


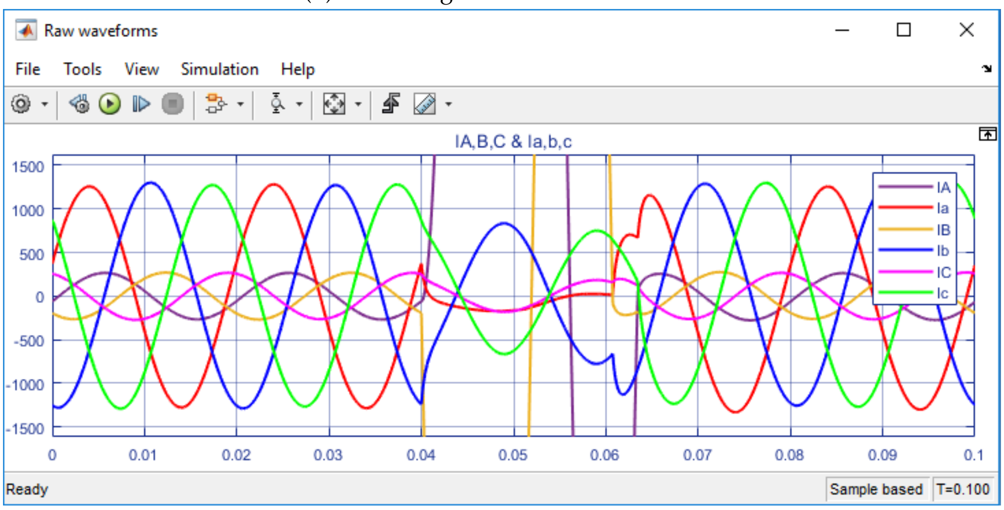
FIGURE 3.5: Phase shift between primary and secondary current



(A) current signals in no fault conditions

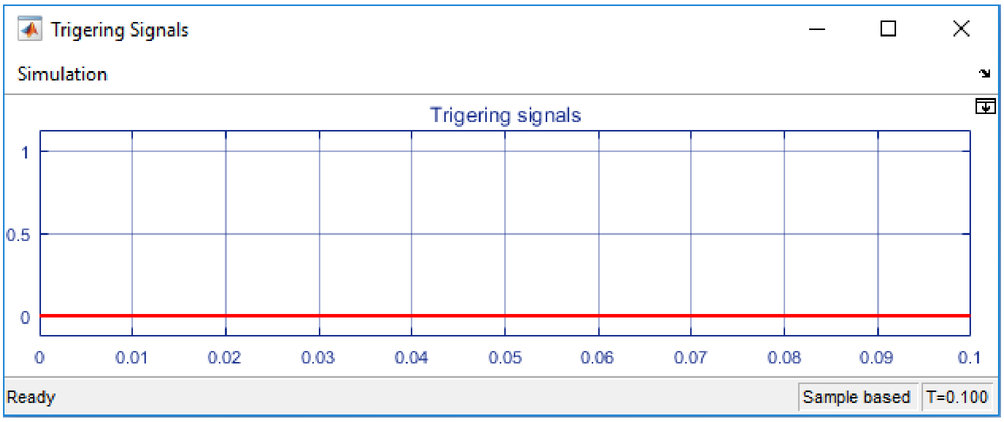


(B) current signal in faulted condition

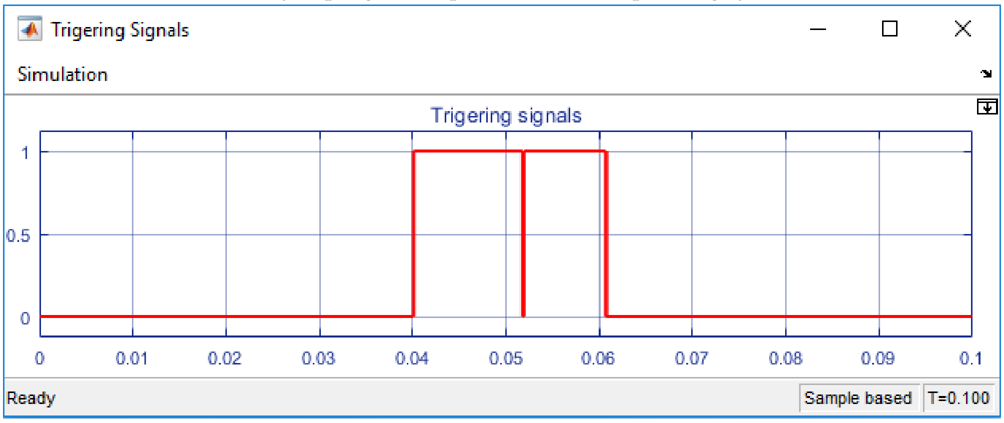


(C) zoomed current signals in faulted conditions

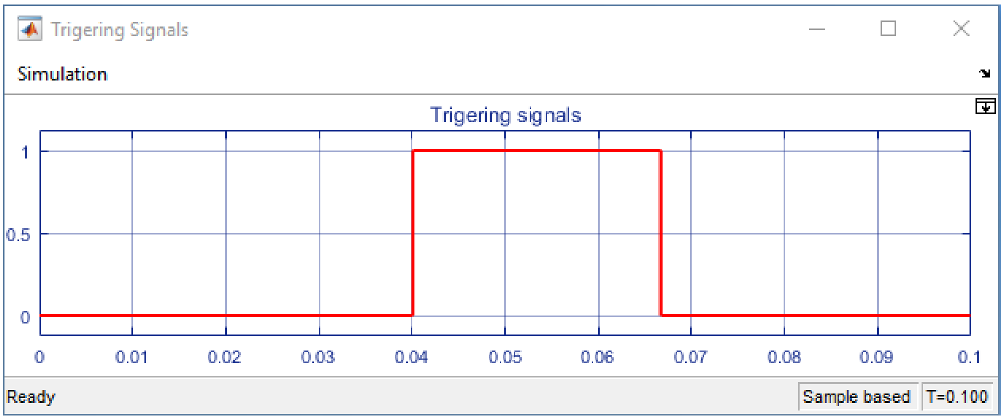
FIGURE 3.6: Current signals obtained from the system before any signal processing (mathematical and computational) algorithm applied.
where: IA, IB, IC are transformer primary currents and Ia, Ib, Ic are secondary.



(A) relay trip signal output in a normal operating system



(B) relay trip signal when a line to ground fault occurs



(C) relay trip signal when a line to Line to ground fault occurs

FIGURE 3.7: Relay trip signal output in normal operating conditions and with a fault from 0.04 till 0.06 seconds

3.4 Summary

These Chapter serves two purposes, the first is to verify the mathematical and logical equations obtained in Chapter 2. This was done by Simiulink, after the algorithm was proven to work as required, then secondly the development of the relay control program in LabVIEW environment commenced. The simulations results are in line with the theories and expected out come.

CHAPTER 4

Experimental Setup of Transformer Differential Relay by Modularization Method

4.1 Introduction

In this chapter, the physical setting of the platform, construction and wiring schematic diagrams for the modules which are specifically developed for this project are discussed. First a brief description of a module is tackled. Then, the layout of the experimental platform on the real time mode is analyzed. Finally, experimental procedures are elaborated.

4.2 Module Concept

A module is a 300mm cube aluminum packaged functional hardware unit designed for use with other components [11]. The modules have five input and output points of connection (3-phase lines, a neutral and ground) each fitted with screws. Electrical wires with ring terminals are used to easily connect and disconnect modules. Figure 4.1 shows the general specification of a module. However, the designed of the front panel is detected by the devices it contains. A module can contain a single devise or many devices wired to give a specified function.The input and output terminals are arranged in such a way, it can be simply connected to other modules. A module weighs 3 - 20 kilograms and can be design and built in 1 week to 1 month, with a cost ranging from 500 - 5000 US Dollars. All these depend on the devices being housed in the module. Three phase 200 V is the standard voltage of the source and can hold to a maximum power of 3kw. Some modules contained devices that require to be powered from single phase 100 V. The importances of modularization include: protect the device(s) from mechanical damage, safety of personnels, and easiness to handle and use during experiment [5]

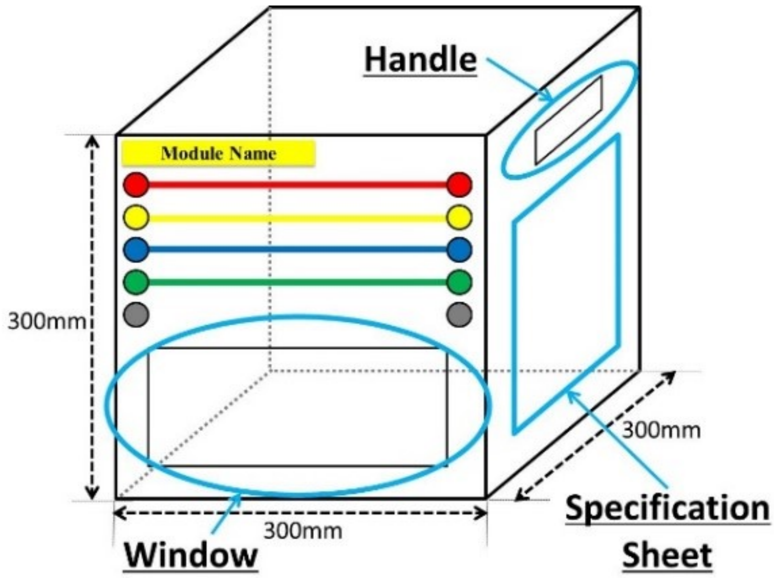
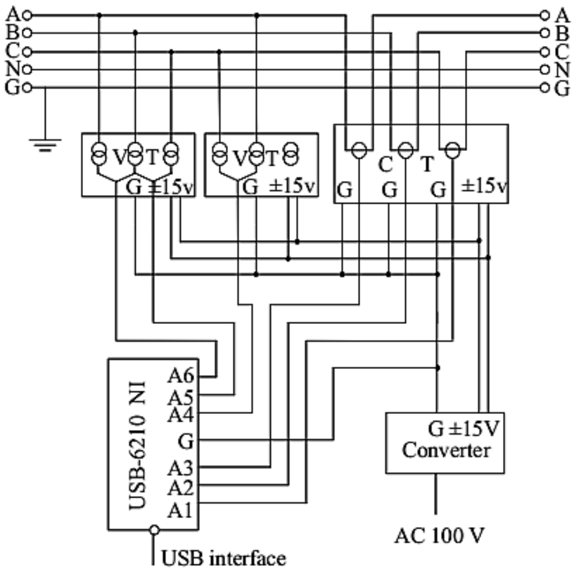


FIGURE 4.1: Specification of a module

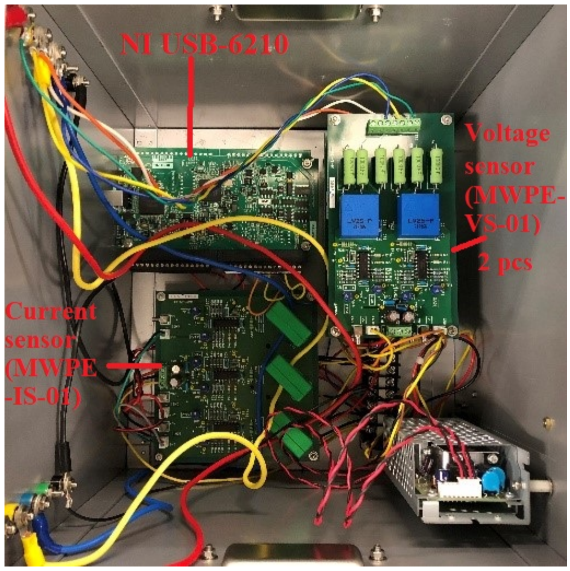
4.3 Modules Design

In this research work, two modules were designed and assembled, Data Acquisition (DAQ) module and a short circuit module.(Figure 4.4). The DAQ module is responsible for measuring the line current and supply a it's proportional scaled down signal to the LabVIEW program for execution and in turn pick the tripping signal (the output of the LabVIEW program) and deliver it to the contactor relay. The DAQ module contains one current sensor (CT) unit (MWPE-IS-01); inputoutput ratio ±50A/5V. Despite not being used for the current differential relay, the DAQ is also fitted with two voltage sensor (VT) units (MWPE-VS-01); input/output ratio 400V/5V for use in other relay analysis such as distance relay. Figure 4.2 (A) shows the schematic diagram for internal wiring and connection of DAQ modules while Figure 4.2 (B) is the picture of its components . USB-6210 from the national instrument is one of the essential devices in the DAQ modules. The USB is a multifunction DAQ devise that offers analog input, digital input, digital output, and two 32-bit counters, it also provides an on board amplifier. Figure 4.3 (A) shows the picture os NI USB 6210 and Figure 4.3 (B) shows it's pin array. The sensor units are powered by DC 5V or 15V from 100V converter.

The short circuit module is a set of wired switches in such a way that it can cause a short circuit to create an intended fault type. However, during experiment the fault point is changed from one location to anther by changing the short circuit module location at a time on points 1 - 4 to generate different types of faults on different locations and the action of differential relay is investigated in such cases. Figure 4.4 (A) shows the connection of wires and switches and Figure 4.4 (B) is the front specifications view of the short ciut current. As highlighted above, the DAQ module is the fundamental module in this experiment as it housed the essentials devices.



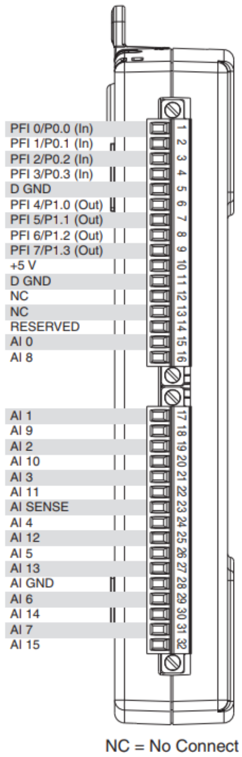
(A) Schematic diagram of the wiring



(B) Interior view, showing the components

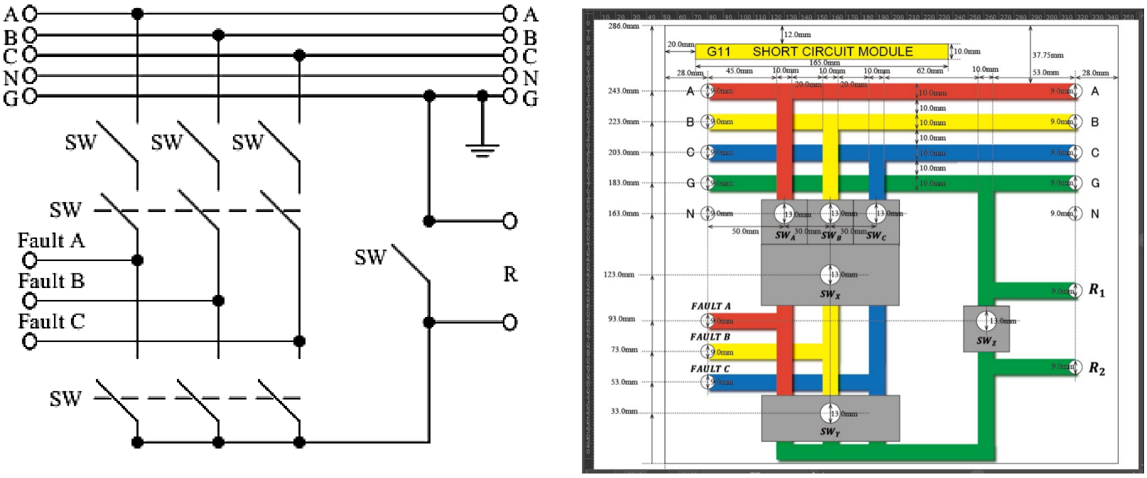
FIGURE 4.2: Data Acquisition(DAQ) module designed for this experiment

(A) NI USB 6210 and connecting cable



(B) USB-6210 pin array (Source: NI USB-621x User Manual - National Instruments)

FIGURE 4.3: NI USB 6210

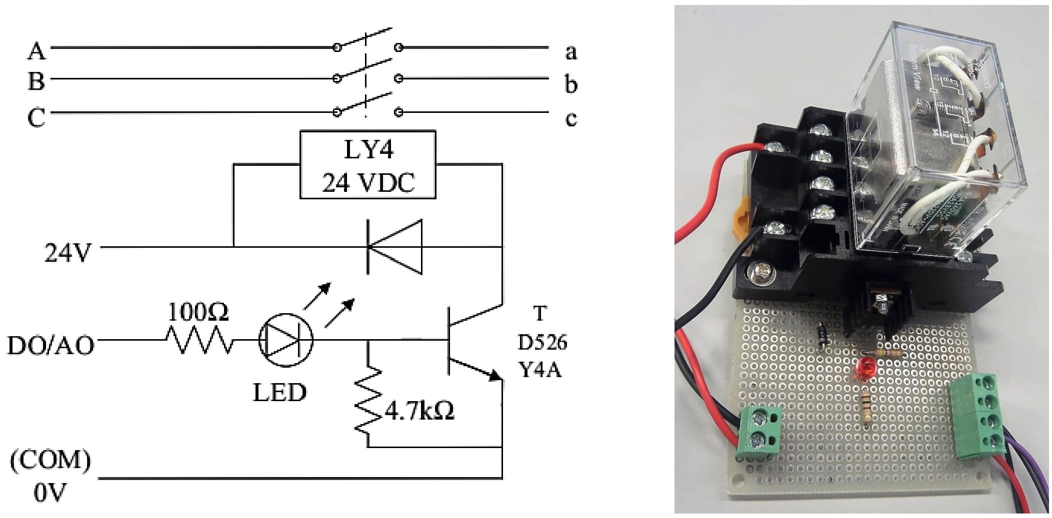


(A) Schematic diagram of internal arrangement and wiring

(B) The front view specifications

FIGURE 4.4: The structure of Short Circuit Module

The contactor relay is composed of an electronic switch circuit that consist of D526-Y 4A Semiconductor Bipolar Transistors- BJT, BYV26C Fast Recovery Diode, LED, and resistors and a LY4 DC24 OMRON contactor relay. Figure 4.5 (A) is the schematic connection diagram of the contactor relay and Figure 4.5 (B) is a picture of the contactor relay. TABLE 4.1 is a partial data sheet of this contactor relay. The tripping signals from the LabVIEW program is to control this contactor.



(A) Schematic diagram

(B) Physical diagram

FIGURE 4.5: Contactor relay

TABLE 4.1: LY4 DC24 OMRON Data sheet
Standard type, Single, Plug-in terminal, 24 VDC 10 A (Resistive load), 110 VAC 10 A (Resistive load), Output 4PDT (10 A 24 V)

Coil ratings	24 VDC 69 mA
Contact type	4PDT
Contact method	Single
Contact material	Ag alloy
Contact rated load	110 VAC 10 A (Resistive load) 110 VAC 7.5 A (Inductive load (cos ϕ = 0.4)) 24 VDC 10 A (Resistive load) 24 VDC 5 A (Inductive load (L/R = 7 ms))
Maximum switching current	AC: 10 A DC: 10 A
Terminal structure	Plug-in terminal

4.4 Setting up the Experimental Platform

In the Power system Laboratory, Shibaura Institute of technology, there are already existing modules of main power system components. For example: Voltage regulators, Meters, Transformers, Transmission lines, distribution lines, loads(resistive, capacitive,and resistive), and more others.

The modules are arranged as shown on the schematic diagram represented on Figure 4.6, and Figure 4.7 shows the pictorial view of the arranged modules. Power source is connected to the Voltage regulator module, then a meter module (POWER HITESTER), DAQ Module, Transformer module, DAQ module, Distribution line, and the Load. The DAQ modules are also linked to the LabVIEW program in a PC through a USB and to the contactor relay.

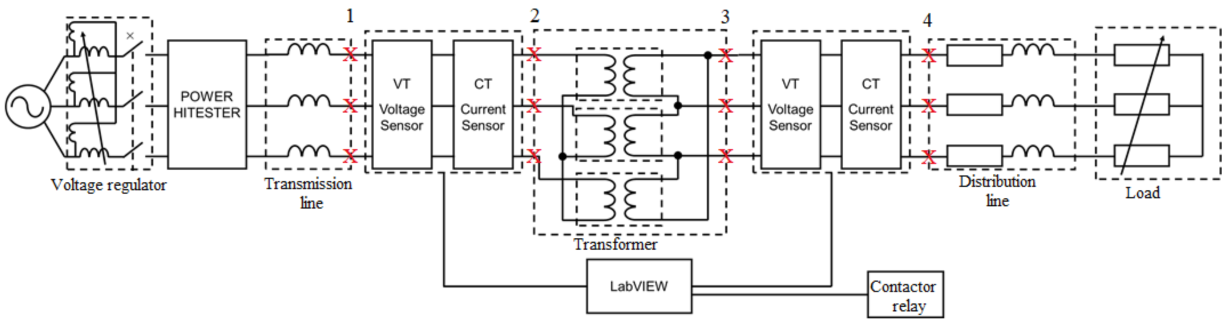


FIGURE 4.6: Schematic diagram of modules used in the transformer digital relay experiment

FIGURE 4.7: Laboratory setup of the modules for transformer digital relay studies

4.5 Digital Transformer Differential Relay's Experimental Results

By following the operation manual (Appendix A) step by step, digital transformer differential relay's experimental can be conducted.

After a correct connect and running the LabVIEW program, the first interface shows as shown in Figure 4.8. that also indicates that the experiment is well set and is the interface when the system is in it normal state of operation, the scale shown on the meters is 1:1.

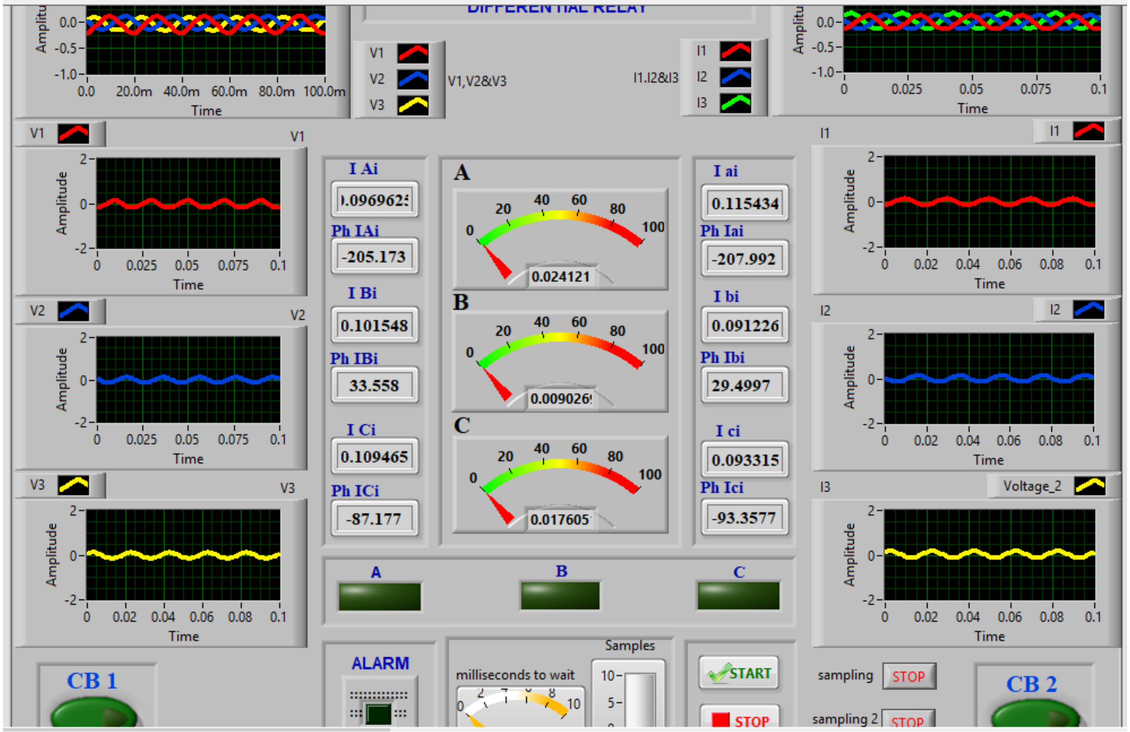


FIGURE 4.8: LabVIEW interface for a normal (no fault) state. Meters' ratio is 1:1.

The differential current is just around 0.02 A, due to some little power loss in the transformer winding, otherwise in theory the differential current should be zero. This margin is covered in deciding the threshold value.

When a short circuit is created by the use of the short circuit module, by shorting phase A and C, the effects of the fault was clearly visualized, and a tripping signal from the LabVIEW program successfully ignite the contactor relay to open its contacts. Figure 4.9 shows the LabVIEW interface for this fault conditions. Figure 4.10 shows for phase B and Phase C faults and Figure 4.11 for three phase faults (Phase A to Phase B and phase C shorted)

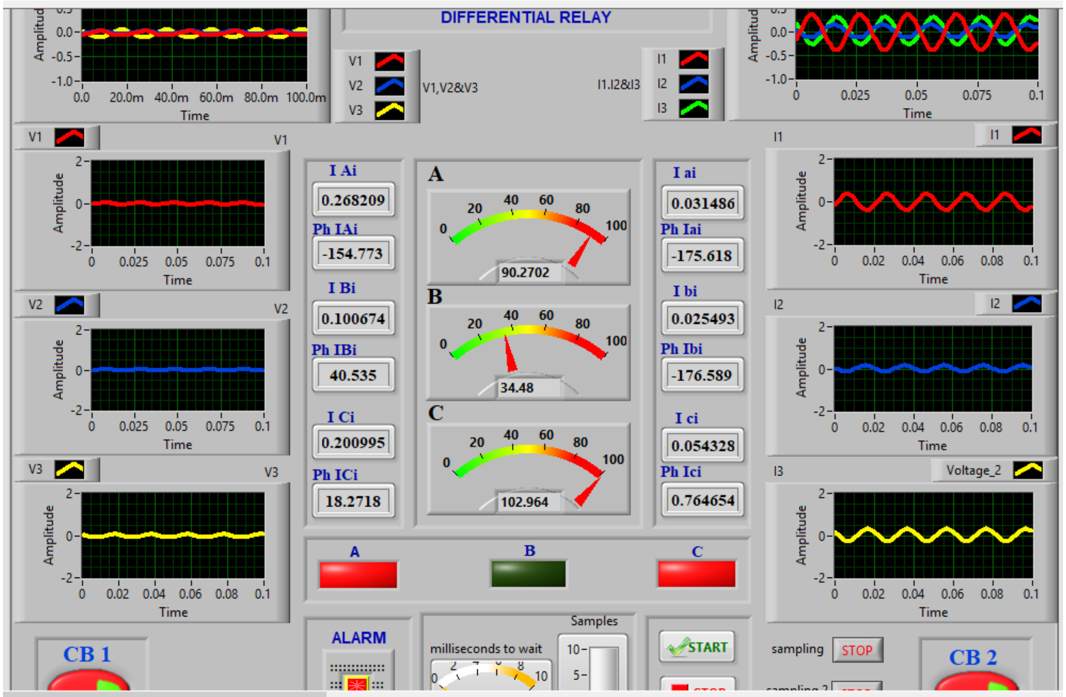


FIGURE 4.9: LabVIEW interface for Phase A and Phase C shorted fault. Meters' ratio is 1:500.

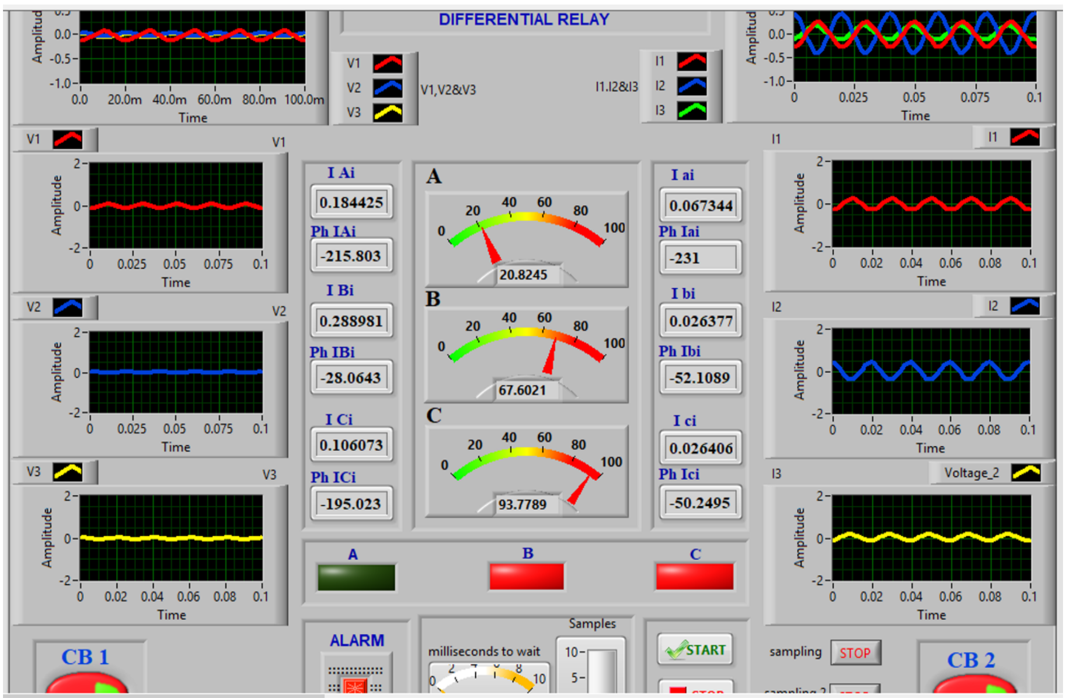


FIGURE 4.10: LabVIEW interface for Phase B and Phase C shorted fault. Meters' ratio is 1:500.

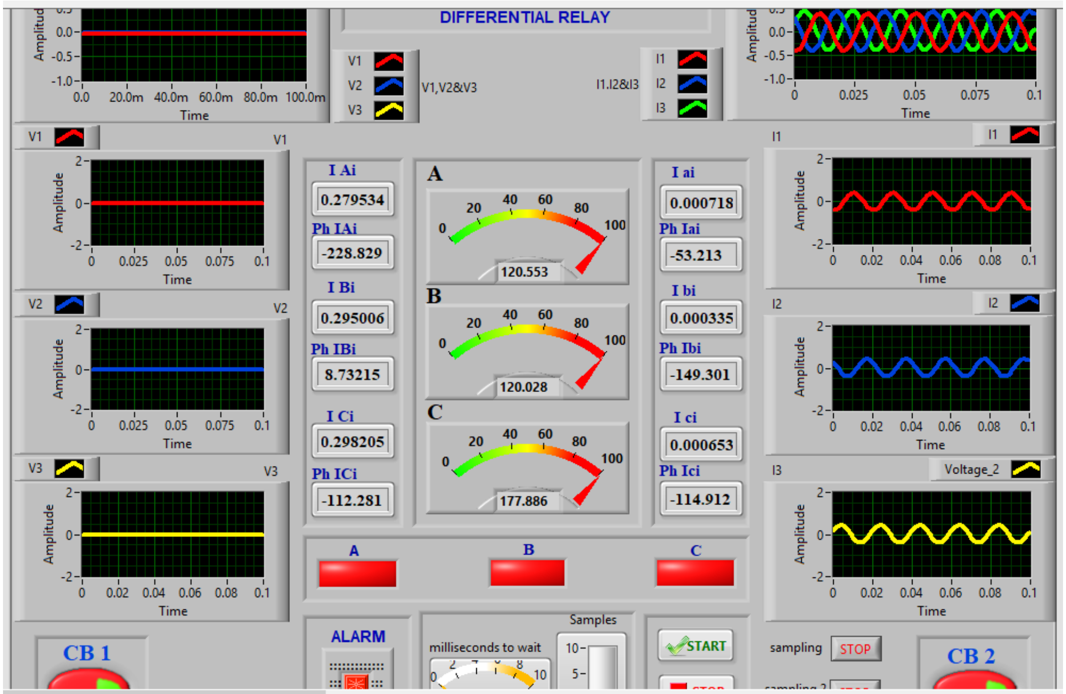


FIGURE 4.11: LabVIEW interface for three phase faults (Phase A, Phase B and phase C shorted. Meters' ratio is 1:500.

4.6 Consideration for possible Failure of the Relay

When dealing with relay experiments, close attention should be paid to among others, the following possible causes of failures:

1. Current or voltage supply to the relays.
2. DC supply failure, all relays are powered by a DC power source.
3. Protective relays.
4. Failure of the relay software itself.
5. Failure of Circuit Breaker (tripping circuit or mechanism, or signal to trip the breaker) in this experiment a contactor relay is used.
6. Failure of current or voltage signal to the relays due to CTs malfunction (Data Acquisition Module)

4.7 Summary

The experiment was successful, the main principles of the differential relay were visualized and actualized. The experiment operation manual is well articulated and easy to follow, so undergraduate student can be able to conduct this experiment by themselves. It has been tried for conducting experiments for third years electrical students admitted for research in power system laboratory, Shibaura Institute of Technology. The software simulation can be copied and stored in any form, though can only open in a simulink and in LabVIEW environments. Students who intend to do research in differential relays can pick off from this experiment.

However, due to zero sequence current elimination and Phase shift correction algorithm complications, faults on different phase can sometime be seen indicated on the others on the LabVIEW interface.

CHAPTER 5

The Effectiveness of Line Differential Relay in Microgrid Protection

5.1 Introduction

In the pass decade, especially after the United Nations Climate Change Paris Agreement (COP21) amongst 196 countries, has triggered the rise in penetration of renewable distributed energy resources (DER) in term of microgrid into AC interconnected power systems. Microgrid therefore, has been identified as a key component of smart grids and as the best way to encourage the use of sustainable, clean and renewable energy sources. Many researchers, power utilities and governments embrace it.

A microgrid in its broader view is a localized group of interconnected loads and Distributed Energy Resources (DERs) (in medium or low voltage) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid normally operates connected to and synchronous with the traditional centralized grid (grid mode) or can disconnect and function autonomously (island mode) when physical and/ or economic conditions dictate [23]. Figure 5.1 shows typical Microgrids of different scales.

The integration of this different technologies and varying scales of renewable generation across interconnected transmission and distribution grids will accelerate resulting pressure on ensuring safety and operational integrity of existing reliable power system operation. Microgrid as a complement to the existing grid infrastructure, many papers have discussed the economical, losses avoidance, operational, and Environmental (emissions reduction) benefits of microgrid and concluded affirmatively [24]-[25].

However, some of the shortcomings of microgrids at distribution level are fault protection and isolation difficulty. Renewable energy based DERs, connected to a microgrid through inverters can only supply limited fault current during islanding mode. Many DERs in a microgrid such as solar photo-voltaic, and wind generation are intermittent in nature. Therefore, different fault current levels can be experience in the grid. The mesh configuration of the DERs within a microgrid makes power flow in bi-directional manner. These affect the use of over current and directional relays in microgrid especially when it switched to islanding mode [27]. Line differential relay operates on the bases of differential current. Its principle of operation does not concern much about the magnitude of current and could be the best option for protection of microgrid lines [28].

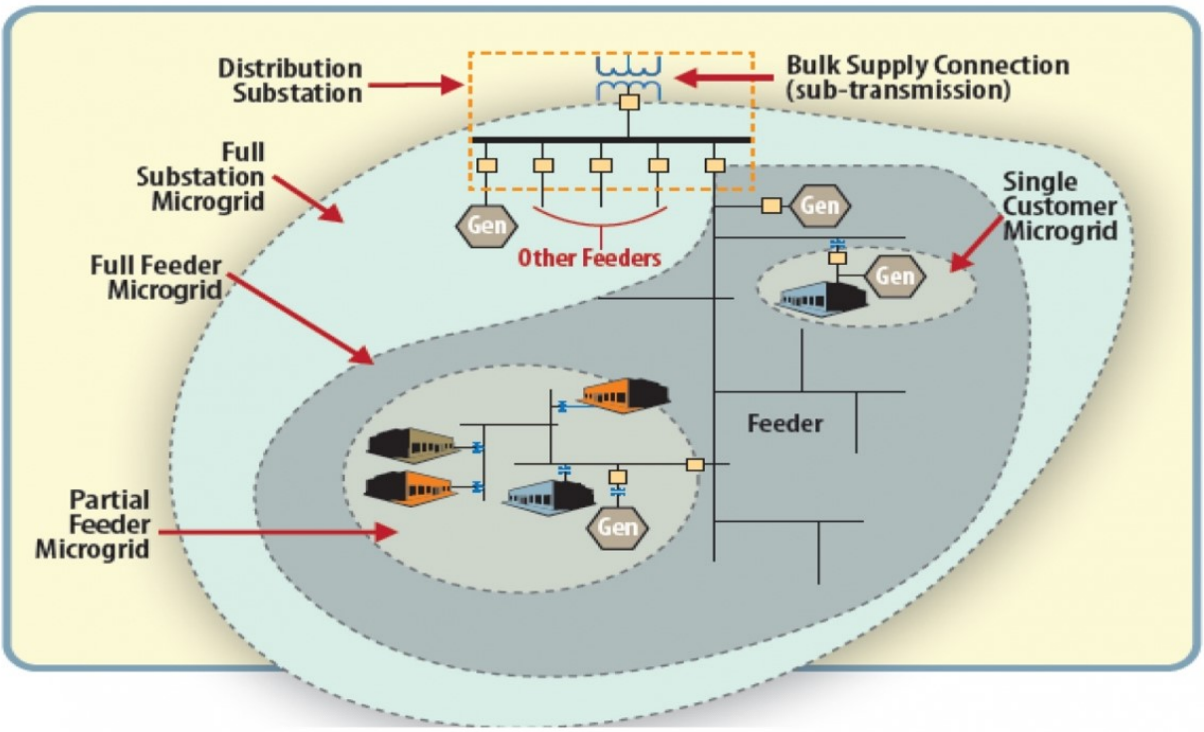
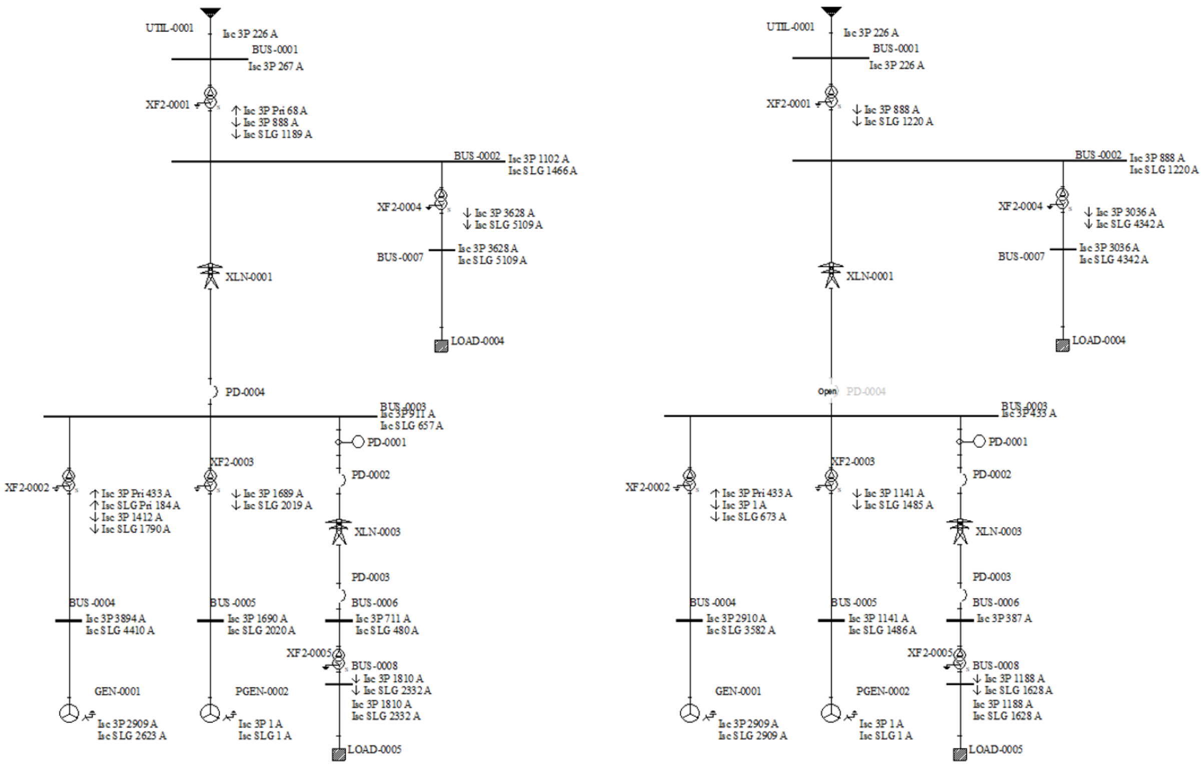


FIGURE 5.1: Microgrid system (Source: Office of Electricity U.S. Department of Energy)

This Chapter is divided into two parts: first it investigates the short circuit current levels of a microgrid in grid-connected and in islanding mode using SKM Power Tools. Secondly, the ability of the line differential relay to response to faults on microgrid's distribution lines during grid connected and islanding mode without changing the settings.

5.2 Investigation of Short Circuit Current Level during Grid Connected, and in Islanding Mode

The SKM Power tools software was used to investigate the short circuit current levels. First, a microgrid connected to a main grid with the system parameters as shown on TABLE 5.1 were simulated and the short circuit levels were obtained at each node. Then the switch at the Point of Common Coupling (PCC) was opened to signifies the condition of islanding phenomena and the simulation ran again. The short circuit currents at each node were also noted and compared. Figure 5.2 (A) shows the simulations when in grid connected mode as it can be seen that PCC (PD-0004) switch is closed while Figure 5.2 (B) is when it is in islanding mode, as the PCC is open. After finding a significant difference in the short circuit current in this investigation, a simulation was built to test the operation of line differential relay in both modes without changing the settings.



(A) Grid connected mode (B) Islanding mode

FIGURE 5.2: Simulated relay trip signals

TABLE 5.1: simulated system parameters.

Parameters	Value
Main grid contribution	47 MVA / 120KV
System frequency	50 Hz
main grid transformer ratio	4.8 : 1 (Step Down)
Distribution Voltage	25000V
DGs transformers ratios	4.5 : 1(Step Up)

5.3 Simulink Analysis for the Effects of Short Circuit Currents Variation on Line Differential Relay

A Simulink module of a microgrid with similar parameters shown in TABLE 5.1 was simulated. A line differential relay controlled algorithm as discussed in Section II was also moduled and used to protect a 10 km distribution line. Several faults were created at different locations and during both grid connected and islanding modes as shown in Figure 5.3. The findings are summerised in the results section.

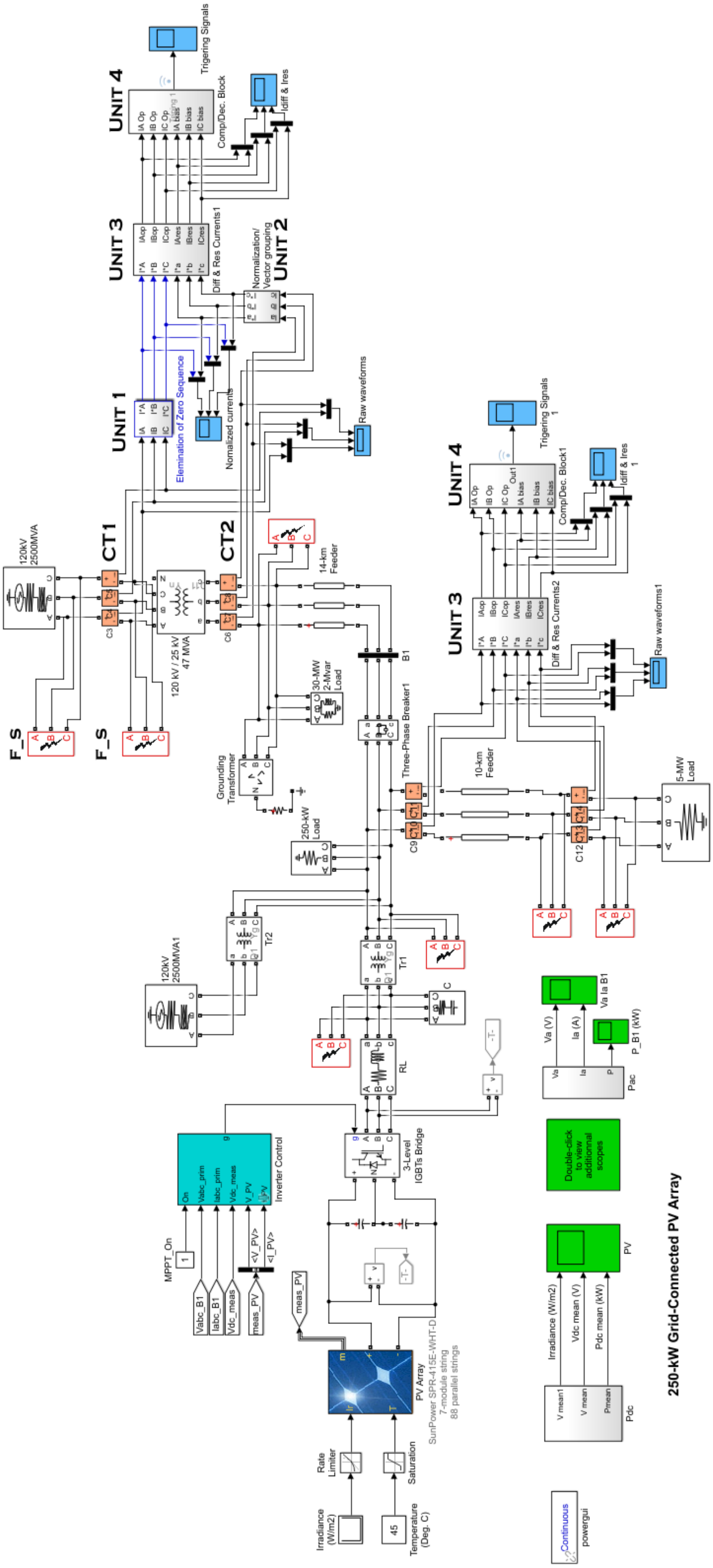


FIGURE 5.3: Simulink module for testing the functionality of the relay in grid and in islanding modes

5.4 Experimental Procedures

An experimental platform was also designed using modules and LabVIEW. As has been describe in the previous chapters, the same hardwares for the transformer differential relay: Data acquisition modules, Short circuit module, Voltage regulator module, Transmission and Distribution Lines modules, and the variable resistive load were used. These modules were arranged as in schematic diagram shown in Figure 5.4. Figure 5.5 show the picture of the arrange Modules. In this figure the LabVIEW program in the PC was not connected

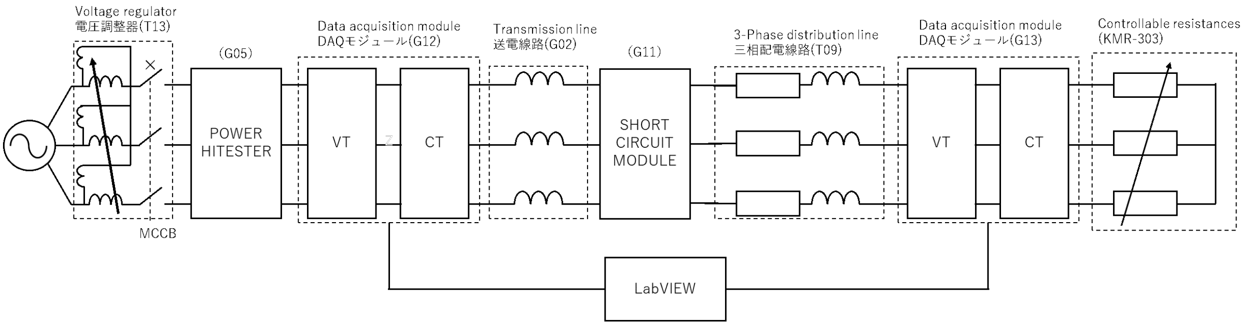


FIGURE 5.4: Arrangement of modules for line differential relay

FIGURE 5.5: Arrangement of modules for line differential relay

The control algorithm was implemented using LabVIEW software just as the transformer differential relay. refer to chapter 3 of this thesis. However, in this case the LabVIEW algorithm units were designed to reflect transmission parameters. For example, in line differential relay, the unit for phase shift correction is not necessary.

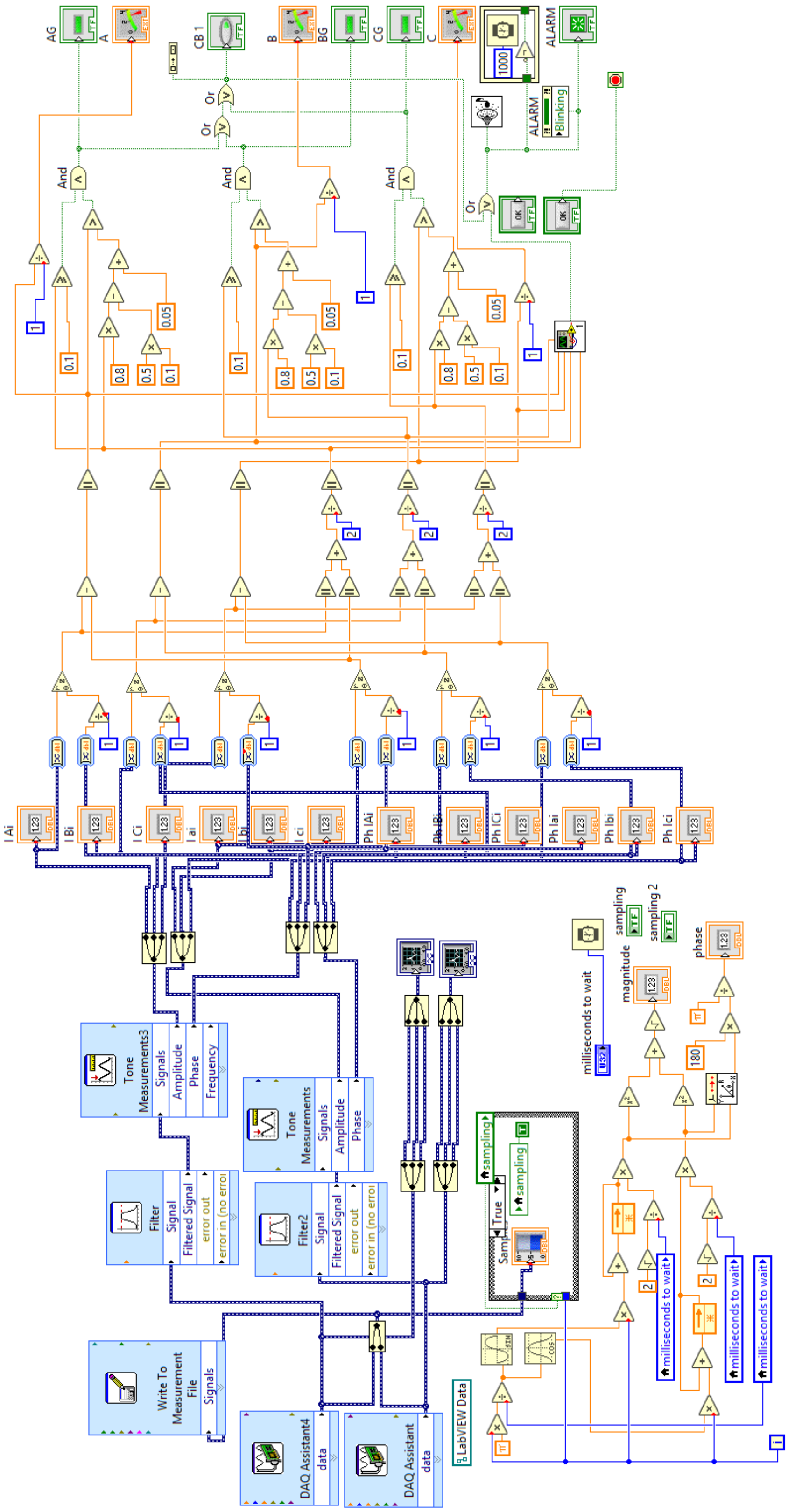
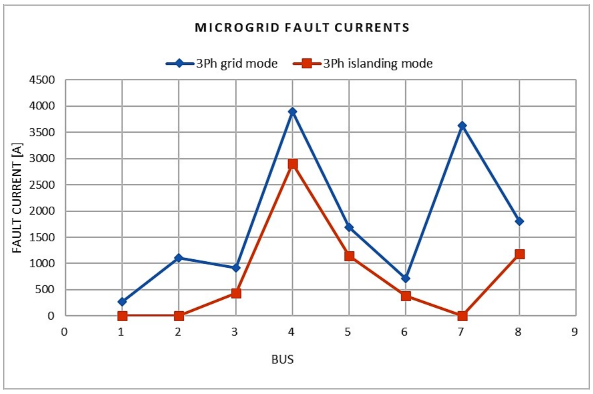


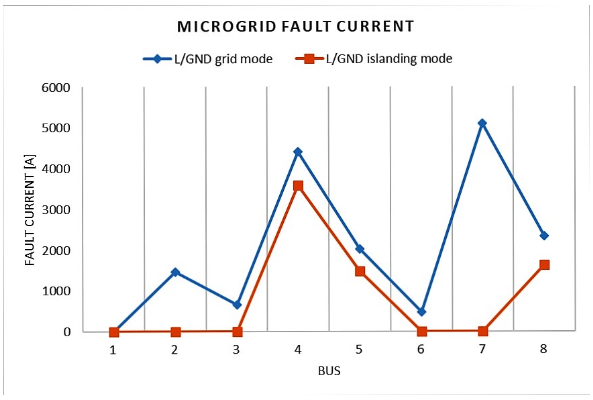
FIGURE 5.6: LabVIEW program for line differential relay

5.5 Simulation Results

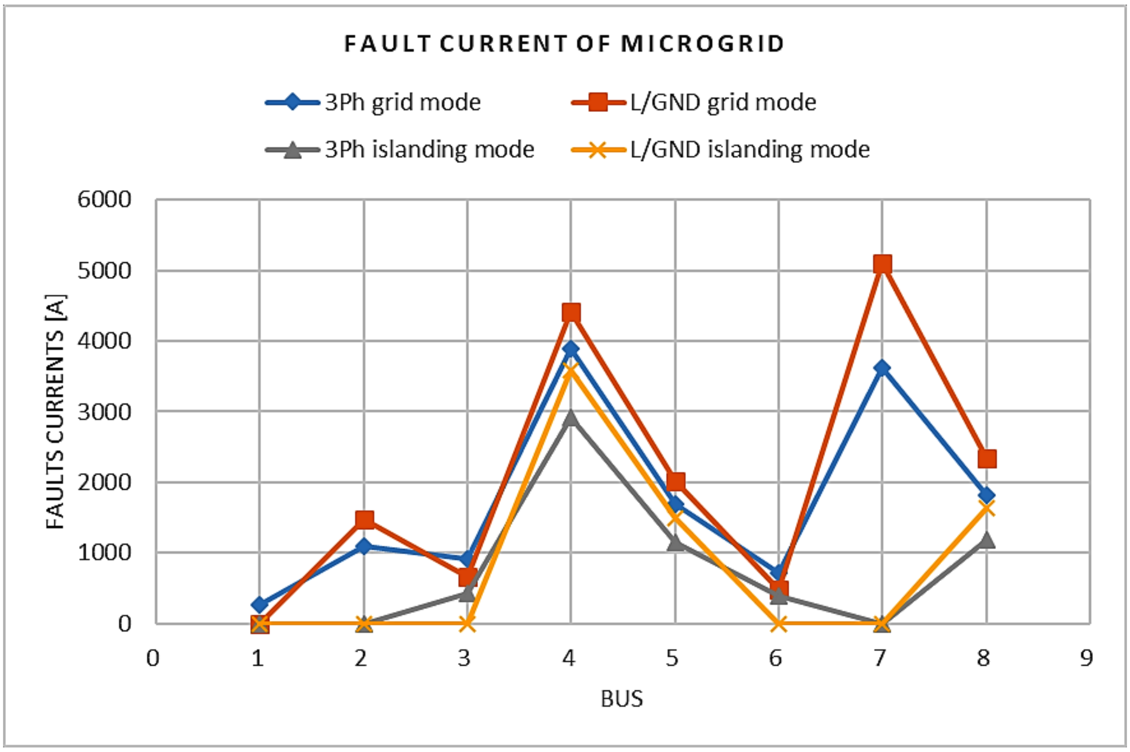
The available fault current on each node during grid connected were significantly higher compared to during islanding mode as shown on Figure 5.7 (A)(B) and (C). Bus 1 and 2 has 120 kV and 25 kV respectively and are on the main grid, that is why no fault current during islanding mode. Bus 3 and 6 are 25 kV buses and are on the distribution line. While Bus 4, 5, 7, and 8 are 6.6 kV and are the DGs and Load buses.



(A) 3 phase fault currents



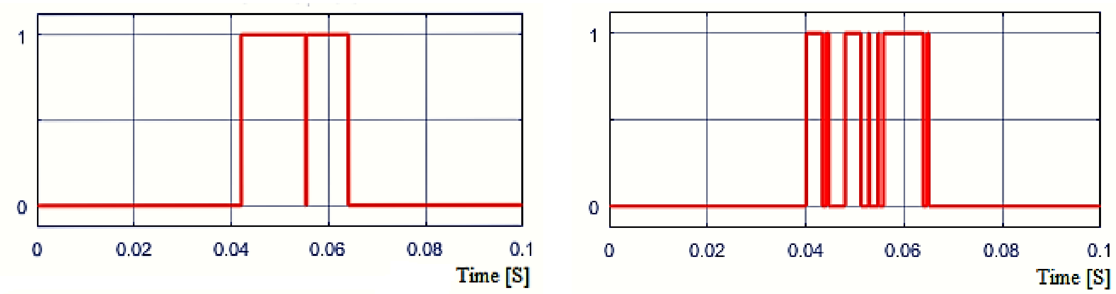
(B) Line to ground faults currents



(C) Combine 3 Phase and line to ground

FIGURE 5.7: Variation of fault currents in grid, and islanding modes of microgrid

The line differential relay set for internal faults during Grid connected mode was able to positively response to a similar fault during islanding conditions.
Figure 5.8 shows the relay trip signals in both grid connected and islanding mode.



(A) Grid connected mode

(B) Islanding mode

FIGURE 5.8: Simulated relay trip signals

5.6 Experimental Results

The experiment was successfully conducted. However we only use three phase 200V source and about 0.1 A. The short circuit current was up to 0.5A to avoid any hazardous effects on the electrical system in the laboratory or tripping of the main circuit breaker. Nonetheless the experimental results were as expected in the theory. Figure 5.9 shows the LabVIEW interface when the system is running normally, it can be seen that both the incoming current to the protected zone and the current leaving the zone are balanced (same magnitude and phase). In this normal operation the differential current theoretically should be equal to zero, but due to some current losses in the transmission line, the differential current in this experiment is 0.072 A. Therefore, the threshold was set slightly above this value, at 0.25 A. The properties of the alarm were also investigated by increasing the line current by increasing the load. The differential current also increased and the alarms perfectly responded as observed on Figure 5.10.

The faults were then created, by short circuiting, using the short circuit module. First, Line A and Line B were short circuited and the interface is Figure 5.11. Then line A and Line C (Figure 5.12), Line B and Line C (Figure 5.13) and finally Line A to Line B to Line C as presented in Figure 5.14.

The last case was a short circuit done out of the zone, see Figure 5.15, the results is also in line with the principle of differential relay. The fault disturbance can be seen on the current signal, but the relay do not send trip signals.

This is because the external fault affects all the primary and secondary current equally and in the same direction, hence the different is approximately zero.

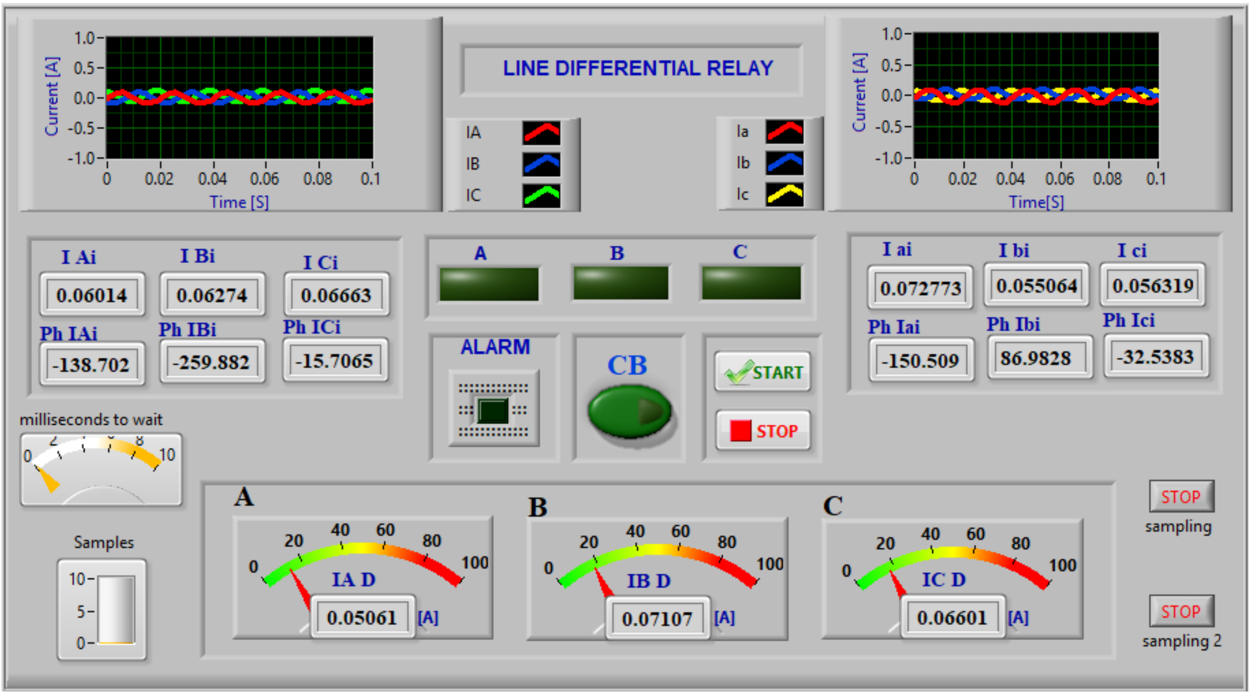


FIGURE 5.9: LabVIEW HMI for line differential relay experiment during a no fault (Normal) operation

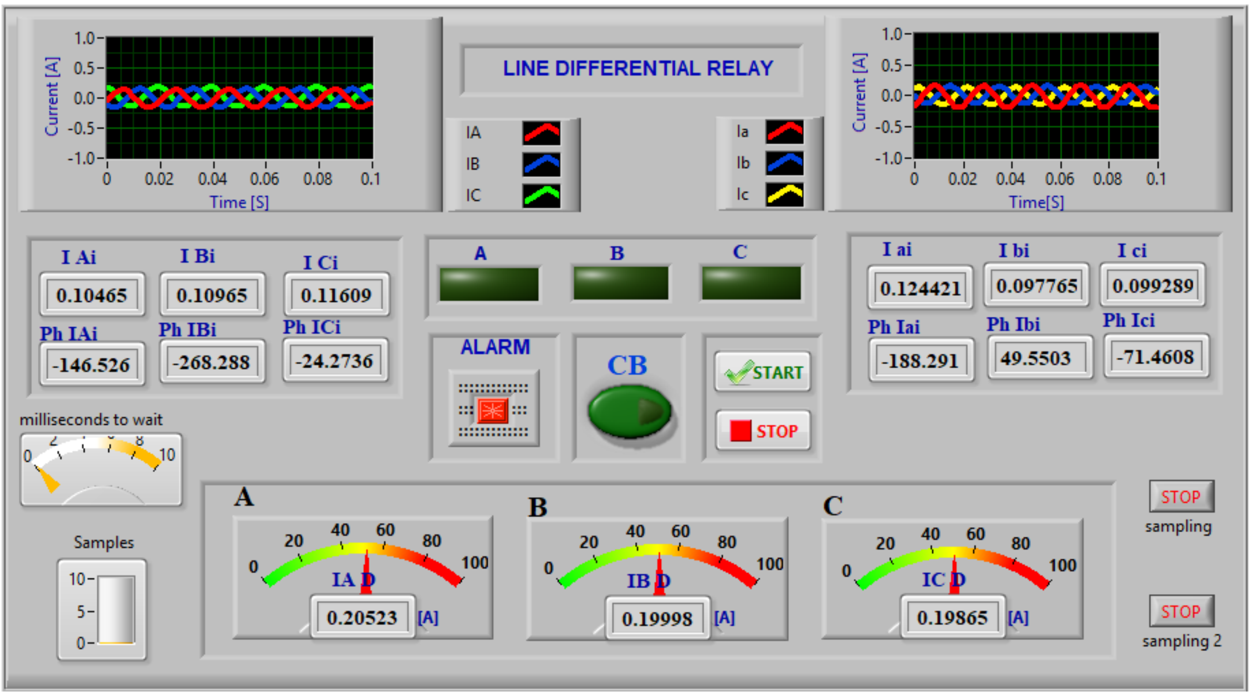


FIGURE 5.10: LabVIEW HMI for line differential relay experiment when the line current was raised

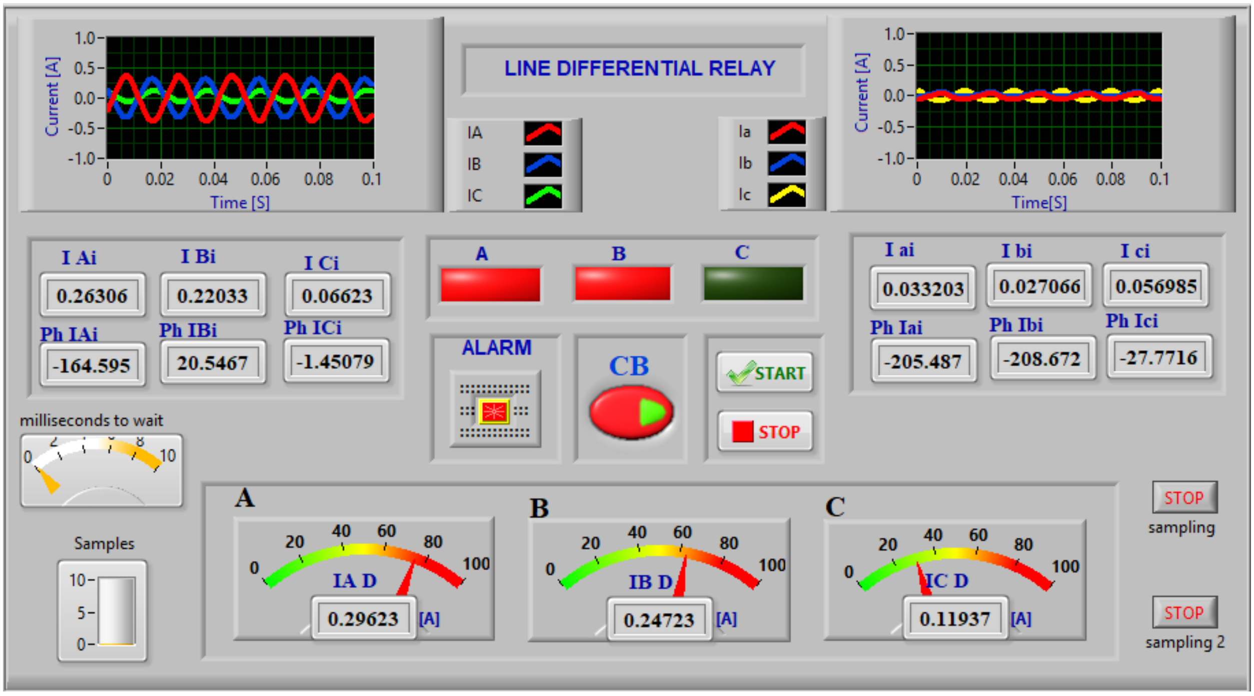


FIGURE 5.11: LabVIEW HMI for line differential relay experiment when a (L-L) between A-B fault is created

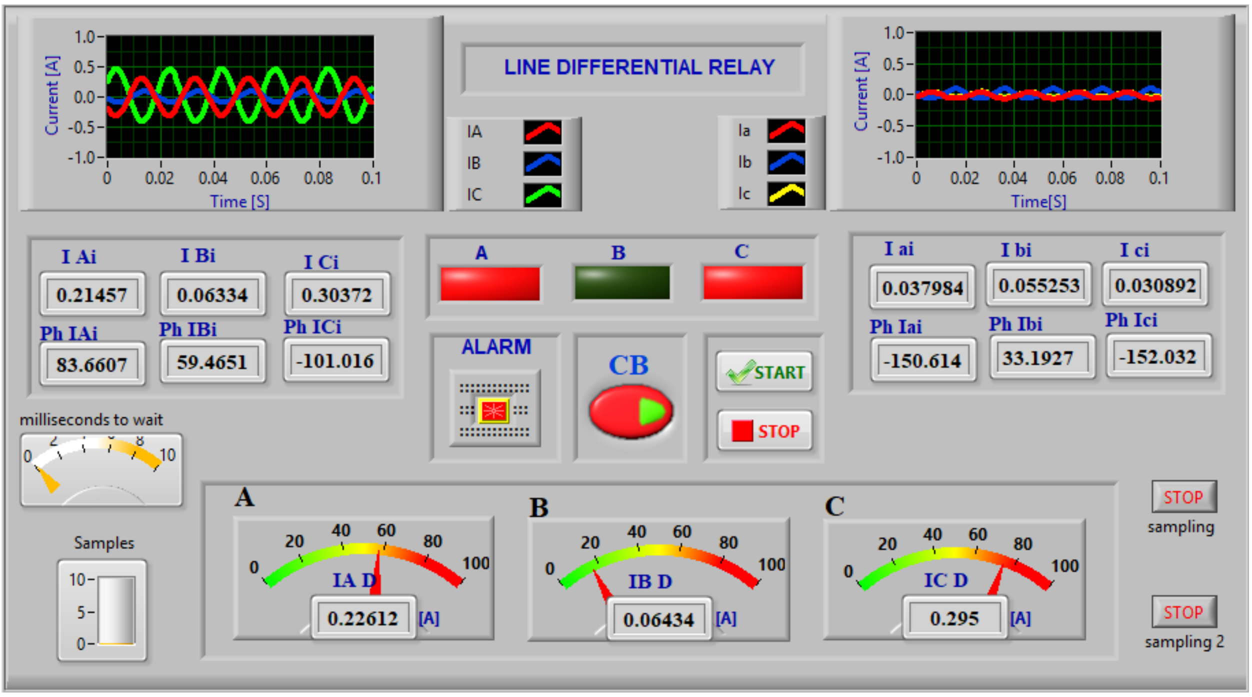


FIGURE 5.12: LabVIEW HMI for line differential relay experiment when a (L-L) between A-C fault is created

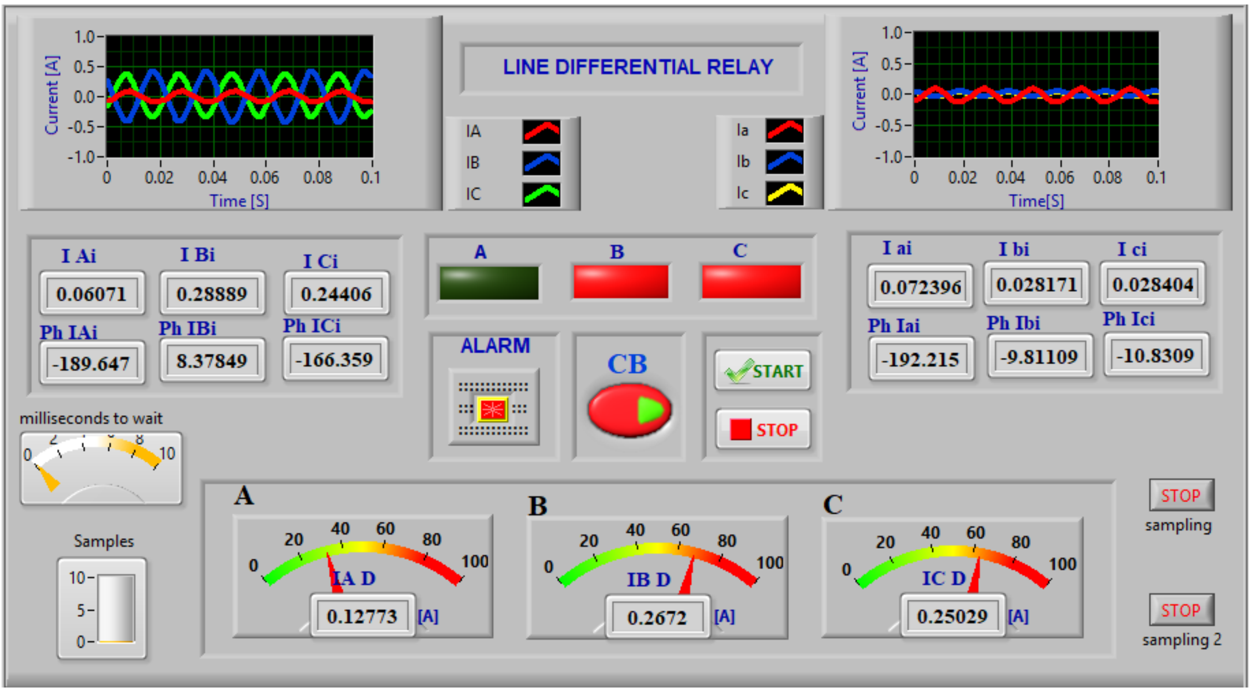


FIGURE 5.13: LabVIEW HMI for line differential relay experiment when a (L-L) between B-C fault is created

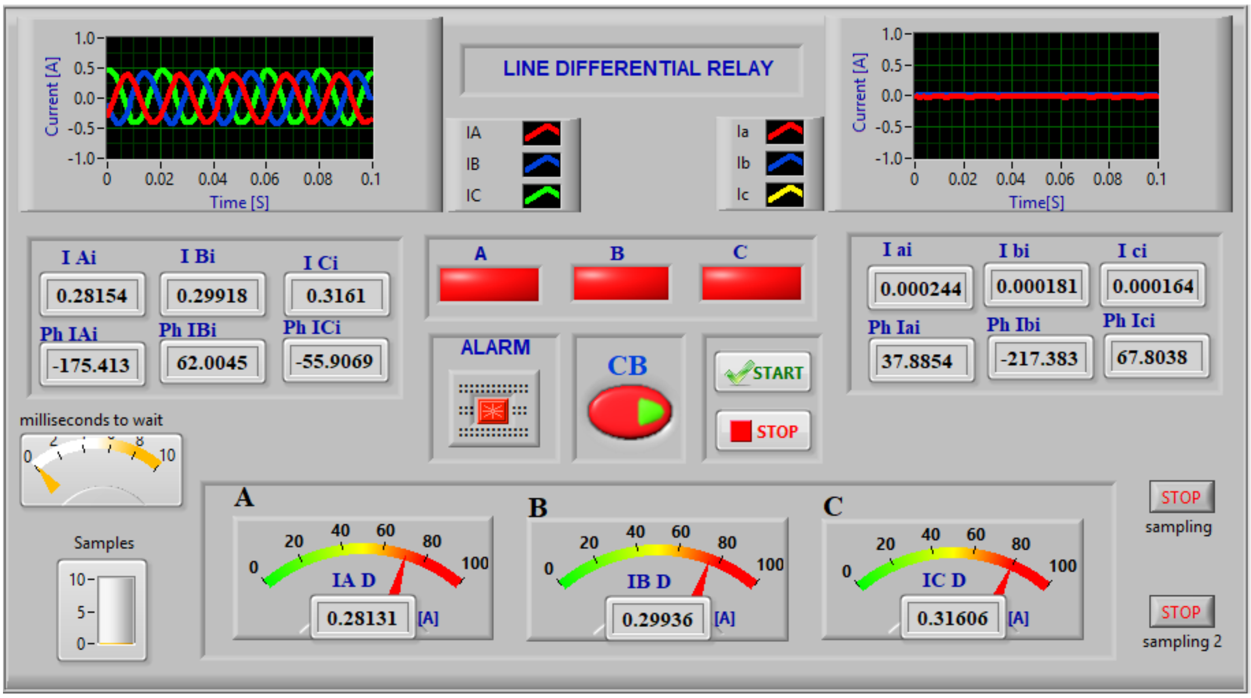


FIGURE 5.14: LabVIEW HMI for line differential relay experiment when a (L-L-L) between A-B-C fault occurs

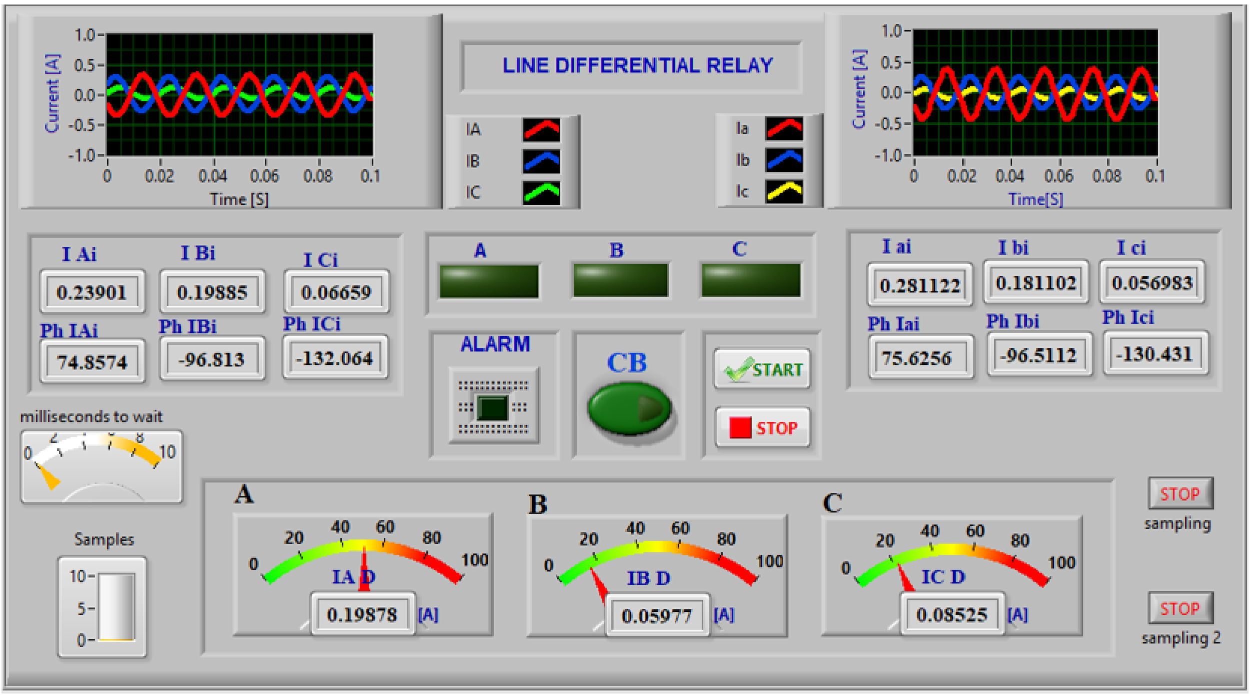


FIGURE 5.15: LabVIEW HMI for line differential relay experiment the faults is out of protection zone of the relay.

5.7 Summary

Simulation using SKM Power Tools (software) shows that during islanding mode of microgrid, the fault current decreases. Many relays, including over current relays set and or coordinated during the grid connected mode will malfunction in islanding mode. Therefore it requires re-settings. Furthermore, due to the mesh configuration of DERs, microgrids may experience bidirectional current flow, this will limit the used of directional relays Nonetheless, Line differential relay, base on the the facts that, it uses differential current for detecting the faults is proposed and being investigated on this study. Simulations shows that, indeed there is a current decrease in islanding mode. However, a differential relay set for microgrid lines during grid connected mode was able to operate on fault in the islanding mode. More studies are needed on CTs ratios and saturation, and communication channel delay and distortion.

One of the challenges in line differential relay is signals transmission. The protected zone which in this matter is a line, is so long, hence it requires a transmission media that does not distort the signals otherwise, it will malfunction.

CHAPTER 6

Conclusion and future works

6.1 Conclusion

Power system as a whole and power system protection in particular is on the rise in term of volume and technologies. The advancement is due to the continues invention of modern technologies especially in power electronics and semi conductors, sensors and communication(Internet). The dependent of life and economy on electricity is increasingly fastening. That is to say "no electricity no life". Due to this dependent, any blackout is a catastrophe of highest order. The economic cost of the August 2003 U.S blackout that resulted in the loss of $61,800$ MW of electric load was approximated at $7-10$ billion and idling over 100,000 workers. In another development, electrical and lighting equipment ranked second in the most common causes of fires in both commercial and residential building. The first being cooking equipment which in turn is indirectly electricity if not gas fueled.

In addition to proper design, sizing and many other aspects of electrical equipment, the power system protection is the most important attribute to prevent the development of faults or spread of its effects to other equipments. Therefore, there is a continues effort to improve protection system over the years. The protection relays have been shifted from Electromagnetic to Numerical and now trending in digital technology (digital relays). A lot of success have been registered in that regard.

The challenge remains in the teaching of power system in general and especially in power system protection, Many researches have pointed out that, for better understanding of protection courses, Lab sessions play greater roles. However, the type of the experimental platforms differ from industrial commercial model, to On-demand Model and to self-made model. As good and they are in some specific occasions, there are a handsome of disadvantages. For example, Commercial and on-demand models are expensive, difficult to update and repair, difficult to learn the internal design and the Self-made model are uneasy to arrange, exposure to electric shock, inconvenient interface, not flexible.

In the researches that were done to produce this thesis, emphases was put on the development of a suitable laboratory platform in the context of modularization of the devises and the controlling algorithm in form of software for teaching digital differential relay. This platform as discussed throughout the thesis incorporates both the software and hardware design of the platform. Other advantages of this platform are easiness to follow and understand the digital differential relay concept, easy to set up experiments, safe, cheap and flexible in term of usages (can be used for doing different types of experiments). It also takes a small space to keep and conduct experiment. The software design is accessible to learners and the GUI provides a user-friendly environment which allows a better interaction with trainees.

The module-based projects are suitable for power system engineering learning as Students are involved during the design and testing processes, which is good for Project Based Learning. In this era where digital relays are being widely deployed in power systems, it's important to train inexperienced and young electrical engineers as well, how to adjust and set different schemes of protection equipment. This platform offers a good opportunity in industry to train protection engineers and enrich them with new skills in power system protection in an efficient way and with minimum cost.

The developed model is able to execute the algorithm successfully and identify fault condition in the protection zone. It can also sent signals to the alarms and contactor relay to trigger them to actions.

6.2 Future works

For future work, the following points need to be research upon:

- Highly effective algorithm in the LabVIEW program that takes care of: CT saturation, inrush current, and harmonics.
- For complete package of power system protection, LabVIEW programs with algorithms for other types of relays need to be developed. Note: distance (MHO) relay is already developed in this laboratory.
- For line differential relay, a suitable compensation algorithms is needed to compensate the loses due to the long distance for current signals transmission.

APPENDIX A

Experiment Manual for Transformer Differential Relay

A.1 Transformer differential relay experiment manual

A.1.1 Purpose of experiment

The power transformer is one of the most important classes of hardware in the electric power system, and transformer protection is an essential part of the overall system protection strategy. Transformers suffer different types of stresses, due to both external hazards such as over load, overvoltage, and under frequency and internal faults such as overheating, over fluxing, overpressure, windings short circuit, and core and tank faults.

The most common form of the transformer protection is differential relay, which treats the transformer as a unit and only detects internal faults (faults in and around the transformer i.e within the CTs) Its tripping logic is based on Kirchhoff's current law. In this experiment, we shall investigate the tripping logic, faults contribution, and settings by using LabVIEW simulation of transformer differential relay and power system modules. The aim of this experiment is to detects, visualize the fault location, and provide tripping algorithm of differential relay by using LabVIEW. It can also be used to detect transformer ratio and vector group notation

A.1.2 Basic circuit

Refer to Figure 2.4 for general over view of differential relay, Figure 4.6 to show the schematic digram of the modules used in this experiment and finally Figure 4.7 to show the picture of arranged experiment.

A.1.3 Modules

The modules used are listed below. 1) Voltage regulator (T1) 2) Power HiTester (G05) 3) Transmission Line (G02) 4) Data acquisition module (G12) 5) Short-circuit module(G11) 6) Data acquisition module (G1) 7) Three-phase distribution line (T09) 8) 3 phase load (KMR-303) 9) LabVIEW program (PC) 10) Contactor relay Important pointIn the transmission line and three-phase distribution line, since the maximum current of the reactor is 2 A, a current exceeding it is not allowed to flow for a long time.

- Voltage regulator (T1)
- Power HiTester (G05)
- Transmission Line (G02)
- Data acquisition module (G12)
- Transformer Y D (T12)
- Short-circuit module(G11)
- Data acquisition module (G1)
- Three-phase distribution line (T09)
- 3 phase load (KMR-303)
- LabVIEW program (PC)

Important pointIn the transmission line and three-phase distribution line, since the maximum current of the reactor is 2 A, a current exceeding it is not allowed to flow for a long time.

A.1.4 Experimental procedures

- Connect the red, yellow, and blue wires on the voltage regulator to the main power.
- Next, connect the data acquisition module, transmission line, short-circuit module and the load bank from the left as shown on Fig.3. Be careful when wiring the modules (For example, red→red, blue→blue, yellow→yellow, etc). Be careful to not entangle wires since there are many. To prevent any accident or problem, ensure that the black wire is connected to the body-grounding terminal.
- After connecting, set the LabVIEW program

  Open “TXdiffDAQLabscale”.

  Click “Window” → “Show Block Diagram. A block diagram is displayed (Fig. A 4)

  Connect the G12DAQ module to the PC with a USB cable. When the screen as shown in Figure 5 pop up, delete it on x symbol.

Click “DAQ Assistant ” . Change all (Voltage 0 Voltage 2) “Terminal Configuration” to “RSE”. After making changes, click “OK”. “Building VI” is set, and the setting is completed

Connect the G13DAQ module to the PC with a USB cable

Click “DAQ Assistant ” .Change all “Terminal Configuration” to “RSE”. After making changes, click “OK”. At this time, note that selecting“DAQ Assistant” different from the previous one. “Building VI” is set, and the setting is completed.

Display the front panel. Click Run in the figure to confirm that it operates

- If nothing abnormal happen, increase the sending voltage to 20V for connection checking. Confirm if there is no noise or smell
- Increase the voltage up to 150V by adjusting the voltage regulator. Turn the load knob to the 0 step. Create the short circuit between phase A and phase B using short circuit module. For safety, the short circuit time shall be a maximum of 5 seconds. Confirm that it looks like Figure 10
- If you can confirm the above, LabVIEW is operating normally. If it does not work properly, set LabVIEW program according to (Fig. 11).
- Turn the load knob to the 2 step. Confirm that the current value has changed. After that, turn the load knob to the 3 step. Confirm that ALARM lights up
- Turn the load knob to the 1 step. Create the short circuit between phase A and phase B. At this time, confirm that CB 1 and CB 2 operate
- Decrease the voltage to 0V and disconnect the voltage regulator from the main source. Do not save the LabVIEW program.
- Set the LabVIEW program program (PC)

Open “TXdiffDAQLabscale”

Click “Window” → “Show Block Diagram. A block diagram is displayed

First of all, connect the G12 module to the PC. Delete “DAQ Assistant” in the block diagram on the screen

Connect the G12DAQ module to the PC with a USB cable. The following is how to connect a module to LabVIEW

Select “View” → “Functions Palette” → “DAQ Assistant[Input]”. “DAQ Assistant [Input]” can be selected by “Express” → “Input” → “DAQ Assist”.

Place “DAQ Assistant [Input]” back to its original position

Select “Acquire Signals”→“Analog Input”→“Voltage”→“ai1,ai2,ai3” of “Dev1(USB-6210)” and click “Finish”

Change all (Voltage 0 Voltage 2) “Terminal Configuration” to “RSE”. After making changes, click “OK”

Connect the wiring of “DAQ Assistant [Input]”.

Next, connect the module of G13 and the PC. Delete “DAQ Assistant” in the block diagram at the bottom of the screen

Connect the G13DAQ module to the PC with a USB cable. The following is how to connect a module to LabVIEW

Select “View” → “Functions Palette” → “DAQ Assistant[Input]”. “DAQ Assistant [Input]” can be selected by “Express” → “Input” → “DAQ Assist”.

Place “DAQ Assistant [Input]” back to its original position

Select ““Acquire Signals”→“Analog Input”→“Voltage”→“ai1,ai2,ai3” of “Dev3 (USB - 6210)” and click “Finish”

Change all “Terminal Configuration” to “RSE”. After making changes, click “OK”

Click Run in the figure to confirm that it operates

A.1.5 Discussion content

- About faults in substations,

  [A] What are the causes of faults in the transformer.

  [B] What are the types of Transformer faults.

  [C] What are the effects (results) of faults in the transformer.

  [D] Examine the remedy.

- Please let’s discuss.

  Find out the differences, merits, and demerits from other relays.

APPENDIX B

Experiment Manual for Line Differential Relay

B.1 Line differential relay experiment manual

B.1.1 Introduction

With the development of modern power system and the goal for combating climate change, usage of renewable resources as Distributed Energy resources (DERs) for Micro Grids is trending. For safe transmission High performance protection is becoming increasingly important. The current differential principle is considered superior in selectivity, sensitivity and speed of operation as compared with over current, directional comparison, phase comparison and stepped distance schemes. Therefore, the current differential scheme is widely used in power system protection, especially for transformers, busbars, and transmission lines.
Laboratory experiments for line differential relays in universities could help students to concretely understand line differential relay.

B.1.2 Basic circuit

Refer to Figures 2.6 to show the basic circuit and Figure 5.4 to show the experimental schematic circuit for differential relay. Figure 5.5 shows the state of the experiment.

B.1.3 Modules used in the experiments

The modules used are listed below.
1) Voltage regulator (T13)
2) Power HiTester (G05)
3) Data acquisition module (G12)
4) Transmission Line (G02)

5) Short-circuit module(G11)
6) Three-phase distribution line (T09)
7) Data acquisition module (G13)
8) 3 phase load (KMR-303)
9) LabVIEW program (PC)
Important point In the transmission line and three-phase distribution line, since the maximum current of the reactor is 2 A, a current exceeding it is not allowed to flow for a long time.

B.1.4 Experimental procedures

1) Connect the red, yellow, and blue wires on the voltage regulator to the main power.

2) Next, connect modules from the left as shown on Fig.3. Be careful when wiring the modules (For example, red→red, blue→blue, yellow→yellow, etc). Be careful to not entangle wires since there are many. To prevent any accident or problem, ensure that the black wire is connected to the body-grounding terminal.

3) After connecting, set the LabVIEW program in the PC.

3-1) Open the program folder "LINEdiffDAQLabscaled".
3-2) Click "Window" → "Show Block Diagram. A block diagram is displayed.

3-3) Connect the G12DAQ module to the PC with a USB cable.

3-4) Click "DAQ Assistant " . Change all (Voltage_0Voltage_2) "Terminal Configuration" to "RSE". After making changes, click "OK". "Building VI" is set, and the setting is completed.

3-5) Connect the G13DAQ module to the PC with a USB cable.
3-6) Click "DAQ Assistant " .Change all "Terminal Configuration" to "RSE". After making changes, click "OK". At this time, note that selecting"DAQ Assistant" different from the previous one. "Building VI" is set, and the setting is completed.

3-7) Display the front panel. Click Run in the figure to confirm that it operates.

4) If nothing abnormal happen, increase the sending voltage to 20V for connection checking. Confirm if there is no noise or smell.

5) Increase the voltage up to 150V by adjusting the voltage regulator. Turn the load knob to the 1 step. Create the short circuit between phase A and phase B using short circuit module. For safety, the short circuit time shall be a maximum of 5 seconds.

B.1.5 Result and discussion

Results

TABLE B.1: Table for filling in experiment results.

Fault Location	Fault Type	Id			Fault indicate			Alarm	Circuit Breaker	
		IdA	IdB	IdC	A	B	C		CB1	CB 2
No Fault	-									
In zone fault	AB									
In zone fault	AC									
In zone fault	BC									
In zone fault	ABC									
Out of Zone fault	AB									

Discussion

About faults in substations,
(A) What are the causes of line faults.
(B) What is the cause that make it occurred.
(C) Examine the remedy.
Please let's discuss.
Find out the differences, merits, and demerits from other relays.

APPENDIX C

Author's Biography

Lodu Moses Gabriel earned the Bachelor of Science "Honours" in Electrical Engineering from University of Juba, South Sudan in 2014. From 2015 to 2016, he was a teaching assistant at University of Juba. He is currently a Master student at Shibaura Institute of Technology, Japan, and a student member of The Institute of Electrical Engineers of Japan. His research interests include power system protection and stability.

Bibliography

[1] C. Russell Mason, "The Art and Science of Protective Relaying", Third Edition 2006

[2] J. Duncan Gover, Mulukutla S. Sarma, Thomas J. Overbye *"Power System Analysis and Design"*, 5^{th} edition - Cengage Learning, 2012.

[3] P. M. Anderson, "Power System Protection", *IEEE Power Engineering Series*, ISBN 0-7803-3427-2, 1998.

[4] Cesar Pasten, Juan Carlos Santamarina1, *"Energy and quality of life"*, energy policy Volume 49, October 2012, Pages 468-476

[5] S. Tamronglak, S. H. Horowitz, A. G. Phadke, J. S. Thorp *"ANATOMY OF POWER SYSTEM BLACKOUTS: PREVENTIVE RELAYING STRATEGIES"* , (Published Conference Proceedings style, IEEEexplorer) , IEEE Transactions on Power Delivery, Vol. 11, No. 2, April 1996.

[6] U.S.-Canada Power System Outage Task Force, *"Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations"*, April 2004.

[7] S. Brahma, J. De La Ree, J. Gers, A. A. Girgis, S. Horowitz, R. Hunt, M. Kezunovic, V. madaman, P. McLaren, A. g. Phadke, M. S. Sachdev, T. S. Sidhu, J. S. Thorp, S. S. Venkata, and T. Wiedmamn *"The Education and Training of Future Protection Engineers: Challenges, Opportunities and Solutions"*, IEEE Transactions on Power Delivery, Vol. 24, No.2, April 2009.

[8] Farhad Shahnia, Moayed Moghbel, Hadi Hosseinian Yengejeh, *Motivating Power System Protection Course Students by Practical and Computer-Based Activities*, IEEE TRANSACTIONS ON EDUCATION, VOL. 59, NO. 2, MAY 2016

[9] Mladen Kezunovic, *"The Role of Digital Modeling and Simulation in Power Engineering Education"*, IEEE Transactions on Power Systems, Vol. 19, No.1, February 2004.

[10] J. Ren, M. Kezunovic, *"Modeling and simulation Tools for teaching Protective Relaying Design and application for the Smart Grid"*, Modern Electric Power Systems 2010, Wroclaw, Poland

[11] J. Lewis Blackburn,*"Protective Relaying"*, Marcel Dekker Inc., 1987.

[12] Abdelkader Abdelmoumene; Hamid Bentarzi *"A review on protective relays' developments and trends "*, Signals and Systems Laboratory, IGEE, Boumerdes University, Algeria J. energy South. Afr. vol.25 n.2 Cape Town May. 2014

[13] Qiushi Wang, Zhenmin Tang, Ivan Knezevic, Jicheng Yu, George Karady *Power System Protection Education and Digital Relay Training Based on a Physical Platform*, North American Power Symposium (NAPS), 2016: IEEE Xplore: 21 November 2016

[14] James H. Harlow *Electric Power Transformer Engineering*, Second Edition - 2007

[15] *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition

[16] A. Smolarczyk, and E. Bartosiewicz *" Modeling Differential Protections of Power Transformers and Their Testing Using PSCAD/EMTDC Software"*, International Journal of Systems Applications, Engineering and Development, Issue 3, Vol. 7, 2013.

[17] Quintin VerZosa, Jr. and Wah A. Lee *" Testing Microprocessor-Based Numerical Transformer Differential Protection*,IEEE Transactions on industry Applications, Vol. 53, No.1, January/February 2017.

[18] Power Systems Relay Committee of the IEEE Power Engineering Society *IEEE Guide for Protective Relay Applications to Power Transformers*, IEEE Std C37.91-2000

[19] Hydro-Quebec *SimPowerSystems 5 User's Guide* MATLAB SIMULINK, The Mathworks 2009

[20] Stephen P. Tubbs, P.E. *LabVIEW for Electrical Engineers and Technologists*, 1344 Firwood Dr. Pittsdurgh, PA 15243, ISBN 978-0-9819753-3-7,

[21] T. Hoshino, and G. Fujita, "Visualization of Electric Power by Module-Type Power System Training Device ", in *International Universities' Power Engineering Conference (UPEC 2013)*, Dublin, Ireland, Sept. 2013. IEEEhowto:kopka

[22] Y. Hitotsumatsu, and G. Fujita, *"Proposal of New Module-style Power System Training Device "*, in International Universities' Power Engineering Conference (UPEC 2012), London, UK, Sept. 2012.

[23] D.T. Ton, M.A. Smith *"The U.S. department of energy's microgrid initiative"* Electr J, 25 (2012), pp. 84-94, 10.1016/j.tej.2012.09.013

[24] Matthias Huber, Florian Sanger, Thomas Hamacher, *"Coordinating Smart Homes in Microgrids: A Quantification of Benefits"*, IEEE PES ISGT Europe 2013

[25] Anestis G. Anastasiadis, Antonios G. Tsikalakis, Nikos D. Hatziargyriou *"Operational and Environmental Benefits Due to Significant Penetration of Microgrids and Topology Sensitivity"*, 2010 IEEE

[26] N. D. Hatziargyriou, A. G. Anastasiadis1, J. Vasiljevska2, A. G. Tsikalakis1 *"Quantification of Economic, Environmental and Operational Benefits of Microgrids"*, IEEE 2009.

[27] Johan Driesen, Pieter Vermeyen, Ronnie Belmans *"Protection Issues in Microgrids with Multiple Distributed Generation Units"*,2007 IEEE.

[28] Manjula Dewadasa, Arindam Ghosh, Gerard Ledwich *"Protection of Micrigrid Using Differential Relays"*,

[29] LabVIEW 2016 , *"User Manual"*, National Instruments, 11500 North Mopac Expressway Austin, Texas 78759-3504, USA.

[30] Szilárd Enyedi, *"Electric cars — Challenges and trends"*, 2018 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR), July 2018.

[31] P. G. McLaren, K. Mustaphi, G. Benmouyal, S. Chano, A. Girgis, C. Henville, M. Kezunovic, L. Kojovic, R. Marttila, M. Meisinger, G. Michel, M. S. Sachdev, V. Skendzic, T. S. Sidhu, and D. Tziouvaras, *"Software Models for Relays "*, IEEE Transactions on Power Delivery, Vol. 16, No. 12, April 2001, pp. 238-45.

[32] Sandro Gianny Aquiles Perez, *"Modeling Relays for Power System Protection Studies"*, Ph.D Research, University of Saskatchewan, Saskatchewan, Canada, July 2006.

[33] SKM PTW V8.0, *"Power Tools for Windows V8.0 User's Guide"*, Electrical Engineering Analysis Software forWindows, SKM Systems Analysis, Inc., PO Box 3376, Manhattan Beach, CA 90266-1376, USA.

[34] J. Grice, M. Peer and G. T. Morris, *"Today's aging workforce - Who will fill their shoes?"*, in *64th Annual Conference for Protective Relay Engineers*, College Station, TX, USA , 2011.

[35] J. Gover and P. Huray, *"Educating 21st Century Engineers"*, in *"Meeting the Growing Demand for Engineers and Their Educators 2010-2020 International Summit"*, Munich, Germany, 2007.

[36] T. Sidhu and M. Sachdev, *"A graduate program in power system protection"*, in Power Engineering Society Summer Meeting, Seattle, WA, USA 2000.

[37] G. Joos, *"The role of laboratory exercises in power engineering education - an opportunity to integrate industrial concepts"*, in IEEE Power and Energy Society General Meeting (GM 2008), Pittsburgh, PA, USA, Jul. 2008.

[38] N. Hosseinzadeh, M. R. Hesamzadeh, M. Korki,, *"Role of Laboratory in the Education of Modern Power Systems"*, in IEEE Power and Energy Society General Meeting (GM 2011), San Diego, CA, USA, Jul. 2011.

[39] S. Mohagheghi, R.H. Alaileh, G.J. Cokkinides and A.P. Sakis Meliopoulos, *"A Laboratory Setup for a Substation Scaled Model"*, Power Tech Lausanne, 2007.

[40] Arun G. James S. THorp, Mulukutla S. Sarma, Thomas J. Overbye *"Computer relaying for Power Systems"*, Second Edition - 2009.

Publications

1. Lodu Moses Gabriel, G. Fujita: *"A Module-Based Educational Platform for Transformer Differential Digital Relay Design and Experimentation"* proceedings in the 10th IEEE PES Asia-Pacific Power and Energy Engineering Conference 2018 (APPEEC)), Kota Kinabalu, Malaysia, 7-10 October 2018.

2. Lodu Moses Gabriel, Yamashita CHIHO, G. Fujita: *"Effectiveness of line differential relay in microgrid protection"*, proceedings in the 11th Vietnam-Japan scientific exchange meeting, Sendai, Japan, 15 September 2018.

3. Lodu Moses Gabriel, G. Fujita: *"Modeling and Visualization of Transformer Differential Relay using LabVIEW for Module-Based Learning"* proceedings in the 12th South East Asian Technical University Consortium Symposium (SEATUC), Yog Yakarta, Indonesia, 12-13 March 2018.