



**DISTANCE PROTECTION FUNCTIONAL TESTING FOR A 33KV TRACTION NETWORK
USING HARDWARE IN THE LOOP REAL-TIME SIMULATION**

by

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ABSTRACT

The thesis focuses on designing a distance protection scheme for a medium-voltage system (33kV). Transmission and distribution lines form a critical part of the power system infrastructure. The reliability and high performance of these lines are essential for the efficient transmission of electrical power. To ensure the integrity of the infrastructure, power system protection schemes are crucial. High-level standards and knowledge are necessary for designing effective protection schemes. The thesis centers around the design of a distance protection scheme for a medium-voltage system operating at 33kV. While line differential and overcurrent protection schemes are common for medium voltage systems, the study introduces the Mho distance scheme for short distribution lines.

The 4-bus IEEE network serves as the basis for simulation in DigSilent and RSCAD power simulation software. Two distinct protection relay testing techniques are developed: Laboratory relay testing and Hardware-in-the-loop simulation using the RTDS (Real-Time Digital Simulator) simulator.

The primary goal is to prevent significant damage to the 33kV network infrastructure during abnormal conditions. The Mho distance scheme is applied specifically to protect short distribution lines operating at 33kV. Simulations are conducted using DigSilent and RSCAD, demonstrating a comprehensive analysis of the designed protection scheme. Laboratory relay testing involves physical testing of protection functional on mho distance relays. The hardware-in-the-loop simulation uses the RTDS simulator to emulate real-world conditions for testing the protection scheme.

In summary, the thesis contributes to the field of power system protection by proposing a Mho distance protection scheme for short distribution lines in a medium-voltage system. The comprehensive approach includes simulation in two software tools and the development of relay testing techniques to validate the effectiveness of the proposed mho distance protection scheme. This research is valuable for enhancing the reliability and performance of medium-voltage power systems.

Keywords: Distance protection, Distribution line protection, Mho characteristics, IEC 61850 standard, substation communication, RTDS simulator.

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DEDICATION

This Thesis is dedicated to my wife Unako Nkalitshana and my firstborn Botshelo Mivuyo Nkalitshana.

Thank you for your support and unconditional LOVE.

TABLE OF CONTENT

CPUT copyright information.....	i
DECLARATION	ii
ABSTRACT.....	iii
ACKNOWLEDGEMENTS	iv
DEDICATION	v
LIST OF FIGURES.....	x
LIST OF TABLES	xiii
LIST OF APPENDICES	xv
GLOSSARY	xvii
CHAPTER ONE.....	1
INTRODUCTION	1
1.1 Introduction.....	1
1.2 Awareness of the problem	2
1.3 Problem statement	3
1.3.1 Sub-problems.....	4
1.4 Research aims and objectives	4
1.4.1 Research Aims	4
1.4.2 Research Objectives	5
1.5 Hypothesis.....	5
1.6 Delimitations of the Research	6
1.7 Motivation for the research project	7
1.8 Assumptions.....	7
1.9 Research Methodology.....	8
1.9.1 Literature Review	8
1.9.2 Data Collection.....	8
1.9.3 Modelling and Simulations.....	9
1.9.4 Lab scale test bench, for testing distance relay functionality.....	9
1.9.5 Hardware in the loop (HIL) simulation setup	10
1.10 Thesis Chapters.....	10
1.11 Conclusion.....	11
CHAPTER TWO	12

LITERATURE REVIEW	12
2.1 Introduction.....	12
2.2 Power quality effects on electrical network protection schemes.....	12
2.3 Distance Protection Scheme Overview.....	13
2.4 Distance relays implementation methods and generations of technology	15
2.4.1 Electromagnetic	15
2.4.2 Solid State.....	15
2.4.3 Digital distance relays(microprocessor)	15
2.4.4 Distance relay Characteristics curves.....	16
2.4.4.1 Impedance relay characteristic	16
2.4.4.2 Mho relay characteristic	17
2.4.4.3 Quadrilateral relay characteristic	18
2.4.5 Impedance Calculation Methods	19
2.5 Protective relay test in a real-time digital simulator (RTDS) environment.....	25
2.5.1 Closed-loop HIL testing method in RTDS.	25
2.5.2 Open loop testing method in RTDS.	26
2.7 IEC 61850 Challenges.....	31
2.8 Conclusion.....	31
CHAPTER THREE	33
SIMULATION OF THE DISTANCE PROTECTION SCHEME FOR 33KV DISTRIBUTION NETWORK.	33
3.1 Introduction.....	33
3.2 IEEE 4- Bus system	33
3.3 Load flow analyses.....	36
3.4 Case studies for load flow analysis:	39
3.4.1 Case Study One:	39
3.4.2 Case Study Two:	39
3.4.3 Case Study Three:	39
3.5 Short circuit current.....	44
3.6 Distance Protection Scheme	49
3.7 Distance Relay Settings Configuration	50
3.8 Distance Protection Simulation Results.....	52
3.8.1 Case Study 1:.....	53
3.8.2 Case Study 2:.....	58

3.9	A comparative analysis of the proposed distance protection scheme compared to the benchmark model of a Gautrain study.....	63
3.10	Breaker failure trip logic of the proposed protection relays.....	64
3.11	Discussion of Results	65
3.12	Conclusion.....	65
CHAPTER FOUR		66
IMPLEMENTATION OF THE LAB SCALE TEST BENCH TO TEST DISTANCE PROTECTION SCHEMES FOR THE 33kV DISTRIBUTION NETWORK.....		66
4.1	Introduction.....	66
4.2	Protection settings on a numerical distance relay.....	66
4.2.1	Development of the laboratory test bench	68
4.2.2	Case Study One: line 1 and Line 2 protection design	69
4.2.2.1	OMICRON test universe setup for testing distance relay	76
4.2.2.2	Configuration of the Test Object.....	76
4.2.2.3	Mho relay settings for phase and ground faults	77
4.2.2.4	Practical Experiment Results	78
4.2.3	Case Study Two: line 3 protection design.....	84
4.2.3.1	Practical experiment results for case study two	86
4.2.4	Benchmark Table.....	89
4.3	Conclusion.....	90
CHAPTER FIVE.....		91
IMPLEMENTATION OF THE HARDWARE-IN-THE-LOOP TESTING OF A DISTANCE PROTECTION SCHEME FOR A 33KV TRACTION NETWORK		91
5.1	Introduction.....	91
5.2	RSCAD Software for Network Modelling	92
5.3	Real-time digital simulator (RTDS)	92
5.4	PRASA Three-Bus network modeled on RSCAD software.....	94
5.5	Implementation of the developed protection scheme in RTDS Hardware in the loop (HIL)	95
5.5.1	Instrument Transformers (VT and CT)	96
5.5.1.1	Current Transformer (CT)	96
5.5.1.2	Voltage Transformer (VT).....	97
5.5.1.3	Distance Protective Relay.....	98
5.5.2	Lab-scale setup for HIL implementation.....	99
5.5.2.1	GTAO card	101

5.5.2.2	GTFPI card.....	102
5.5.2.3	Modelling and configuration of fault logic control circuit.....	103
5.5.2.4	Modelling and configuration of circuit breaker logic.....	106
5.5.3	HIL simulation results for Phase-to-ground fault occurring in zone 1 of relay 1. 107	
5.5.3.1	Case Study 1: Voltage and current measurements during normal conditions: 108	
5.5.3.2	Case Study 2: Voltage and current measurements during single phase to ground fault conditions.	111
5.5.3.3	Case Study 2: Voltage and Current Measurements During Double-Phase Fault Conditions.....	116
5.5.3.4	Case Study 4: Voltage and Current Measurements During Three-Phase Fault Conditions.....	119
5.6	Discussion on Simulation for all four Case Studies	124
5.7	Conclusion.....	125
CHAPTER SIX.....		127
CONCLUSION.....		127
6.1	Introduction.....	127
6.2	Deliverables.....	128
6.2.1	Literature Review	128
6.2.2	DigSILENT simulation and implementation of the distance protection scheme for 33kV traction distribution network	128
6.2.3	Implementation of the lab scale test bench to test distance protection schemes for the 33kv distribution network.	129
6.2.4	Implementation of the hardware-in-the-loop test bench to test the distance protection schemes for a 33kV traction network.	129
6.3	Academic and industrial applications	130
6.4	Future work	130
6.5	Conclusion.....	130
6.6	Publications	131
BIBLIOGRAPHY		132
APPENDIX		135

LIST OF FIGURES

Figure 1.1: Single-line diagram of traction power system network under study.....	3
Figure 1.2: Lab-scale test bench setup.....	9
Figure 1.3: Implemented hardware-in-the-loop using RTDS simulator.	10
Figure 2.1: Illustration of distance protection zones (Camarillo-Penaranda et al., 2021).....	13
Figure 2.2: Distance protection steps for two zone 1 and zone 2 set in the relay(Abouelenin et al., 2017).....	14
Figure 2.3: Microprocessor-based distance relay(Kasztenny & Finney, 2008).....	16
Figure 2.4: Typical characteristics curve for impedance relay(WG B5.15, 2008)	17
Figure 2.5: Typical characteristics curve for Mho distance relay(Ali et al., 2013)	18
Figure 2.6: Quadrilateral characteristics curve of a distance relay(WG B5.15, 2008)	19
Figure 2.7: Reviewed distance protection papers vs year of publication.....	21
Figure 2.8: HIL closed-loop testing of two distance protection relays(Arnold et al., 2015)	26
Figure 2.9: Open-loop testing of distance protection relay in RTDS simulator.	27
Figure 3.1: Single-Line Diagram of the 4 Bus System.	34
Figure 3.2: Single-Line Diagram network in DigSILENT environment.....	38
Figure 3.3: percentage voltage deviation for all three case studies in all buses.....	43
Figure 3.4: Flow chart Short Circuit Analyses (Handono et al., 2019).....	46
Figure 3.5: Symmetrical and Unsymmetrical faults comparison at the same locations	49
Figure 3.6: Distance protection scheme with three zones(Krishnamurthy & Van Wyk, 2015) ...	50
Figure 3.7: System layout.....	52
Figure 3.8: Time distance plot for Relay 1 and Relay 2	54
Figure 3.9: Mho results for Relay 1 and Relay 2 for three-phase fault.	56
Figure 3.10: Mho results for Relay 1 and Relay 2 for single-phase-ground fault.....	57
Figure 3.11: Time distance plot for Relay 3 and Relay 4	60
Figure 3.12: Mho characteristics curve for relay 3 and relay 4 for three-phase fault.	61
Figure 3.13: Mho curve for relay 3 and relay 4 for single-phase-ground fault.	62
Figure 3.14: SEL 421 Breaker failure trip logic (SEL 2016).	64
Figure 4.1: Electrical network under study.....	67
Figure 4.2: Test universe laboratory test setup.....	68
Figure 4.3: Laboratory test setup connections between devices	69
Figure 4.4: Zone 1 Mho phase distance element logic diagram(SEL 2016).....	72
Figure 4.5: Zone 2 Mho phase distance element logic diagram(SEL, 2016).....	73

Figure 4.6: Zone 1 Mho ground distance element logic diagram(SEL, 2016).	74
Figure 4.7: Zone 2 Mho ground distance element logic diagram(SEL, 2016).	75
Figure 4.8: Test setup connections for testing distance protection functionality.....	76
Figure 4.9: Single phase to earth fault test results.....	79
Figure 4.10: Single phase to ground fault events downloaded from the relay for zone 1.	79
Figure 4.11: Single phase to ground fault events downloaded from the relay for zone 2.	80
Figure 4.12: Single phase to ground fault events downloaded from the relay for zone 3.	81
Figure 4.13: Three phase fault events extracted from the relay for zone 1.	82
Figure 4.14: Three phase fault events extracted from the relay for zone 2.	82
Figure 4.15: Three phase fault events downloaded from the relay in zone 3.	83
Figure 4.16: Power system network under study for protection design.....	85
Figure 4.17: Zone 1 phase-to-earth events from the relay.....	87
Figure 4.18: Zone 2 phase-to-earth events from the relay.....	88
Figure 4.19: Zone 1 three-phase fault events from the relay.	88
Figure 4.20: Zone 2 three-phase fault events from the relay.	89
Figure 5.1: RTDS hardware in CSAEMS lab at Cape Peninsula University of Technology.....	93
Figure 5.2: PRASA Three-Bus system modeled in RSCAD software.	94
Figure 5.3: Single-line diagram of a power system.....	96
Figure 5.4: SEL 421 Engineering configuration	98
Figure 5.5: Single-line diagram of power system for a simulated network in RSCAD	100
Figure 5.6: Hardware-in-the-loop lab-scale setup for testing distance protection relays	100
Figure 5.7: GTAO card used in RTDS simulator and RSCAD software for HIL testing.	101
Figure 5.8: GTFPI card used in RTDS simulator and RSCAD software for HIL testing.....	103
Figure 5.9: Single phase to ground fault logic.....	104
Figure 5.10: Single phase to ground fault logic configuration and settings.	104
Figure 5.11: Three-phase (A) and Double-phase (B) design fault logic	105
Figure 5.12: Double-phase fault logic configuration.....	105
Figure 5.13: Circuit breaker control logic to control circuit breaker 1 and circuit breaker 2 status.	106
Figure 5.14: Power system in RSCAD software	108
Figure 5.15: The power system measured voltage and current by VT1 and CT1 respectively.	109
Figure 5.16: The voltage measured waveforms by VT1 during normal state.	110
Figure 5.17: The current measured waveforms by CT1 during normal state.	111

Figure 5.18: Voltage during a single-phase fault in zone 1 of line 1.....	112
Figure 5.19: Single-phase fault current results in zone 1 of the line 1.....	113
Figure 5.20: SEL 421 HMI view indicating single phase to ground fault trip.....	114
Figure 5.21: SEL 421 event report for a single phase-to-ground fault of relay	115
Figure 5.22: Voltage results during a double-phase fault in zone 1 of line 1.	116
Figure 5.23: Current results during a double-phase fault in zone 1 of line 1.	117
Figure 5.24: SEL 421 HMI view indicating double phase to ground fault trip.	118
Figure 5.25: Double-phase fault event report from relay 1.....	119
Figure 5.26: Voltage results during a three-phase fault in zone 1 of line 1.....	120
Figure 5.27: Current results during a three-phase fault in zone 1 of line 1.....	121
Figure 5.28: SEL 421 HMI view indicating three-phase fault trip.....	122
Figure 5.29: Three-phase fault event report from relay 1.....	123

LIST OF TABLES

Table 2.1: Voltage and current combinations for detecting phase-to-phase faults.	20
Table 2.2: Voltage and current combinations for detecting phase-to-ground faults.	20
Table 2.3: Comparative table of some reviewed papers and their objectives.....	22
Table 2.4: RTDS-based publications and their aim of study in close-loop and open-loop testing methods.	28
Table 3.1: External grid data.....	34
Table 3.2: IEEE 4-bus data.....	35
Table 3.3: Load demand data.	35
Table 3.4: Transmission line data.	36
Table 3.5: Three-phase system voltage measured in all substation buses when all lines are in service.	40
Table 3.6: Loading percentage of transmission lines during normal conditions.....	40
Table 3.7: Three-phase system voltage measured in all substation buses when line 3 is out of service.	41
Table 3.8: Loading percentage of transmission lines when distribution line number three is out of service.	41
Table 3.9: Three-phase system voltage measured in all substations bus when circuit breaker one (CB1) is opened.	42
Table 3.10: Loading percentage of transmission lines for case study three.	43
Table 3.11: Types of short circuits that affect electrical networks (IEC International standard 60909, 2001).....	45
Table 3.12: Minimum Fault Level for Unsymmetrical (Unsy) and Symmetrical (Sy) faults.....	48
Table 3.13: Protective device type and measuring instruments.	51
Table 3.14: Power system data and transmission line length.....	51
Table 3.15: Mho distance protection settings for Relay 1 and Relay 2.....	53
Table 3.16: Fault locations and Relays protecting line 1 and line 2.....	55
Table 3.17: Relay 1 and Relay 2 results for a three-phase fault in line 1.....	56
Table 3.18: Relay 1 and Relay 2 results for a single-phase-ground fault in line 2	58
Table 3.19: Mho distance protection settings for relay 3	58
Table 3.20: Relay 3 and Relay 4 results for a three-phase fault in line 3.....	62
Table 3.21: Relay 3 and Relay 4 results for a single-phase-ground fault in line 3	63
Table 3.22: Comparison of protection settings for two different studies	64
Table 4.1: Technical details for instrument transformers.....	67

Table 4.2a: General and line configuration data	70
Table 4.2b: Relay protection setting configurations.	70
Table 4.2c: Output and trip logic configuration.....	71
Table 4.3: Device settings for test object function in test universe software.....	77
Table 4.4: Relay settings in test universe software	77
Table 4.5: Relay operation test points summary	78
Table 4.6: Relay operation summary for case study one.	84
Table 4.7: Relay settings configured using AcSELerator software and inserted into the relay. .	85
Table 4.8: Omicron settings configuration using test universe software.....	86
Table 4.9: Relay operation test points summary	86
Table 4.10: Relay operation summary for case study two.....	89
Table 4.11: Comparison of distance relay time tripping comparison for two relays of different studies	90
Table 5.1: Load flow results for both RSCAD and DigSilent simulations.....	95
Table 5.2: Current transformer data.....	96
Table 5.3: Voltage transformer data	97
Table 5.4: GTAO parameter description	102
Table 5.5: Description of components used to build circuit breaker control logic.....	106
Table 5.6: Node Voltage and primary current mapping with the VT1 & CT1 in RSCAD	109
Table 5.7: RTDS simulation results compared with the DigSilent simulation results.	124
Table 5.8: Benchmark literature versus obtained findings of this research.....	124

LIST OF APPENDICES

APPENDIX A: DIGSILENT PARSA NETWORK LOAD FLOW SIMULATION RESULTS FOR DIFFERENT LOADING CONDITIONS	135
1. Appendix A.1: Three-phase system voltage measured in all substation buses when all lines are in service.	135
2. Appendix A.2: Loading percentage of transmission lines during normal conditions....	135
3. Appendix A.3: Loading percentage of transmission lines when line 3 is out of service.....	136
4. Appendix A.4: Three-phase system voltage measured in all substations bus when line 1 is out of service.	136
5. Appendix A.5: Loading percentage of transmission lines when the section between main 2 and Goodwood substation is out of service.	137
6. Appendix A.6: IEC standard used to calculate load flow on DigSilent software.	137
APPENDIX B: SEL 421 DISTANCE RELAY ENGINEERING CONFIGURATION SETTINGS	138
1. Appendix B.1: Line configuration in AcSELerator quickset software for relay settings configuration	138
2. Appendix B.2: Mho Phase distance zones, impedance, and time element settings for SEL 421 relay 1&2.	139
3. Appendix B.3: Mho Ground distance zones, impedance, and time element settings for SEL 421 relay 1 & 2	140
4. Appendix B.4: Trip logic and Main Board configuration	141
5. Appendix B.5: Mho Phase distance zones, impedance, and time element settings for SEL 421 relay 3&4.	142
6. Appendix B.6: Mho Ground distance zones, impedance, and time element settings for SEL 421 relay 3&4.	143
APPENDIX C: TEST UNIVERSE DISTANCE RELAY ENGINEERING CONFIGURATION SETTINGS.....	144
1. Appendix C.1: Omicron CMC configuration to test protection relays	144
2. Appendix C.2: Test univers test results for three-phase fault in line 1 and line 2	147
3. Appendix C.3: Test univers test results for three-phase fault in line 3	147

APPENDIX D: RSCAD PARSANETWORK MODELLING AND SIMULATION RESULTS.....	148
1. Appendix D.1: RSCAD modelled network	148
2. Appendix D.2: Circuit breaker status on the RSCAD network	148
3. Appendix D.3: RSCAD Breaker control pushbuttons	149
4. Appendix D.4: RSCAD Measured voltage (L-L), and current by CT1 and VT1	149
5. Appendix D.5: RSCAD Line configuration settings	150
6. Appendix D.6: RSCAD current transformer configuration.....	150
7. Appendix D.7: RSCAD voltage transformer configuration	151
APPENDIX E: CMD AND SEL 421 RELAY HMI COMMUNICATION	151
1. Appendix E.1: Communication establishment between a laptop and RTDS Simulator	151
2. Appendix E.2: Communication establishment between a laptop and the SEL 421 relay	152
3. Appendix E.3: HMI view of an SEL 421 protection settings during conditions when there is no fault in one line.	152
APPENDIX F: REAL-TIME DIGITAL SIMULATOR (RTDS) GTAOCARD CONFIGURATIONS AND HARDWARE-IN-THE-LOOP SIMULATION SETUP IN CSAEMS LAB AT CPUT	153
1. Appendix F.1: GTAOCard of the RTDS simulator found in CPUT CSAEMS research lab.....	153
2. Appendix F.2: Hardware-in-the-loop setup implemented for testing the SEL 421 distance relays.....	153

GLOSSARY

TERMS / ABBREVIATIONS	Definition/ Explanation
IED:	Intelligent Electronic Device
SEL 421	Distance protection automation control produced by SCHWEITZER ENGINEERING LABORATORIES
RSCAD	A power simulation software
RTDS	Real-time digital simulator
DigSILENT	A power system simulation tool
AcSELerator Quickset	An engineering software used to configure SEL products
CMC 256 plus	A secondary test set that is used to inject voltage and current when testing the relays
CMS 156	A voltage and current amplifier produced by OMICRON
GTO	Gigabit processor card
GTAO	Gigabit twelve-channel analogue output card
GTNET	Gigabit transceiver network interface card
GTFPI	Gigabit transceiver front panel interface card
GTWIF	Gigabit transceiver workstation interface card
IEEE	Institute of Electrical and Electronic Engineers
CPUT	Cape Peninsula University of Technology
HIL	Hardware-in-the-loop
CB	Circuit Breaker
CT	Current Transformer
VT	Voltage Transformer
OHTE	Over Head Track Equipment
PRASA	Passenger Rail Agency of South Africa
CSAEMS	Centre for Substation Automation and Energy Management Systems
GOOSE	Generic Object-Oriented Substation Events
SAS	Substation Automation Systems

IEC	International Electrotechnical Commission
IEC 61850 standard	A substation communication standard
ACSI	Abstract Communication Service Interface
SC	Short Circuit
CTR	Current Transformer ratio
VTR	Voltage Transformer ratio
L-G	Single-phase to-ground faults
L-L-G	Double phase to ground faults
L-L-L-G	Three-phase to-ground faults
NFRQ	Nominal Frequency
PHROT	Phase rotation
SID	Substation Identifier
RID	Relay Identifier
Z1MAG	Positive sequence impedance magnitude
Z1ANG	Positive sequence angle
Z0MAG	Zero sequence impedance magnitude
Z0ANG	Zero sequence angle

CHAPTER ONE

INTRODUCTION

1.1 Introduction

An electrical system is made up of expensive electrical components that are prone to damage during abnormal system conditions. The study will concentrate on hardware-in-the-loop testing methods as well as lab-scale setups for simulation, protection settings design, and testing of distance relays. Because of its benefits, the distance protection scheme has been selected as the recommended protection method for the PRASA 33kV distribution network. In this research work, the distance protection scheme is examined for short and medium-voltage systems to assess the relay functional testing and protection requirements.

This study is conducted on a 33kV traction network owned by the state company known as PRASA which is responsible for passenger train service. This network is a short network that distributes power to all traction DC substations that are directly connected to the DC network (catenary system) that is feeding power to the electric train. The current protection system of this 33kV traction network has the following shortfalls:

- **Defective Protection mechanism:** this can result in power outages even in the absence of line faults.
- **Incorrect protection settings:** the settings of the relays are designed incorrectly, in most cases main protection scheme (distance relays) does not trip for the fault on the line, and the faults are always cleared by the backup protection relays (overcurrent relays).

In this research, new protection engineering configuration settings for distance relays are designed and tested for the protection functionality. The new fourth-generation numerical relays with modern technology are used in this study to substitute the old second-generation electromagnetic relays currently used to protect the PRASA network.

DigSilent power system model was conducted to examine, assess, and compare the system parameters under operating settings. Digsilent distance protection strategy was designed to verify that the relay settings are accurate and to determine relay operating times to satisfy the distance relay protection requirements. The protection settings were created and tested on the DigSilent

power system simulation tool, and then they were configured into the SEL 421 relay in the CSAEMS lab at CPUT. It is crucial to ensure that the settings are tested and assessed on a lab scale before being placed on the relay protecting the PRASA network.

The hardware-in-the-loop protection simulation has been developed to test the relay functionality on a real-time simulator, this is done to evaluate the relay settings and relay functionality on a real-time embedded system. Implementing the recommendations made in this study will improve the speed and reliability of the protective relaying system for the 33kV distribution network.

This chapter provides awareness of the problem and a description of the distribution network in section 1.2, the problem statement in section 1.3, the research aims and objectives in section 1.4, the hypothesis in section 1.5, the research design and methodology in section 1.9 and the thesis breakdown structure in section 1.10.

1.2 Awareness of the problem

The study is done on PRASA's distribution network. Passenger Rail Agency of South Africa (PRASA) objective is to transport commuters to their destination. This organization runs electrical locomotives which use DC motors. The 33kV distribution network is fed from the main substation which is an interfacing point between PRASA's network and ESKOM network. This substation is the main source of power for the railway network in the Western Cape region. The focus of this study will be on the protection of the 33kV network that is currently protected by a distance protection scheme that uses the old electromagnetic relays. Since the 33kV distribution network is the main supply for the railway system, the efficiency, reliability, and integrity of the network can never be compromised. The PRASA network must be reliable, efficient, and a safe cost-effective transportation system for all rail passengers in South Africa.

An appropriately designed protection system is required because the present 33kV network protection scheme at PRASA is not working well. The scope of this research work outcomes will reduce power outages, prevent damage to the system equipment, and enhance train service. The organization's (PRASA) core goals are jeopardized when the protection relays malfunction, making the system unreliable and inefficient. A typical traction power system structure is shown in Figure 1.1. the load receives electrical power from the traction substation, which is supplied by the 33kV traction distribution network.

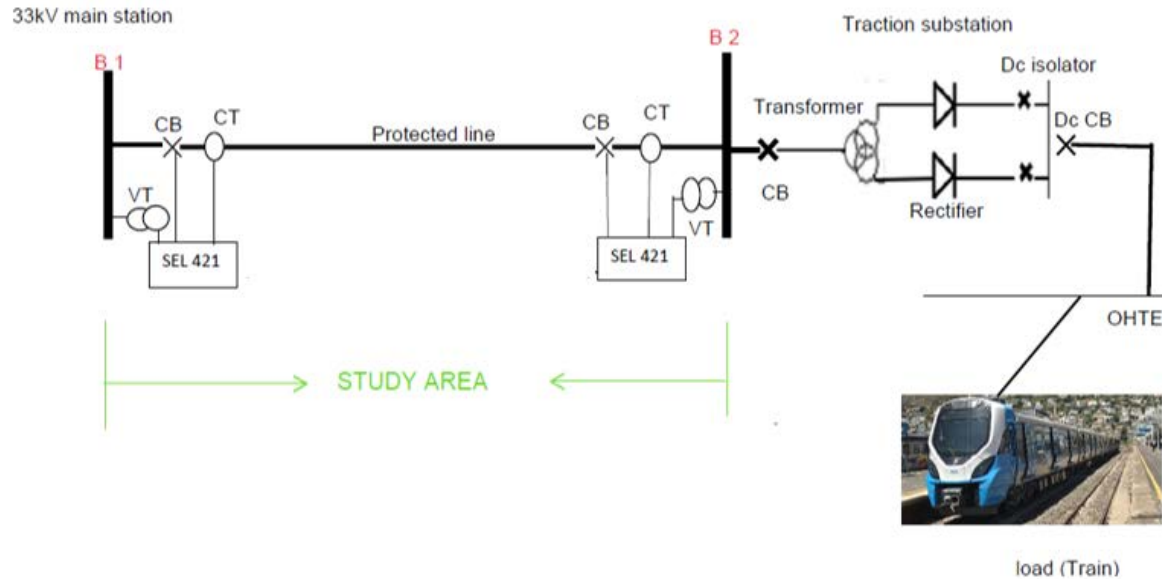


Figure 1.1: Single-line diagram of traction power system network under study

Figure 1.1 further presents the focus area (line protection between Bus 1 and Bus 2) of this study.

Where:

CB is a Circuit Breaker

VT is a Voltage Transformer

CT is a Current Transformer

SEL 421 is a Protection relay

B is Bus bar

DC is a Direct current

OHE is Overhead track equipment

1.3 Problem statement

The thesis study focuses on improving the existing distance protection scheme for the PRASA 33kV network. The old electromagnetic distance protection relays are currently utilized to protect the 33kV PARSA traction network which produces false trip signals because of low fault resistance, and small voltage at the relay location.

The above-mentioned research problem is addressed in the thesis through newly developed protection engineering configurations for the proposed distance protection relay. In addition to

that, the study tested the developed distance protection engineering configurations in the hardware-in-the-loop protection functional testing using RTDS and SEL relays at the CSAEMS lab at CPUT.

The distance protection scheme is mostly used for its high-speed fault-clearing capabilities. The transmission and distribution lines are one of the most valuable and important equipment of the power system, so these lines need to be protected against short circuit currents to maintain the stability of the system(Hosseini Moghadam et al., 2021). Power transmission and distribution line experiences a lot of disturbances and contingencies in their path due to different environmental conditions (Yamuna and Thresia, 2022)

Research problem statement: The old electromagnetic distance protection relays used to protect the 33kV traction distribution network produce false trip signals because of low fault resistance, small voltage at the relay location, current, and voltage harmonics. Traditional electromagnetic distance protection relays when used to power transmission lines are prone to the effects of fault resistance(Vaidya & Venikar, 2013).

1.3.1 Sub-problems

- Investigate the performance of the distance protection scheme for short and medium-voltage systems.
- Investigate the existing 33kV traction network protection engineering configuration settings.
- Investigate Mho distance relay application in short and medium voltage system

1.4 Research aims and objectives

1.4.1 Research aims

The research aims to simulate, investigate, design protection configuration settings, and develop a testing method for a 33kV distribution network protection system. This research further aims to utilize the distance protection relays with the capability of monitoring, metering, control, and data exchange abilities. The research also aims to develop a protection scheme that meets the crucial requirements of the protection system which include selectivity, sensitivity, speed, and reliability to protect the PRASA network.

1.4.2 Research Objectives

The research objectives include conducting a literature review, power system modeling and simulation, distance protection engineering configuration setting, laboratory scale test bench development for testing the relay functionality, and hardware-in-the-loop embedded system development for relay testing.

The main Research objectives are listed below:

1. Conduct a **literature review** on distance protection and transformer overcurrent protection schemes for distribution systems.
2. **Model the 33kV distribution system in the DigSilent** software and study load flow, fault current, and protection (line distance) configuration settings for different system operating conditions.
3. Implement the **lab-scale test bench setup** to test the 33kV line distance relay configuration settings, relay functional and characteristics testing, and analyze its simulation results.
4. Implement the **Hardware-in-the-Loop lab-scale setup** and test the distance relay functional characteristics using Real-Time Digital Simulator (RTDS) and protection relays in the closed-loop simulation.

1.5 Hypothesis

SEL 421 distance protection relays with new technology and improved protection settings are utilized to solve the present relay malfunctions in the 33kV PARSA traction network. A lab-scale setup is developed to test the protection settings and relay functionality. The setup consists of devices such as CMC 256 plus Omicron secondary injection test set, SEL 421 distance relay, laptop, and an ethernet switch. The real-time simulation was done to identify the performance and evaluate the behavior of the protection scheme using an RTDS simulator.

To evaluate the configured protection settings and relay operation, a lab-scale setup is established in the CSAEMS lab at CPUT. The lab scale setup consists of CMC 256 with Omicron secondary injection test set, SEL 421 distance relay, and Ethernet switch are part of the configuration. Using an RTDS simulator, a real-time simulation was conducted to study the effect and assess the mho distance relay protection characteristics.

1.6 Delimitations of the Research

This research project is limited to the following:

- Modelling of the PARSA 4-bus power system using DigSilent and RSCAD power system simulation tool.
- Development of a protection lab-scale test bench using SEL421 relay and secondary test injection devices.
- Implementation of the hardware-in-the-loop protection testing using RTDS simulator, Amplifiers, and SEL421 relay in the closed loop simulations.
- The distance protection relay functional testing is limited to the SEL vendor in this research work, however same principles could be utilized for other vendor relay engineering configurations.
- The existing PARSA network investigated Circular Mho distance relay characteristics for functional testing, therefore Offset Mho, Polarized Mho, and Polygonal (quadrilateral) are not part of the investigations.
- The distance relay backup protection directional overcurrent functionality is limited in this research work.
- The PARSA network is not equipped with modern protection technology, i.e. without IEC61850 substation automation concepts, therefore Thesis is limited to hardware-in-the-loop simulation with RTDS.
- The PARSA network maximum line length is about 16km, therefore Thesis only conducted distance protection functional testing on Zone 1 for LG, LL, and three-phase fault conditions.

This research did not cover the following to manage and limit the scope of work:

- Overcurrent protection schemes: the overcurrent relay has some drawbacks such as lack of selectivity and lack of sensitivity for transient currents.
- Line differential protection schemes: this protection scheme is suitable for very short distribution lines
- Traction and power transformer protection: these transformers are protected using overcurrent and earth fault relays
- Harmonic analysis and power quality: power quality is a study on its own, therefore the focus of this research does not include it.

1.7 Motivation for the research project

The conducted research will benefit PRASA as it aims to identify ways to improve the performance of the system. Further intentions of the research are to provide technical solutions related to this critical infrastructure for an organization responsible for providing a cheap and reliable mode of transport for commuters.

In addition, technology is changing at a very high rate, and electrical system digitalization and modernization are common languages worldwide. Implementing the recommendations of this research will assist PRASA in modernizing its electrical system using relevant technologies.

1.8 Assumptions

This research work is conducted under the following assumptions:

- The distance protection scheme is mostly used and applicable to high voltage and long transmission lines.
- Phase rotation of the electrical system under study is ABC
- Distance relay can be configured to protect multiple zones of the line where zone 1 should be set to operate with no time delays.
- Voltage transformer connection is a STAR configuration, the STAR connection provides a neutral point that can be earthed to safeguard the device.
- 33 kV PARSA network is modeled and simulated in both DigSilent and RTDS power system simulation tools.
- CT secondary currents configured at 5A with a current scaling of 25A set in the GTAO card for real-time simulation using RTDS. 5 Amp CT has less burden and more accurate for short distribution lines in comparison with 1A CT.
- VT secondary voltages configured at 110V with voltage current scaling of 250 V set in GTAO card for real-time simulation using RTDS.
- Circular Mho impedance characteristics are used to configure the distance protection relay in this research work, in this curve, the fault area is well-defined, and it can be set to protect the line in both directions forward and reverse.

- Zone 1 protection is tested for symmetrical and unsymmetrical faults, to evaluate the speed of the relay as it is expected to trip very quickly in this zone.
- The distance relay should only operate and clear a fault occurring in the protected zones of the line. Not tripping for the out-zone faults.
- Hardware-in-the-loop (HIL) implementation provides more realistic results since the network under study is simulated on a real-time basis using an RTDS simulator to test the functionality of the protection relays.

1.9 Research Methodology

By examining the distance protection plan through a literature analysis, this research aims to propose a well-designed protection strategy for a 33kV traction network. The network under examination has new protection configuration settings that are created and put into effect. DigSilent and RSCAD software tools are used in network modeling and simulation. Developed engineering configuration settings in the DigSilent environment are validated in the HIL protection simulation using RTDS, amplifiers, and 421 SEL relay in the CSAEMS lab at CPUT.

1.9.1 Literature review

The literature review indicates that there are several protection schemes and methods for electrical equipment used in the power system structure. A literature review studied line distance and transformer overcurrent protection schemes for distribution systems and IEC61850 standard and GOOSE message applications for the distribution system. The information gathered for this research is from scientific and engineering publications such as IEEE conference papers, books, relay manuals, and technical journals.

1.9.2 Data collection

The technical data of the existing PARSA network have been collected and analyzed. These parameters were used to simulate and model the network in the (DigSilent & RSCAD) simulation software.

1.9.3 Modelling and Simulations

Load flow analysis was conducted for the 33kV PARSA network using two simulation software tools (DigSilent & RSCAD), distance protection schemes were developed in the simulation tool, and software relays were configured for the protection of the system against faults. Protection functionality has been tested and results were analysed.

1.9.4 Lab scale test bench, for testing distance relay functionality

The lab-scale test bench has been developed as indicated in Figure 1.2 below.

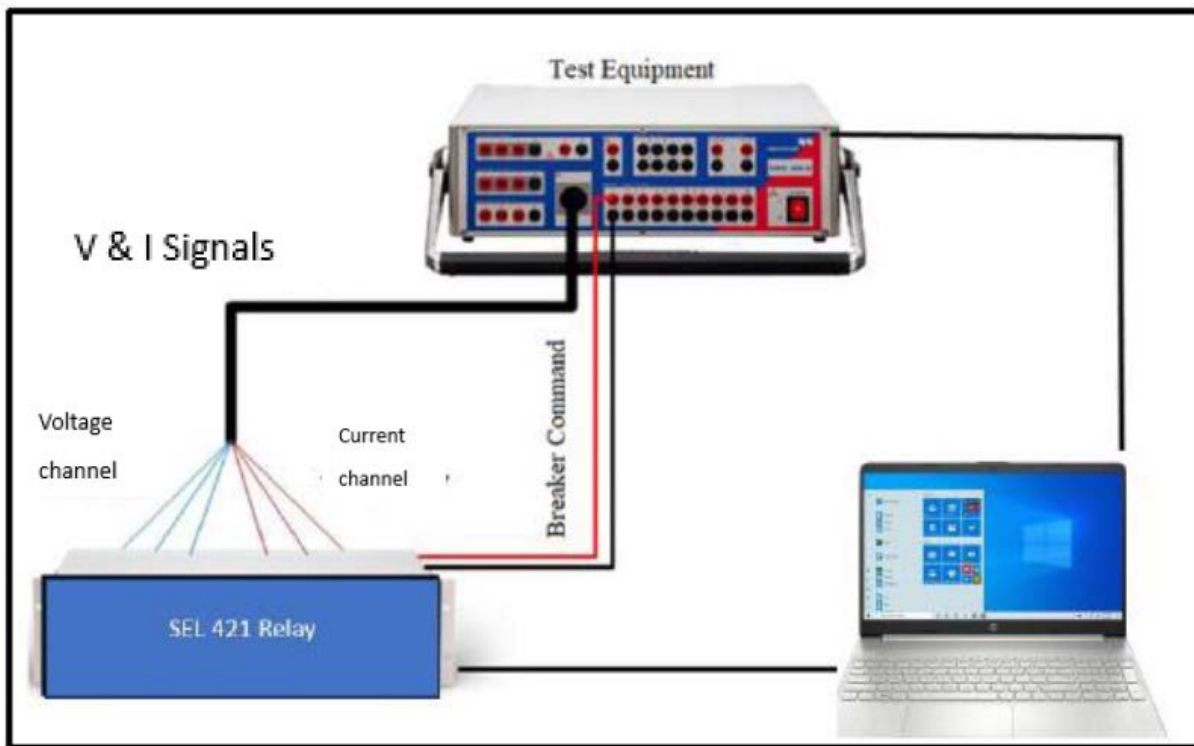


Figure 1.2: Lab-scale test bench setup

Figure 1.2 shows the lab scale that consists of a physical IED (SEL 421), Omicron CMC 256 plus secondary injection set, and laptop (HMI) devices to test the distance relay. Test Universe and AcSEerator QuickSet are two engineering configuration software used to program the relay and configure the secondary test set (CMC 256 plus).

1.9.5 Hardware in the loop (HIL) simulation setup

A typical HIL setup is presented in Figure 1.3 below.

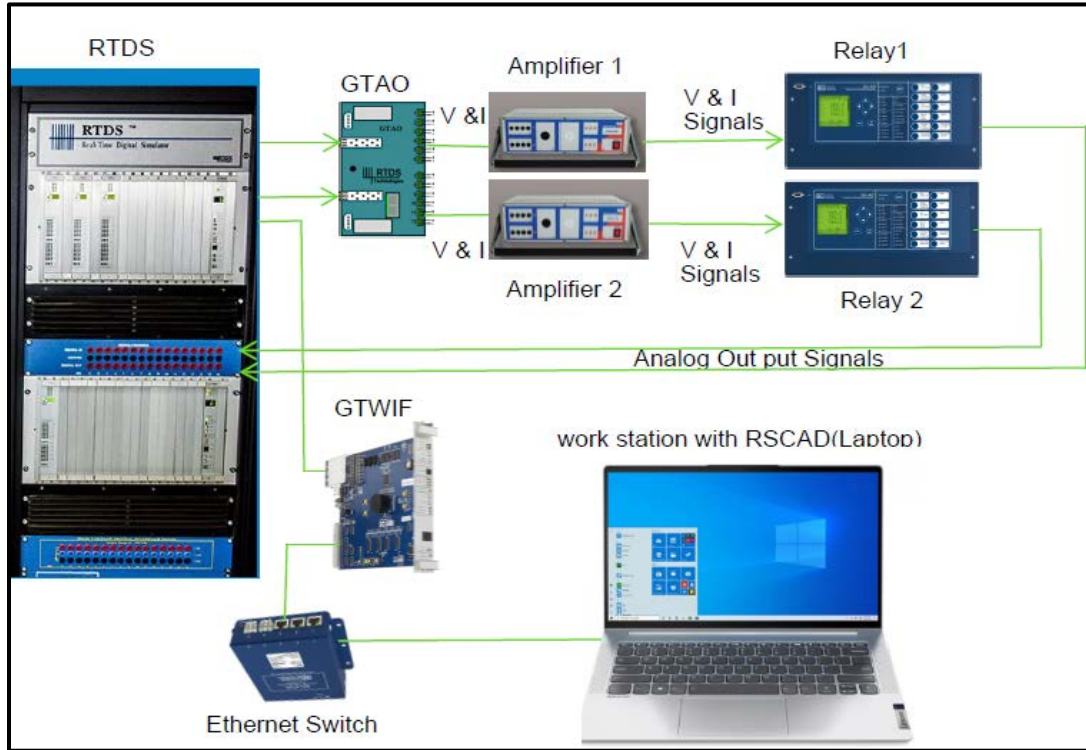


Figure 1.3: Implemented hardware-in-the-loop using RTDS simulator.

The 33kV distribution network protection scheme is simulated and tested in a hardware-in-the-loop (HIL) simulation using a physical SEL421 IED, amplifiers, a laptop with RSCAD software, and in real-time digital simulator (RTDS). Figure 1.3 below presents a typical HIL setup.

1.10 Thesis Chapters

This thesis consists of six Chapters and an appendix section.

Chapter One overview: presents the aim and objective of chapter one is to present the introduction of the study and provide the overview structure of the thesis chapters and conclusion. This chapter provides the scope of the research work with the details of the Awareness of the research problem, Problem statement, Hypothesis, Delimitation of the research, Research assumptions, and Proposed research methodology

Chapter Two overview: presents the literature review on distribution and transmission distance protection schemes. The chapter further discusses the hardware in the loop testing distance protection scheme.

Chapter Three overview: presents the model, simulates, and investigates the distance protection scheme on a power system simulation tool. The distance relay functionality is investigated for both symmetrical and unsymmetrical faults and the obtained results are discussed/analyzed.

Chapter Four overview: describes the implementation of a lab-scale test bench for testing the functionality of the physical distance protection relay (SEL 421) using the Omicron CMC 256 plus secondary injection test set. Software such as the AcSELeator and Test Universe are used to perform engineering configuration on the SEL 421 relay and the CMC 256 plus test device respectively. Obtained results from the lab-scale testing are compared with the results obtained from the DigSilent simulation in chapter three.

Chapter Five overview: provides the implementation of hardware-in-the-loop (HIL) testing for an IEC 61850 standard-based distance protection scheme using the GOOSE messaging for communication purposes. The HIL simulation is conducted to test the designed protection settings on a real-time digital simulator (RTDS).

Chapter Six overview: presents the key findings of this research and thesis deliverables are summarized in this chapter. The recommendations and future works related to this study are discussed as well in chapter six.

1.11 Conclusion

Chapter one of this thesis introduces the research project, describes the research aim and objectives, indicates the motivation behind the study, and introduces the proposed research methodology to test the distance protection functionality using HIL simulation.

The next chapter (Chapter Two) addresses the literature review conducted in this study. The review investigates the distance protection scheme for power system networks, and hardware in the loop simulation using the RTDS simulator.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Distance relays are mostly used in transmission line protection schemes because they provide not only main protection but also a backup protection system(Cho et al., n.d.). Due to the unchangeable operating ranges of the distance protection relays, these relays are regarded as ones that are highly affected and influenced by the power system variations.

The difference between the actual line impedance and the measure impedance at a relaying point causes malfunction of the distance relays. According to (Cho et al., n.d.), these malfunctions are very common in high-impedance faults.

Maintaining constant reach in ideal system conditions in different fault current levels makes the distance protection scheme more reliable when compared to an overcurrent protection scheme(Kasztenny, n.d.), and due to this ability, it is easier to set the distance relays.

According to (Apostolov et al., n.d.), a wide range of applications of distance relays for the protection of transmission lines with different levels of voltage leads to several power systems and protection analyses in everyday life. The literature review in this chapter provides an investigation into applying a distance protection scheme for short medium voltages and focuses on implementing the IEC 61850 standard base protection scheme for such networks.

2.2 Power quality effects on electrical network protection schemes

Current and voltage are two quantities that form part of the building blocks of electrical power, the quality of supply in any electrical network is very important, not only for technical impacts that may result in a malfunction of the protecting relay but also for the life span of electrical equipment.

The distance protection scheme is a scheme that is dependent on the current and voltage to determine the impedance at the location of a fault. Any disturbance to these quantities may have a huge impact on the performance of the power system network.

According to (Wang & Bollen, 2000), disturbances in voltage and current waveforms can interfere with the normal operation of protective relays. When the power quality of the system is poor, this is because the voltage and current waveforms flowing through the system have been disturbed and this leads to a mis-operation of distance protective relays.

2.3 Distance Protection Scheme Overview

Distance protection relays are types of relays that react/ function when the circuit impedance, reactance, resistance, or admittance increases above or decreases below the preset value in the relays(Camarillo-Penaranda et al., 2021).

Distance relays compute the distance of the line from the relay point to the fault location using measured values of voltage and current and the reaction of the relay depends on these two measured quantities.

Like any other protection system, distance relays have disadvantages as well, one zone of this protection scheme cannot protect the whole line in a network, and there is always a need for two or more zones of protection set in the relay to protect the whole length of the line(Camarillo-Penaranda et al., 2021).

Figure 2.1 below illustrates a typical two-zone distance protection scheme protecting a transmission line.

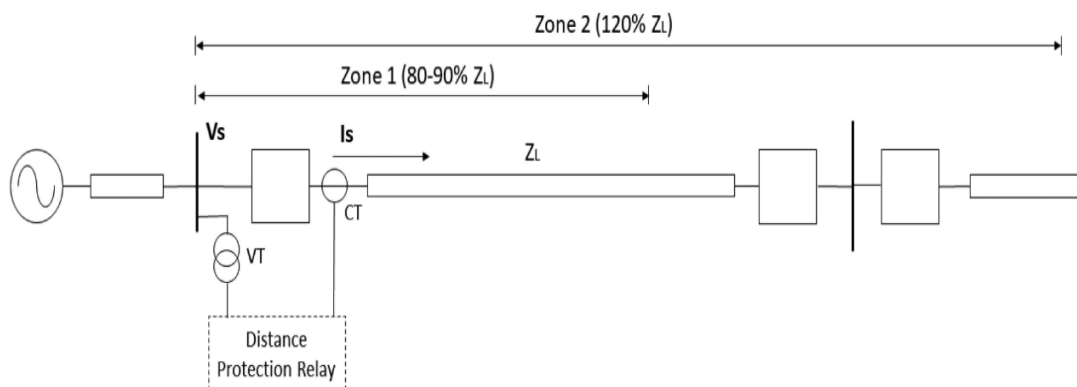


Figure 2.1: Illustration of distance protection zones (Camarillo-Penaranda et al., 2021)

Figure 2.1 shows two zones for the distance protection scheme, for a particular transmission line, zone 1 is indicated to cover 80-90% of the line while zone 2 provides backup protection for the line covering 120% of the length of the line.

Voltage and current are measured by the protection relay and analogue signals are received from two measuring instruments, the Voltage transformer, and the current transformer. Figure 2.2 below shows the operational steps of a distance relay set to operate into two zones.

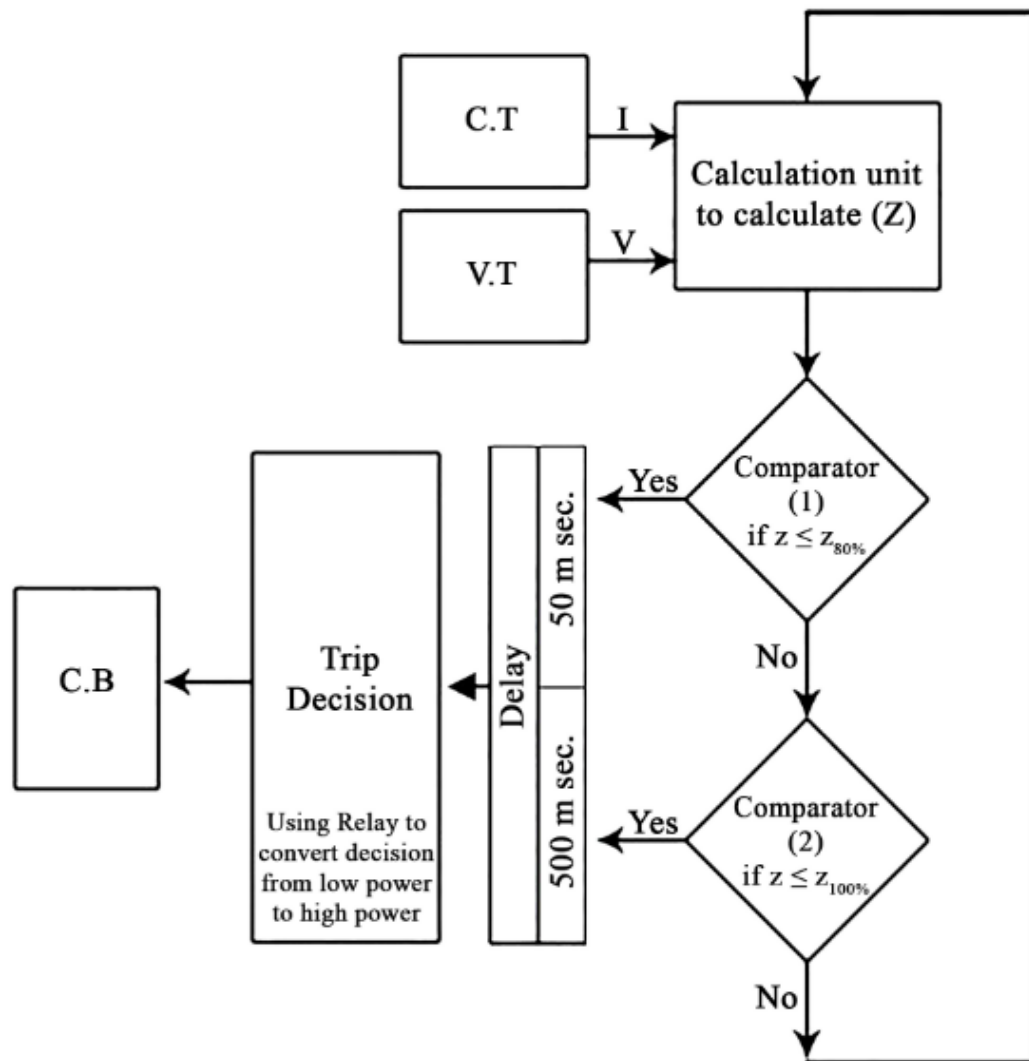


Figure 2.2: Distance protection steps for two zone 1 and zone 2 set in the relay(Abouelenin et al., 2017)

Figure 2.2 illustrates the steps taken by the distance protection relay before it gives a trip signal to the circuit breaker. The relay receives signals from VT and CT and calculates the impedance, two comparators assist the relay in deciding if the relay must trip or not. When the relay decides to trip, these two comparators determine whether the relay should trip to zone 1 or zone 2 within the stipulated times as indicated.

2.4 Distance relays implementation methods and generations of technology

2.4.1 Electromagnetic

Distance protective relays were first designed to be electromagnetic protective devices that were operating on the principles of magnetic force(Norouzi, 2021). Voltage and current signals produce magnetic force for attraction against the mechanical force such as the spring force and the tripping mechanism will be achieved.

2.4.2 Solid State

Around the 1930's the possibility of using electronics in distance relays was realized, even though a lot of electronic components such as semiconductors, were still not yet invented(Norouzi, 2021). Present electronic technology at that time was electron tubes and these relays were not widely used compared to electromagnetic relays.

2.4.3 Digital distance relays(microprocessor)

In the 1970s a new generation of relays were invented. These relays were the first generation of relays using microprocessors. The voltage and current are lowered to a level suitable to be processed using solid-state devices. The voltage and current phasor values are obtained from the microprocessor which converts the time domain representation of voltage and current signals. Figure 2.3 presents the microprocessor-based distance relay layout.

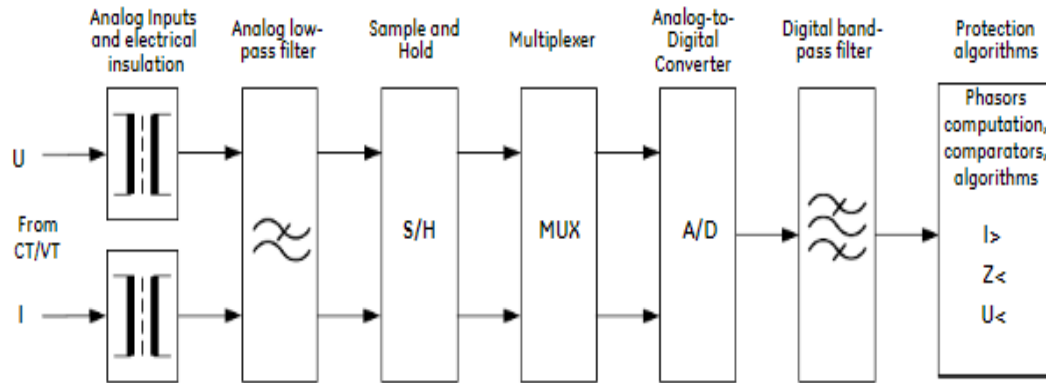


Figure 2.3: Microprocessor-based distance relay(Kasztenny & Finney, 2008)

Figure 2.3 shows the path taken by the voltage and current signals from the measuring instrument to the comparators of the relay.

2.4.4 Distance relay Characteristics curves

- i. Impedance relay characteristics
- ii. Mho relay characteristics
- iii. Quadrilateral relay characteristics

2.4.4.1 Impedance relay characteristic

Protection relays that respond to the RMS values of the system voltage and current, that is flowing through the system are known as impedance relays (WG B5.15, 2008).

The functionality used on these relays is that they measure impedance magnitude and compare it with the preset impedance value in the relay. When the measured impedance is less than the present value the relay will recognize that there is a fault on the line and initiate a trip signal.

A typical impedance characteristic of an impedance relay is presented in Figure 2.4 below.

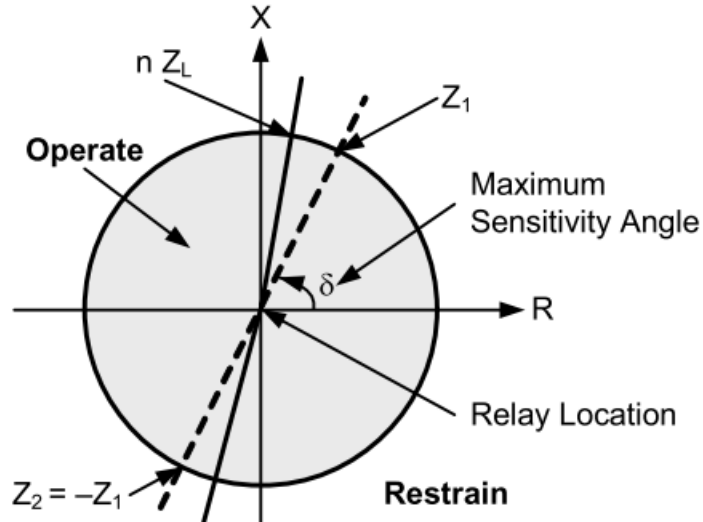


Figure 2.4: Typical characteristics curve for impedance relay(WG B5.15, 2008)

Figure 2.4 shows that the impedance relay will only operate if the measured impedance lies within any of the four quadrants of the Cartesian plane. One of the disadvantages of the impedance relay is that it can trip for a line that is adjacent to the protected line, and from Figure 2.4, this trip would only happen in the third quadrant.

To prevent the operation of the relay from the adjacent line, a different type of relay is used together with the impedance relay and this relay is called a directional relay. A directional relay is introduced for selectivity purposes. Selectivity is achieved when the tripping contacts of these two relays are connected in series, in that case, the impedance relay will be blocked from tripping when the fault lies on the third quadrant.

2.4.4.2 Mho relay characteristic

Mho relays are also known as admittance protection relays, these relays are a type of relay that has an operational zone that starts at the origin of the Cartesian plane(WG B5.15, 2008). Having an operational curve that starts from the origin, makes the mho relays more suitable for protecting the lines as they have more selectivity capabilities compared to the impedance relays. Figure 2.5 shows a Mho characteristic curve.

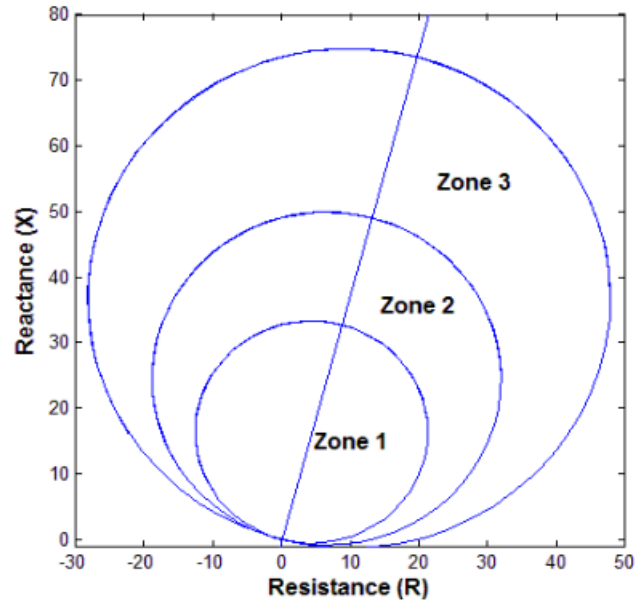


Figure 2.5: Typical characteristics curve for Mho distance relay(Ali et al., 2013)

Figure 2.5 shows three-zone settings in the Mho distance relay characteristics curve.

2.4.4.3 Quadrilateral relay characteristic

Quadrilateral relays are types of distance relays that have the capability of having a non-circular characteristic curve. These relays were developed in late technologies to make it possible to control resistance and reactance individually in a characteristic curve. Figure 2.6 illustrates an example of these quadrilateral relay curves.

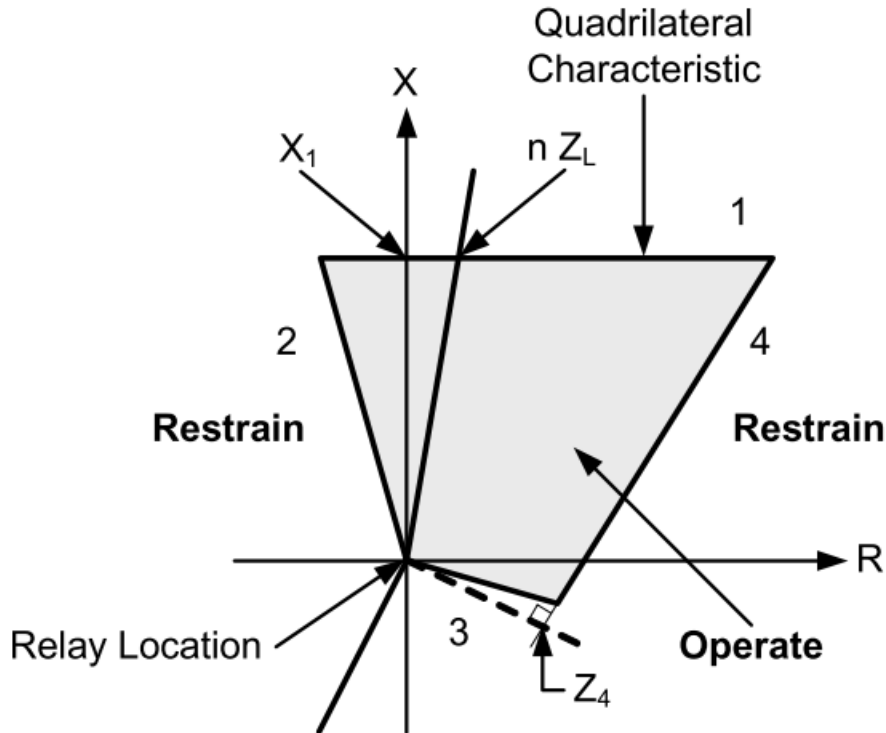


Figure 2.6: Quadrilateral characteristics curve of a distance relay(WG B5.15, 2008)

Figure 2.6 provides a quadrilateral curve where the operational zone is shaded grey, and the relay does not operate when the fault is outside this area as indicated.

2.4.5 Impedance Calculation Methods

Distance relays are voltage and current-dependent, so the impedance is measured by the relay using voltage and current to calculate it. During fault conditions, when a three-phase occurs, the measured impedance is different from the measured impedance when a single phase to ground occurs.

Consistency measurements are obtained by using different combinations to detect different types of faults as indicated in Table 2.1 and Table 2.2.

Table 2.1 presents a table showing voltage and current combinations to detect phase-to-phase faults.

Table 2.1: Voltage and current combinations for detecting phase-to-phase faults.

	Voltage applied	Current Applied	Relay responds to a fault between
Relay element 1	$V_a - V_b$	$I_a - I_b$	Phase A to Phase B Phase A to Phase B to Earth
Relay element 2	$V_b - V_c$	$I_b - I_c$	Phase B to Phase C Phase B to Phase C to Earth
Relay element 3	$V_c - V_a$	$I_c - I_a$	Phase C to Phase A Phase C to Phase A to Earth

Table 2.1 provides a table that illustrates elements needed to detect phase-to-phase faults and two phase-to-ground faults.

Table 2.2 presents a table showing voltage and current combinations to detect phase-to-ground faults.

Table 2.2: Voltage and current combinations for detecting phase-to-ground faults.

	Voltage applied	Current applied	Relay responds to a fault between
Relay element 4	V_a	$I_a + k3I_0$	Phase A to Earth
Relay element 5	V_b	$I_b + k3I_0$	Phase B to Earth
Relay element 6	V_c	$I_c + k3I_0$	Phase C to Earth

The k factor on this equation is calculated using the following equation:

$$\frac{Z_0 - Z_1}{3Z_1} = k \quad (2.1)$$

Where:

Z_0 = Zero sequence impedance

Z_1 = Positive sequence impedance

Table 2.2 illustrates three elements needed in a distance relay to detect phase A, phase B, and phase C to ground faults. Several publications have been reviewed to give more scientific and technical perspectives for discussing implementation and technologies for distance protection relays. Figure 2.7 presents the number of reviewed publications per year.

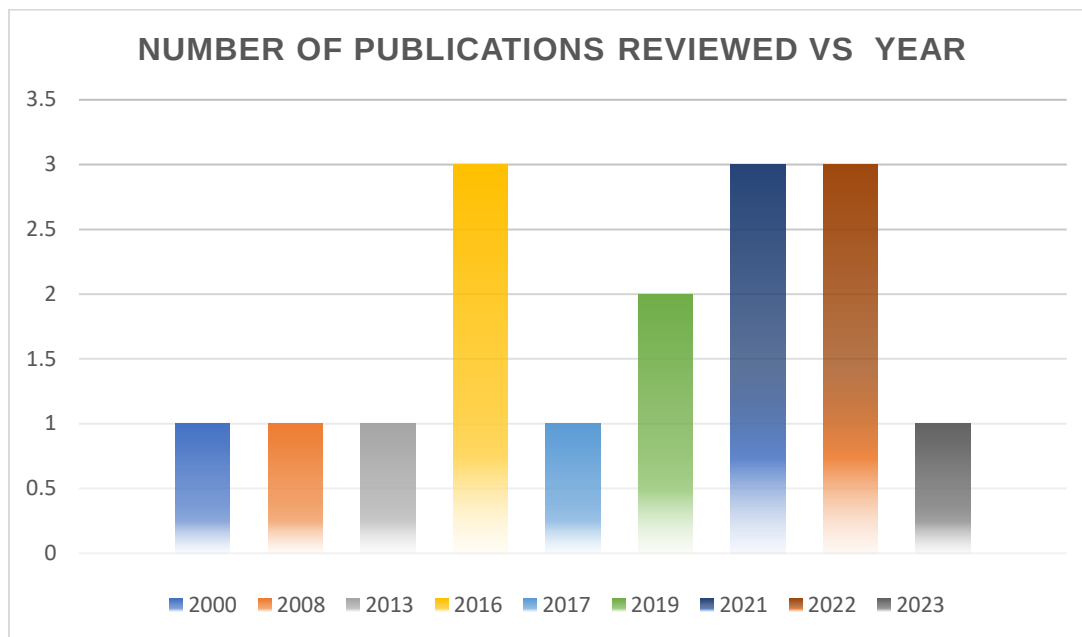


Figure 2.7: Reviewed distance protection papers vs year of publication

Figure 2.7 provides the data in a graph form presenting the number of published papers that were reviewed and related to the technical and scientific information expressed in this research.

From the above figure, it is shown the highest number of publications were in (2016, 2021, and 2022) respectively. Table 2.3 presents a table showing the reviewed papers with their achievements and objectives

Table 2.3: Comparative table of some reviewed papers and their objectives

PAPER'S AUTHOR	OBJECTIVES AND AIM OF THE PAPER	CHARACTERISTIC CURVE USED	USED SOFTWARE & HARDWARE IMPLEMENTATION	ACHIEVEMENTS
(WG B5.15, 2008)	To give and discuss the principles of distance protection schemes	Mho & Quadrilateral curves	N/A	Giving an overview of the distance relay settings and types of distance relay elements
(Norouzi, 2021)	To discuss the generation of distance relay schemes, from electromagnetic to the new digital relays	Impedance, Mho, and Quadrilateral	N/A	N/A
(Kasztenny & Finney, 2008)	To provide fundamentals of measurements of distance to a fault	Mho and impedance relays	N/A	N/A
(Abouelenin et al., 2017)	To provide effects of harmonics in distance protection relays	Impedance characteristic curve	MATLAB software	Results showing THD were produced in the form of graphs
(Wang & Bollen, 2000)	Evaluation of voltage and current disturbance in protection relays	N/A	N/A	This paper expressed the practical setup for classifying the effect of power

				disturbance on protective relays
(Igberaese et al., 2022)	Short circuit analysis for a 132kV network	N/A	Neplan software	The fault current was observed to be high values that could damage the transmission lines
(Ali et al., 2013)	Impact of loss sample values on the performance of IEC 61850	Mho characteristic curve	MATLAB Software	The paper analyzed the performance of distance relay in MATLAB software
(Firdaus et al., 2022)	To implement GOOSE massaging between distance protective relays	N/A	N/A	Design and implement the GOOSE message for the Teleprotection distance scheme
(Zhang et al., 2016)	To study the distance protection relays on Digsilent software	Mho characteristic curve	Digsilent software	the article outlines steps that need to be taken when simulating an electrical system in a DigSilent environment
(Monemi & Boghzian, 2023)	Implement relay settings and modeling of the power grid	N/A	RSCAD software	Lab scale and protection settings were tested
(Penthong et al., 2023a)	Providing testing methods for checking the performance of distance	Mho, and Quadrilateral characteristics	RSCAD software	Two distance relays were tested for their performance when a fault occurs

	relays used in transmission lines			
(Sreeram & Raja, 2013)	Illustrating DSP based three step distance schemes for line protection	Mho characteristic	PSCAD software	Simulation for testing the relays was done and events and results were recorded showing how the relay performs

2.5 Protective relay test in a real-time digital simulator (RTDS) environment

In the 1990s, the first project of RTDS was introduced, and since that time a lot of upgrades and improvements have been made(Ou et al., 2014). Due to the developments of modern power system networks, the high performance of protective relays has been a great concern, and in addressing these challenges and concerns manufacturers have developed new protective relays with advanced technologies(Marttila et al., 1996).

Real-time data for power systems has become more needed and monitoring is now a key feature of modern networks. RDTS plays a key role in achieving the goal of evaluating the performance of protective relays in real-time cases. Hardware-in-the-loop (HIL) testing is achieved in RTDS, and it is done in two test modes which are known as closed-loop testing and open-loop testing.

2.5.1 Closed-loop HIL testing method in RTDS.

The possibility of testing the protection relays in highly realistic operational conditions is to apply a closed-loop testing method. This testing method allows the relay under test or investigation to send back data into the modeled network(Marttila et al., 1996). According to (Roekman et al., 2004), the closed-loop testing mode is a much more realistic and efficient way of investigating a protection relay behavior during fault conditions when connected to the electrical system network. When performing closed-loop testing for distance protective relays, RTDS becomes the power system network and this RTDS is connected to the relay under test through voltage and current amplifiers. These amplified signals are then sent to the relay as shown in Figure 2.8 below.

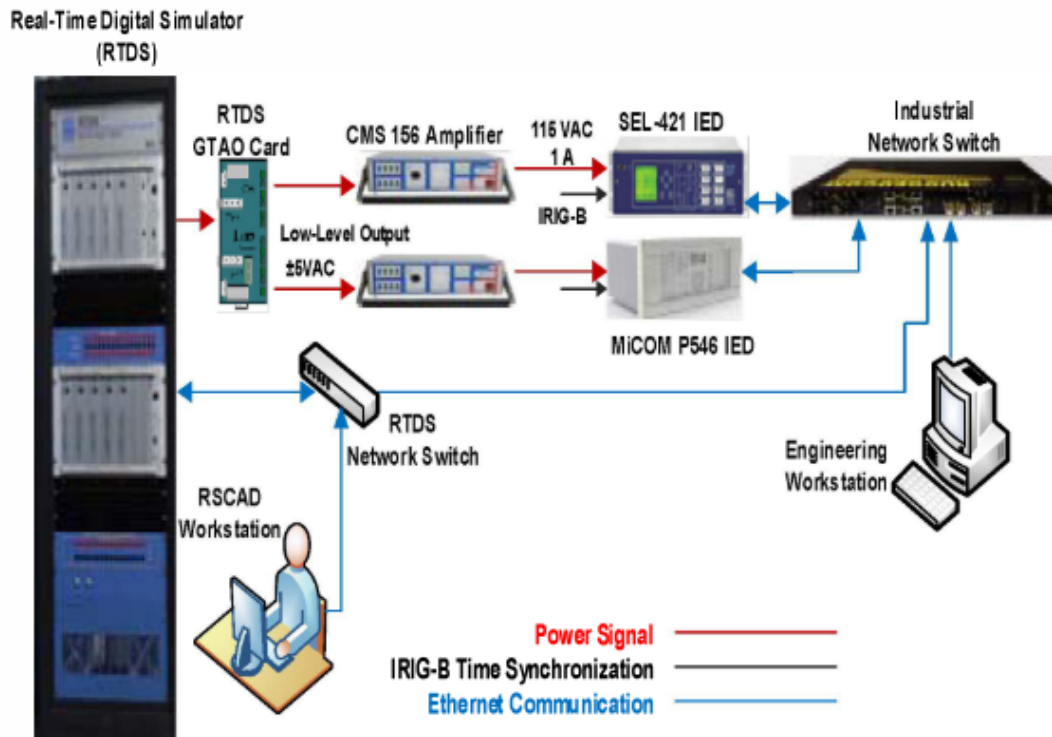


Figure 2.8: HIL closed-loop testing of two distance protection relays(Arnold et al., 2015)

Figure 2.8 presents a lab test scale for the implementation of the closed-loop testing method in the RTDS simulator. From Figure 2.8 two different distance relays are used to demonstrate how to test the protection functionality of a relay in closed-loop testing. Analog signals of voltage and current are sent to the relay via two amplifiers (CMS 156) as indicated. RSCAD software is used to model the network and all types of faults are simulated on the simulation and relays respond when measured values are less than pre-set values for zones of protection. Signals from the relay are sent back to the system to operate circuit breakers that need to clear the fault on the protected line.

2.5.2 Open loop testing method in RTDS.

Open loop testing method of protection relays in RTDS is achieved by interfacing the RTDS hardware and RSCAD software. The power system network is modelled on RSCAD software which drives the RTDS hardware which acts as the actual network of the system. The low analog

signals produced by the network are supplied to the protection relay via current and voltage amplifiers, these signals are key components in testing distance protection relays. For open loop testing, it is not necessary to connect the device under test back to the RTDS network as shown in Figure 2.9 below.

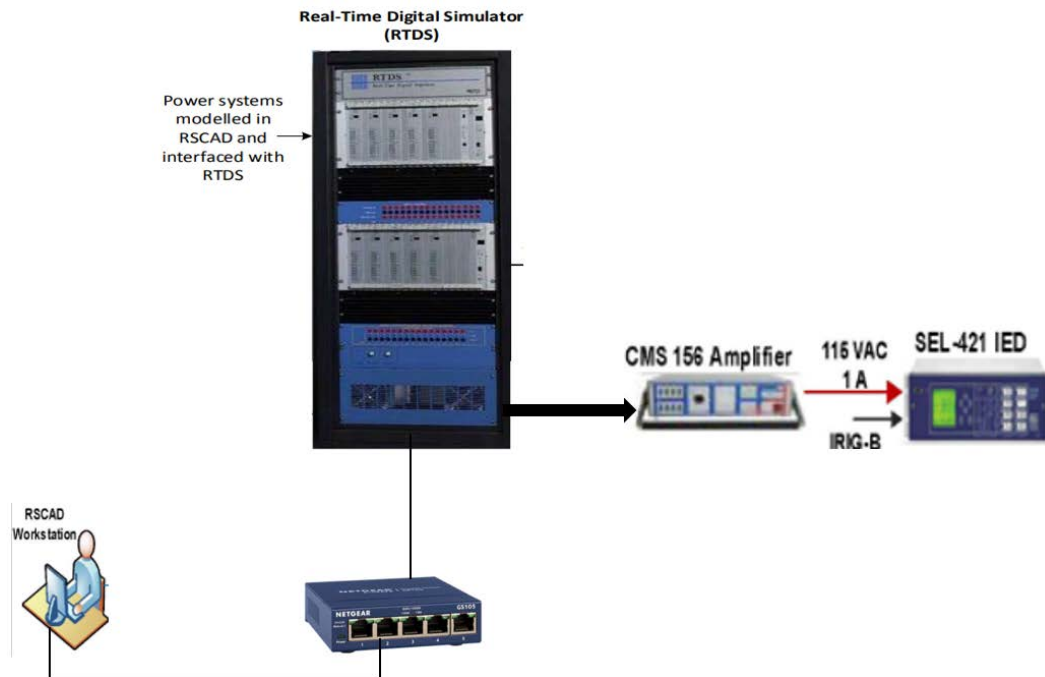


Figure 2.9: Open-loop testing of distance protection relay in RTDS simulator.

An SEL 421 relay is shown in Figure 2.9, and this presents an open loop testing of the distance protection relay in a real-time condition. In Figure 2.9, the relay is monitored on the front panel to see if the relay reacts to the faults simulated on the software or not.

The advantage of performing an open loop testing method is that it limits errors in the relay response to the event and this is a great idea for testing the relay in the open loop method before it can be tested on the closed loop testing method.

Table 2.4: RTDS-based publications and their aim of study in close-loop and open-loop testing methods.

Author	Aim of the paper	Protection scheme under study	Discussed method	Simulation/ implementation/ Hardware/ Software	Achievements/ Challenges
(Mirzahosseini et al., 2019)	Testing of traveling-wave Relay using RTDS	Traveling- Wave Relay Testing (TWRT)	TW-based protection principle in closed-loop testing of TWRs	Hardware: RTDS, and NovaCor simulator	Successfully test the TW-based protection elements
(Moravej & Bagheri, 2017)	Relay operation testing for power transformers in RTDS	Differential scheme for power transformers	Implementation of transformer protection scheme in RTDS device	RTDS hardware was used together with RSCAD software	The paper examined the function and tested the differential relays by using RTDS in a proposed power system it also evaluated the relay operating time to clear faults
(Jung et al., 2000)	Presenting, Dynamic characteristic testing for protection relay in RTDS application	Distance protection scheme and line differential scheme	This paper discusses a test model in an RTDS environment.	RTDS hardware simulator	The paper provides a test procedure using RTDS to verify the possibilities of relay malfunction.

(Marttila et al., 1996)	Describing closed-loop testing method in RTDS environment	Testing of power system stabilizer and testing of breaker controller	This paper presented testing methods for feeder protection relay	RTDS hardware simulator	The paper provided application methods for closed-loop testing of circuit breaker controllers and power system stabilizer
(Forsyth & Kuffel, 2007)	Evaluation of RTDS application for utility	N/A	The paper describes the application of RTDS in utility industries	N/A	The paper provides the theoretical application of the RTDS simulator
(Ens & Brazil, 2009)	Studying protection performance analysis in short transmission lines using RTDS	Distance and line differential schemes	N/A	N/A	The paper provides the theoretical application of distance and line differential relays in the RTDS simulator
(Ou et al., 2014)	Investigating and implementing small-time step (STS) simulation in RTDS	N/A	This paper studies an HVDC system in the RTDS application	RTDS hardware simulator	The paper presents a new approach in small-step modeling implementation for application in the RTDS simulator
(Monemi et al., 2020)	Evaluation of power system	Line differential scheme	This paper provides methods	RSCAD software, AcSElerator Quickset	The paper successfully implemented a test bench

	protection using RTDS		for implementing a line differential protection scheme in a closed-loop method in an RTDS simulator	software, and RTDS hardware simulator	for testing the SEL 311 relay in the RTDS simulator
(Du et al., 2006)	Design of real-time digital simulator-based relay testing system	N/A	New design of testing protective relays in RTDS environment	RSCAD software	The paper presented a new design for testing protective relays in RTDS that has several advantages when compared with other methods. The advantages include reduction of costs and increased capabilities
(Roekman et al., 2004)	Application of RTDS in assessing the performance of distance relay for 500kV power system	Distance protection scheme	Close loop testing of distance protection relays	PSCAD software and RTDS hardware simulator	The paper validates the protection algorithm using the RTDS simulator

2.7 IEC 61850 Challenges

Perform compliance testing to ensure that the implemented solution adheres to the IEC 61850 standard. This may involve testing interoperability with other devices and verifying the correct interpretation of standard-defined behaviors. Implement security measures as per the IEC 61850 standard to ensure the integrity and confidentiality of communication. Consider using encryption and authentication mechanisms.

It's important to note that the complexity of the implementation may vary based on the specific requirements of the distance protection application and the features supported by the IEDs involved. Therefore, future project work involves consulting relevant standards and seeking support from vendors or experts in IEC 61850 can be beneficial during the implementation process.

Based on the consultant's recommendations, the project seeks PARSA network protection engineers to advise and collect the IEC61850 configurations and requirements before proceeding to implement the IEC61850 GOOSE application for the distance protection scheme. The future project's recommendations will consider Implementing IEC 61850 GOOSE (Generic Object-Oriented Substation Event) messaging for distance protection after a thorough understanding of the challenges due to the complexity of the IEC 61850 standard and the specific requirements of distance protection applications.

2.8 Conclusion

The literature review analyses various techniques used for transmission and distribution line protection schemes. Challenges such as digital algorithms for power system protection in terms of speed, reliability, dependability, selectivity, security, and stability have brought noticeable challenges to protection engineers across the world. As power demand increases daily, more challenges are experienced in the power grid. These challenges include power swings, power dips, and system instability. These challenges may greatly impact the power flow on the electrical networks.

Different transmission systems are designed to meet specific needs and demands, for an electrical system to achieve these demands a proper protection system must be developed. All electrical components in the structure of the power system must be properly protected. Transmission and distribution lines are a high priority when it comes to protection requirements,

these lines are responsible for transporting power from generation stations to the consumers. Due to technical challenges, the power transmission can be disturbed, and power supply cut-offs are also common. Line protection schemes are designed to protect the network against electrical faults when they occur in the system. Malfunctions of protection relays may also lead to serious damage to the electrical network.

This chapter focused on reviewing distance protection methods applied to safeguard the electrical network against fault conditions. The literature review indicates that using new protective technologies improves the protection capabilities of the protection scheme. Chapter three will focus on modeling the 33kV distribution network and implementation of a distance protection scheme in the DigSILENT environment.

CHAPTER THREE

SIMULATION OF THE DISTANCE PROTECTION SCHEME FOR 33KV DISTRIBUTION NETWORK.

3.1 Introduction

Transmission of power through the power system structure heavily relies on the electrical distribution lines. These lines' reliability and high performance are of utmost importance, necessitating high-level standards and knowledge for designing appropriate power system protection schemes. Such schemes are designed to ensure no significant damage to the infrastructure during abnormal conditions.

Depending on the requirements of the power system network, an electrical protection scheme is created to meet specific needs. This chapter outlines the recommended protection scheme for a 33kV distribution network that supplies power to traction substations (3kV DC Substations) in the Western Cape region for PRASA, a state-owned company also known as the Passenger Rail Agency of South Africa.

The chosen network is being analyzed and studied in the DigSILENT environment to apply a distance protection scheme that will safeguard the distribution lines. This chapter provides a four-bus 33kV power system network that is simulated on DigSILENT for load flow analysis. A distance protection scheme is designed to safeguard the power distribution lines against high fault currents that can occur in the system. Case studies (case study one and case study two) are presented in this chapter to analyze the functioning of the protection relays when different scenarios of faults are simulated, and the last part of the chapter is the conclusion.

3.2 IEEE 4- Bus system

A 4-bus power system network is shown in Figure 3.1. The distance protection scheme is designed to protect the network against fault currents.

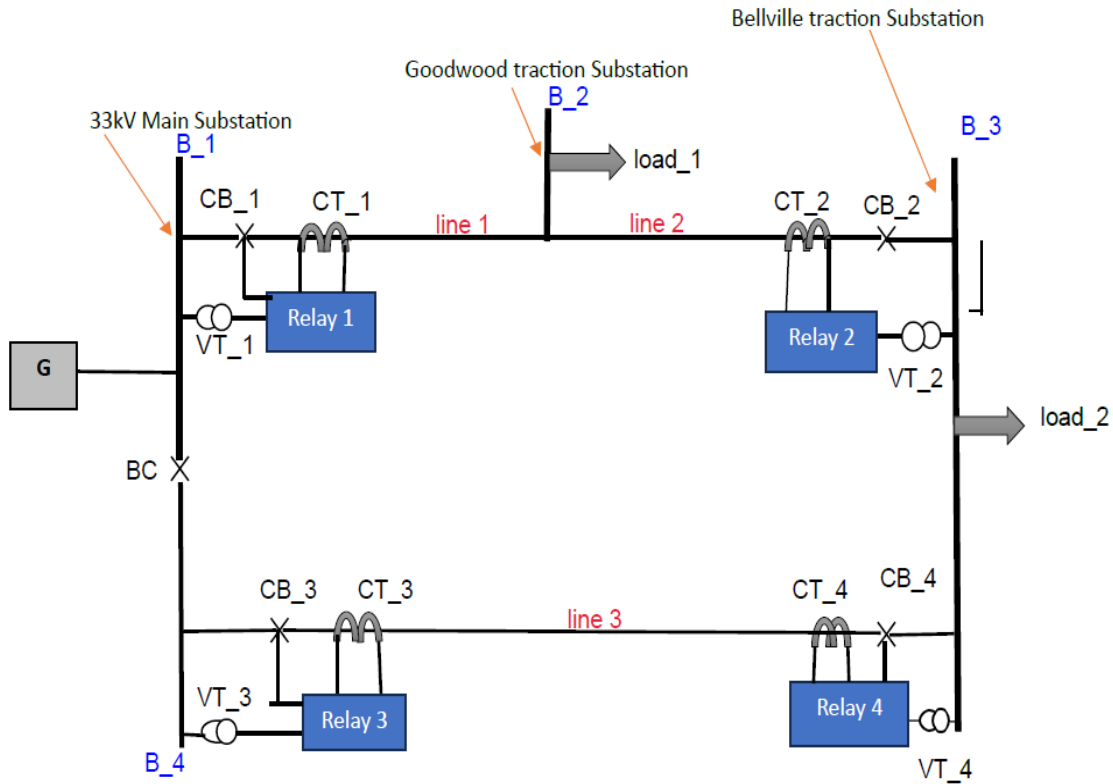


Figure 3 1: Single-Line Diagram of the 4 Bus System.

Figure 3.1 presents a single-line diagram of the 33kV network under study and its designed protection scheme layout.

Where:

CT: Current Transformer, **VT:** Voltage Transformer, **BC:** Bus Coupler and **CB:** Circuit Breaker: **B:** Bus bar

The input data of the 4-bus system is given in Tables 3.1, Table 3.2, Table 3.3, and Table 3.4 respectively. Table 3.1 provides external grid data, where the grid's power rating, and power factor, and other parameters are indicated respectively.

Table 3.1: External grid data.

External Grid Data	
Grid type	SL
Angle in degrees	0
Apparent power (MVA)	80

Power Factor	1
Voltage setpoint	1
System Frequency (Hz)	50
System Voltage (L-L)	33kV

Table 3.2 provides 4-bus data: system phase rotation, rated voltages, and maximum fault levels at each bus.

Table 3.2: IEEE 4-bus data.

4- Bus Data				
Bus No	Description			
	Rated voltage (L-L)	Minimum fault values (MVA)	Maximum fault values (kA)	Phase Technology
1	33kV	1042.6	18.2	ABC
2		347.6	3.59	
3		283	2.83	
4		1042.6	18.2	

Table 3.3 below shows the type of loads used on this network, presenting power factor, voltage setpoints at load type, and rated MVA loading.

Table 3.3: Load demand data.

Load No	Load size in (MVA)	Power factor	Voltage setpoint
1	8	0.9	1
2	10	0.87	1

Table 3.4 provides information on the transmission line used in this 4-bus system, where the length of the lines, impedance of the line, and rated current are indicated.

Table 3.4: Transmission line data.

Transmission line data					
Line No	Line impedance (polar form) $Z \angle \delta$		Line Current carrying capacity (kA)	Line length (km)	Line resistance and reactance (R+JX) Ω
	Z (Ω)	δ°			
1	3.18	57.23	0.5	8	1.72+j 2.67
2	3.18	57.23		8	1.72+j 2.67
3	6.36	57.23		16	3.44+j 5.34

3.3 Load flow analyses

Modeling and simulations of the power systems have been found very necessary in modern power systems, this is done for several reasons, one is that the models give analyses and give results of a system within a short period unlike when all calculations are done in hand. The load flow of the 33kV network under study has been analyzed and discussed in this chapter and the load flow is divided into three sections/ case studies.

The Load flow results are presented to check the voltages at each bus if are still within the +/- 10% limits, during normal operating conditions. Load flow analyses further check if the lines are loaded within the current carrying capacities.

Using single-line models, it is easy to analyze the state of the network under study during normal and abnormal conditions focusing on system parameters and aspects such as voltage drops, voltage angle, current flowing on the line, real power, and apparent power. Figure 3.2 below shows the simulated network in the DigSILENT environment, this shows that the load flow of the system has been calculated successfully.

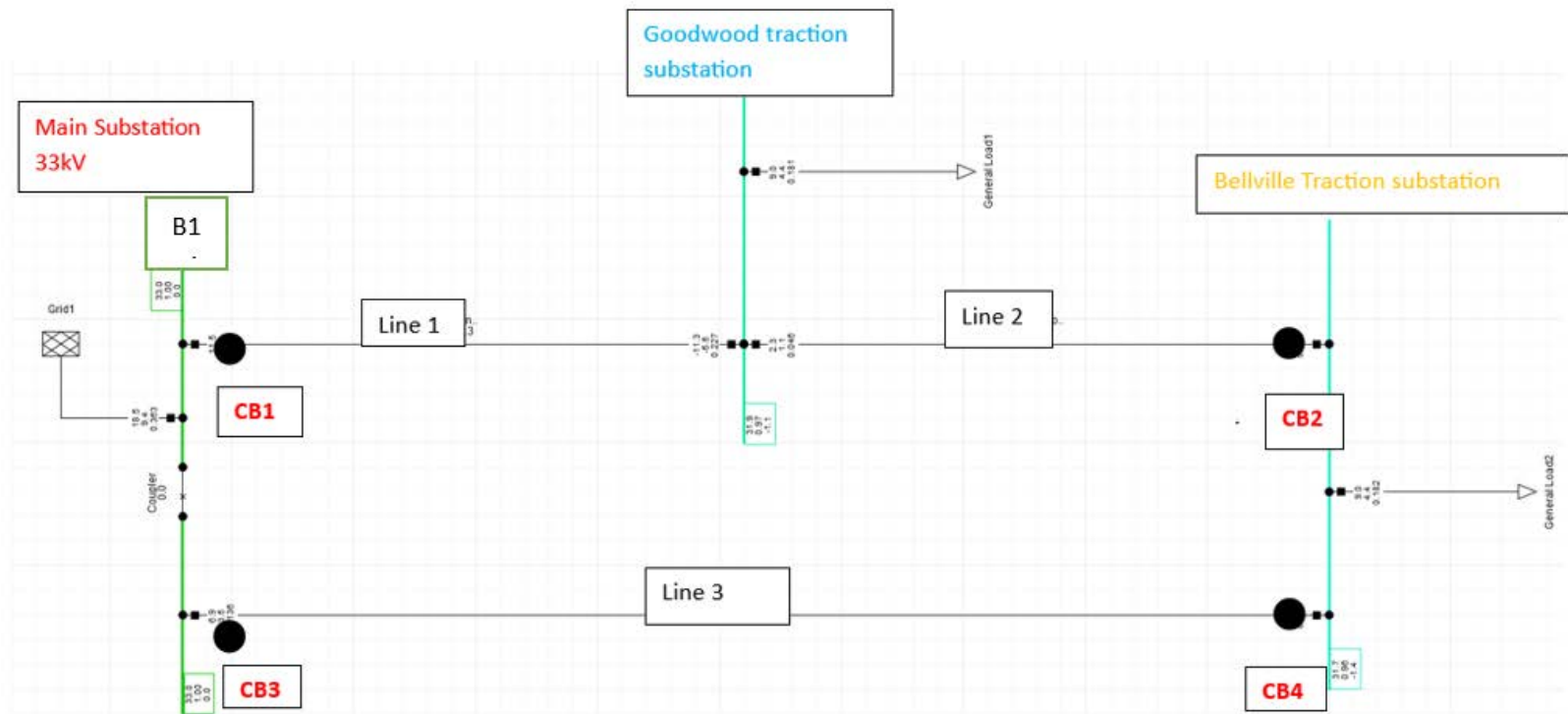


Figure 3.2: Single-Line Diagram network in DigSILENT environment.

Figure 3.2 shows a single-line diagram simulated in a DigSILENT environment to analyze the results obtained.

Where:

CB: is a circuit breaker.

3.4 Case studies for load flow analysis:

3.4.1 Case Study One:

This case study provides and analyzes the results obtained from the system when all lines (line 1, line 2, and line 3) are operational to validate the system performance.

3.4.2 Case Study Two:

Case Study 2 provides and analyzes the results of the system when line three is out of service, this is done to indicate whether the system can operate with on supply or not.

3.4.3 Case Study Three:

Case study three provides and analyzes the results obtained from the system when circuit breaker one (CB1) is open, and the bus coupler is closed. In this case, the system is fed from Breaker Three via Circuit Breaker 4, and Circuit Breaker 2 is fed back to the Goodwood traction substation.

i. Case study one analyses:

Scenario one results are indicated in Table 3.5 and Table 3.6 respectively. Table 3.5 shows the three-phase system voltage measured in all bus bars during normal operating conditions when the Bellville traction substation is fed from both supplies as indicated in Figure 3.2. The voltage profiles are all within the +/- 10% limits, and these values are acceptable.

Table 3.5: Three-phase system voltage measured in all substation buses when all lines are in service.

Substation-Bus	Nominal Voltage[kV]	Bus [P.U]	Actual (measured) voltage[kV]	Voltage deviation (%)
1-Main Substation	33	1	33	0
2-Goodwood		0.972	32.96	- 0.12
3-Bellville		0.964	31.8	- 3.64
4-Main Substation		1	33	0

Table 3.6 provides data about the loading of the network. From the results, it is indicated that the transmission lines are loaded as indicated in Table 3.6. This indicates that the transmission lines operate within the rated values during normal conditions.

Table 3.6: Loading percentage of transmission lines during normal conditions.

Line Number	Loading percentage [%]	Active power [MW]	Reactive power [MVar]	Power factor	line Current	
					[kA]	[P.U]
1	39.76	10.129	5.151	0.89	0.199	0.398
2	10.95	2.726	1.347	0.90	0.055	0.11
3	25.36	6.455	3.293	0.89	0.127	0.254

ii. Case Study Two analyses:

The second case study presents the voltage profile and line loading when both the Goodwood substation and Bellville substation are fed from a single supply, as line 3 has been taken out of

the service. From Table 3.7, Line three has been taken out of service to see the voltage profile at the buses when there is only one supply on the network. As expected, the voltage deviation has increased from the supply to the furthest substation but is still within the acceptable tolerance.

Table 3.7: Three-phase system voltage measured in all substation buses when line 3 is out of service.

Substation-Bus	Nominal Voltage[kV]	Bus [P.U]	Actual (measured) voltage[kV]	Voltage deviation [%]
1-Main Substation	33	1	33	0
2-Goodwood		0.947	32.12	- 2.66
3-Bellville		0.964	31.25	- 5.3

Table 3.8 provides the loading of the lines to see the performance when line 3 is out of service.

Table 3.8: Loading percentage of transmission lines when distribution line number three is out of service.

Line Number	Loading percentage [%]	Active power [MW]	Reactive power [Mvar]	Power factor	line Current	
					[kA]	[P.U]
1	36.95	9.176	4.633	0.89	0.185	0.370
2	36.95	9.35	4.9	0.89	0.185	0.370

iii. Case Study Three analyses:

Table 3.9 and Table 3.10 show the results of case study three, where the circuit breaker 1 (CB1) is open. Table 3.9 gives the voltage profile in each substation feeding from circuit breaker four (CB4) at the main substation. The percentage voltage deviation is much larger in this case, this is due to an increase in line impedance.

Due to the changes in system voltage, distance protection relays may malfunction as they are more dependent on the ratio of voltage and current values. Voltage deviation for this feeding arrangement proved to be not the right feeding arrangement, voltage drop is very high as it is above 10% tolerance, therefore this feeding arrangement is not appropriate for this system, and it must not be excessive.

Table 3.9: Three-phase system voltage measured in all substations bus when circuit breaker one (CB1) is opened.

Substation-Bus	Nominal Voltage[kV]	Bus [P.U]	Actual (measured) voltage[kV]	Voltage deviation [%]
1-Main Substation	33	1	33	0
2- Bellville		0.897	29.59	- 10.33
3- Goodwood		0.874	28.83	- 12.64

Table 3.10 shows a rise in the loading percentage of transmission lines, to be specific line 3 since circuit breaker one (CB1) is not feeding to the network, both traction substations at Bellville and Goodwood are fed from circuit breaker four (CB4). The Goodwood traction substation is fed via circuit breaker two in the Bellville substation and the loading of the line is presented in table 3.10 respectively.

Table 3.10: Loading percentage of transmission lines for case study three.

Line Number	Loading percentage [%]	Active power [MW]	Reactive power [Mvar]	Power factor	line Current	
					[kA]	[P.U]
2	32	7.33	3.693	0.87	0.355	0.32
3	71	17.64	10.07	0.87	0.160	0.71

iv. Comparison graph for voltage deviation:

All scenarios (case studies) have provided bus bar voltage profiles during load flow analysis, and voltage deviation from the source of supply to the load buses has been monitored and analyzed for each case study. Figure 3.3 below presents voltage deviation in all substation buses for all case studies that have been discussed. From Figure 3.3, the main substation does not show any voltage deviation since this is a source of supply bus bar.

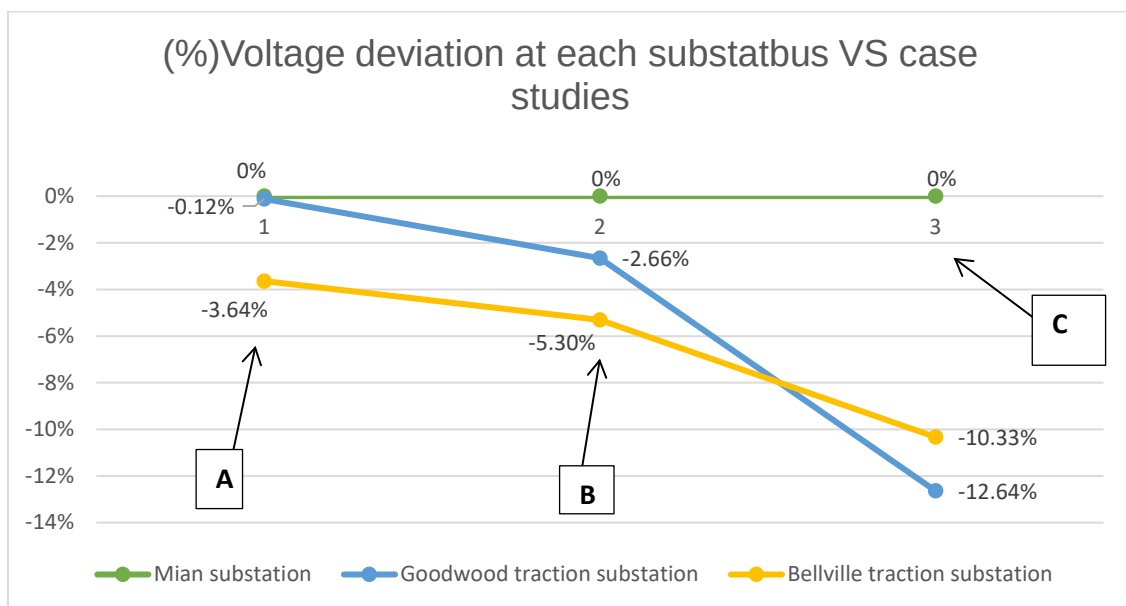


Figure 3.3: percentage voltage deviation for all three case studies in all buses.

where:

A: is the voltage profile in all buses for case study 1.

B: is the voltage profile in all buses for case study 2.

C: is the voltage profile in all buses for case study 3.

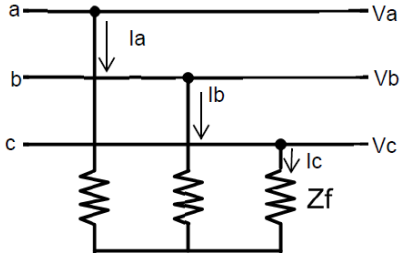
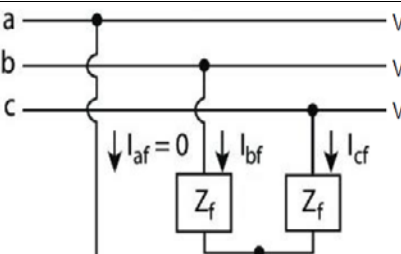
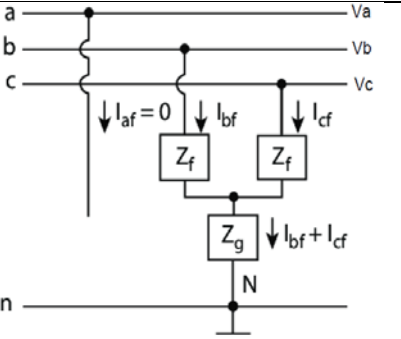
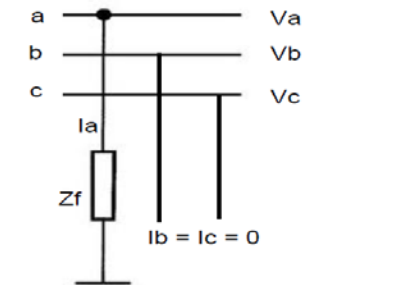
3.5 Short circuit current

A short circuit (SC) is an electrical disturbance that occurs during an abnormal time in an electrical power system. This aspect is one of the critically considered factors when designing an electrical protection scheme. Short circuits can be divided into four sub-divisions as listed below.

1. Three-phase SC.
2. Double phase SC.
3. Double to ground SC.
4. Single phase to ground SC.

Table 3.11 further illustrates the above-listed types of short circuits that are commonly analyzed and addressed during the designing of an electrical network protection.

Table 3.11: Types of short circuits that affect electrical networks (IEC International standard 60909, 2001)

Fault	Circuit diagram of the fault point	Boundary conditions	Description
Three-phase SC		$I_a + I_b + I_c = 0$ $V_a = Z_f I_a$ $V_b = Z_f I_b$ $V_c = Z_f I_c$	• Connection of all conductors with or without simultaneous contact to the ground • Symmetrical loading of the three external conditions • Calculation on a single-phase basis
Line-to-line SC		$I_{af} = 0$ $I_{bf} = -I_{cf}$ $V_b - V_c = Z_f I_{bf}$	• Unsymmetrical loading • All voltages non-zero • SC current higher than in a three-phase near-to-generator
Double line-to-ground SC		$I_{af} = 0$ $V_b = (Z_f + Z_g) I_{bf} + Z_g I_{cf}$ $V_c = (Z_f + Z_g) I_{cf} + Z_g I_{bf}$	• The leakage current flowing to ground is capacitive ground fault current.
Single line-to-ground SC		$I_b = I_c = 0$ $V_a = Z_f I_a$	• Very frequent occurrence in low voltage networks

According to (Handono et al., 2019) short circuit analyses of an electrical network may be done based on the flow chart shown in Figure 3.4 below.

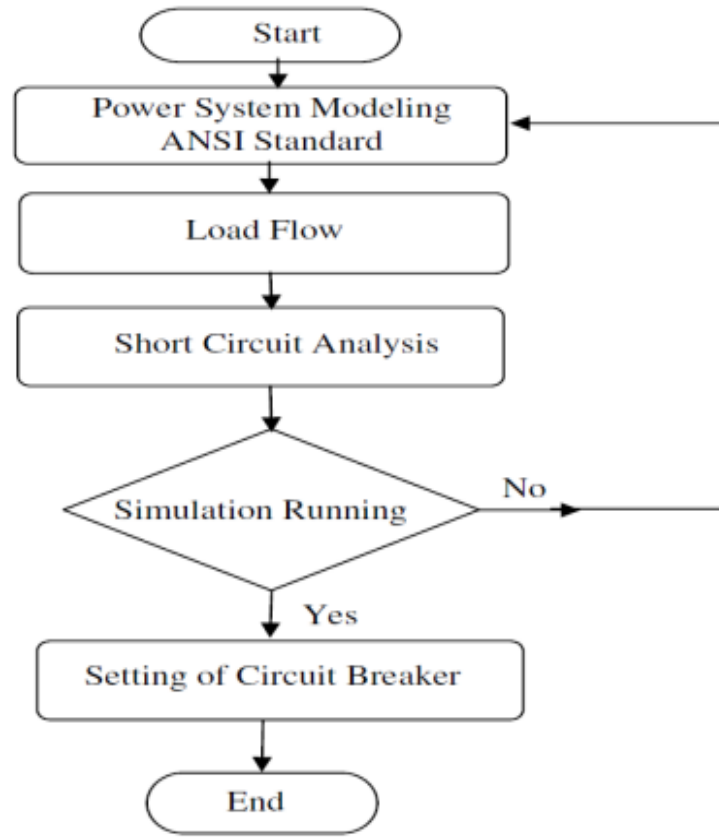


Figure 3.4: Flow chart Short Circuit Analyses (Handono et al., 2019).

Figure 3.4 shows the steps of analyzing short circuits in an electrical system and this flow chart has been adopted to analyze the short circuits in this study.

IEC 60909 standard has been used when calculating maximum fault levels at substation locations using the DigSILENT environment. This is performed to validate at what values the fault current reaches when a three-phase or single-line-to-ground fault occurs.

Once this aspect is identified, that will give a clear guide when the distance protection settings are designed for the protection of transmission lines. Three-phase and single-phase to-ground faults were simulated on the network in different locations to verify the Maximum fault currents and fault current values are calculated by using the following equations (IEC International standard 60909, 2001).

$$I_k'' = \frac{cV_n}{\sqrt{3}Z_k} \quad (3.1)$$

$$I_k'' = \frac{\sqrt{3}cV_n}{Z_{k(1)}+Z_{k(2)}+Z_{k(0)}} \quad (3.2)$$

$$k = 1.02 + 0.98 e^{\frac{-3}{X/R}} \quad (3.3)$$

$$I_p = k \sqrt{2} I_k'' \quad (3.4)$$

$$S_k'' = \sqrt{3} I_k'' V_n \quad (3.5)$$

Where:

I_k'' is the initial symmetrical short circuit current.

I_p is the peak short circuit current.

k is the constant factor.

c is the voltage factor.

V_n is the nominal voltage at the short circuit location.

Z_k is an equivalent short circuit impedance.

$Z_{k(1)}$ is an equivalent positive sequence short circuit impedance.

$Z_{k(2)}$ is an equivalent negative sequence short circuit impedance.

$Z_{k(0)}$ is an equivalent zero sequence short circuit impedance.

R is the resistance of the network.

X is the reactance of the network.

i. Simulated Unsymmetrical and Symmetrical faults.

Single-phase-ground faults were simulated in the model and calculated fault levels are recorded in the table below. In this table, faults were simulated in different locations to identify the fault current and fault apparent power in those locations of choice. Table 3.12 compares fault levels for single-phase-ground and three-phase faults occurring in the system. Faults were simulated in line one and line two respectively, line three is assumed to have the same fault levels since the properties of these lines are the same.

Table 3.12: Minimum Fault Level for Unsymmetrical (Unsy) and Symmetrical (Sy) faults

Location [@]	Apparent Power “Sk” (MVA)		Fault current “Ik” (kA)		Peak circuit “Ip” (kA)	Short current
	Sy	Unsy	Sy	Unsy	Sy	Unsy
2% of the Line 1	278.8	91.4	4.9	4.8	11.9	11.7
50% of the Line 1	210.7	55.0	3.7	2.9	7.6	6.0
100% of the Line 1	176.8	42.2	3.1	2.2	6.0	4.3
25% of the Line 2	167.2	39.0	2.9	2.1	5.59	3.9
100% of the Line 2	156.2	35.5	2.7	1.9	5.1	3.5

Table 3.12 indicates that the fault level along the distribution line reduces as impedance increases, the minimum levels are obtained at the end of line two as well and line three respectively while closer to the source of supply fault levels are found to be at highest due to the minimum of line impedance at this point.

ii. Fault levels comparison

Symmetrical are types of electrical faults where all three phases of the system are affected by the faults occurring on the system, these faults are characterized by high magnitudes of fault currents. Asymmetrical electrical faults are typically faults that only affect a single phase and these faults have less magnitudes of fault levels when compared to the symmetrical type of faults. Figure 3.5

below provides the comparing graph for symmetrical and unsymmetrical faults that were simulated in the system.

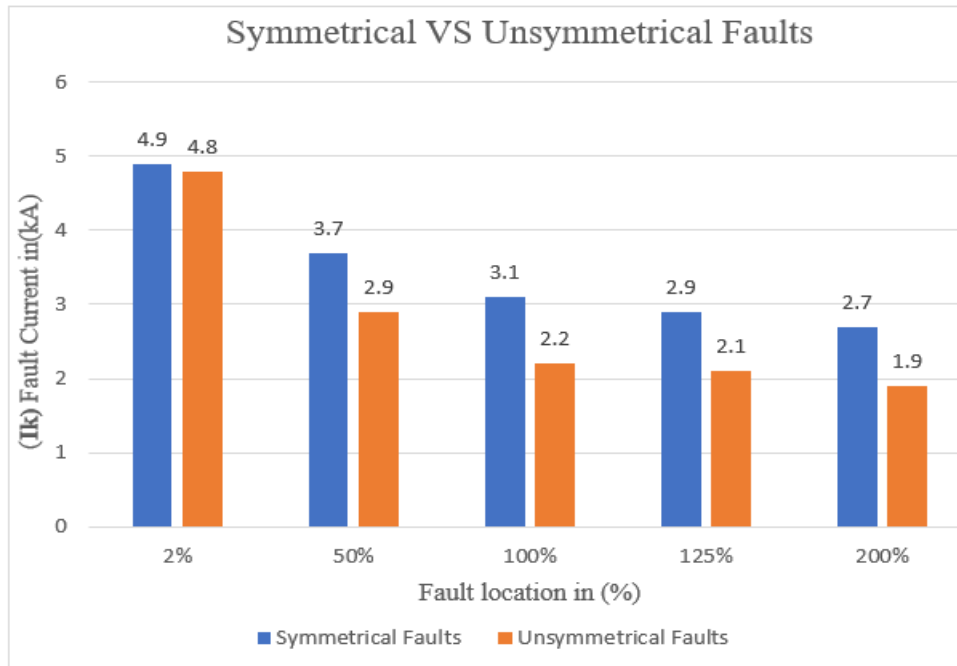


Figure 3.5: Symmetrical and Unsymmetrical faults comparison at the same locations

Figure 3.5 indicates that symmetrical and unsymmetrical faults are not equal even when faults occur at the same location.

3.6 Distance Protection Scheme

The distance protection scheme is an electrical protection scheme generally used to protect high-voltage transmission networks. The working principle of this scheme is based on measured voltage and current parameters to calculate impedance at the fault location. Normally distance relays are set with two types of settings, which are known as reach settings and operating time settings(Delavari et al., 2019).

Reach settings are defined as zone settings, such as zone 1, zone 2, and zone 3 and modern relays go up to zone 5. The protection ranges of each zone are as follows: Zone 1 is set between

80% to 90% of the line, Zone 2 is set between 120% to 150% of the line respectively and Zone 3 is normally set to cover both protected lines as indicated from Figure 3.6 below.

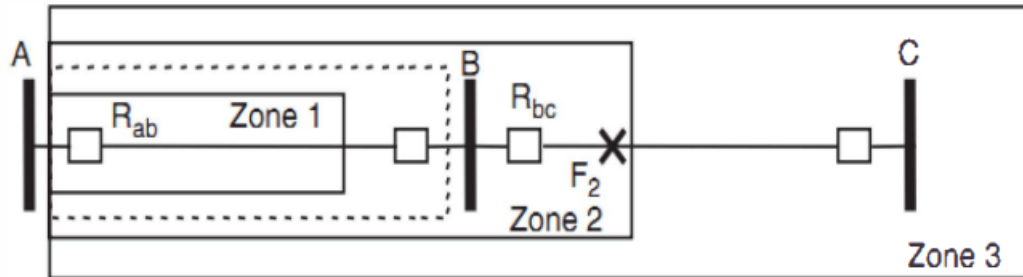


Figure 3.6: Distance protection scheme with three zones(Krishnamurthy & Van Wyk, 2015)

Figure 3.6 shows a three-zone protection scheme, where zone one lines cover about 80% of the first transmission line, zone 2 covers 100% of the first line and 20% of the second line, and lastly, zone 3 acts as a backup for both line since it covers 100% of both lines. In general, Mho and Quadrilateral are two commonly used characteristics of distance protection(Handono et al., 2019). For this study, the Mho characteristic curve will be used in protecting the 33kV distribution network.

3.7 Distance Relay Settings Configuration

Distance protection schemes are designed for long transmission lines with high voltages. The distance protection scheme is reviewed and enhanced in this study using more cutting-edge technologies, making the protection devices even more trustworthy with high data interchange capabilities and an increase in operating speed. In this chapter protection settings are created and validated. Instrument transformers are used for measurements when protecting a transmission line are provided in Table 3.13.

Table 3.13: Protective device type and measuring instruments.

Description	Parameter name	Rating
Distance Protection relays	IED: SEL (421)	5A
Current transformer	CT (Primary/ Secondary)	300 A/ 5 A
Voltage transformer	VT (Primary/Secondary)	33000V/110V

The current transformer and voltage transformer together with the type of protective device are shown in Table 3.13, this table indicates the CT and VT ratings.

Table 3.14: Power system data and transmission line length

Description	Parameter value	Devices and functions
Nominal Frequency	50 Hz	Frequency
Phase rotation	ABC	System rotation
System voltage	33kV	Rated voltage
Overhead lines	Rated 500A	Line current carrying capacity
Line 1 (length)	8 km	Main to Goodwood
Line 2 (length)	8 km	Goodwood to Bellville
Line 3 (length)	16 km	Main to Bellville
Line material	Copper	
Line resistance /km	0.215 ohm	Positive and negative sequence parameters

Line reactance /km	0.334 ohm	Positive and negative sequence parameters
Line resistance /km	0.364 ohm	Zero sequence parameters
Line reactance /km	1.556 ohm	Zero sequence parameters

Table 3.14 presents the power system parameters together with the transmission line length. Per kilometer resistance of the transmission lines is indicated.

3.8 Distance Protection Simulation Results

The distance protection scheme is designed to protect the system provided in Figure 3.7 below. DigSILENT software allows the implementation of a distance protection scheme, and the network under study is protected using the SEL 421 Protection relay which is available on the DigSILENT library.

Two designed protection schemes are provided and discussed as two separate case studies.

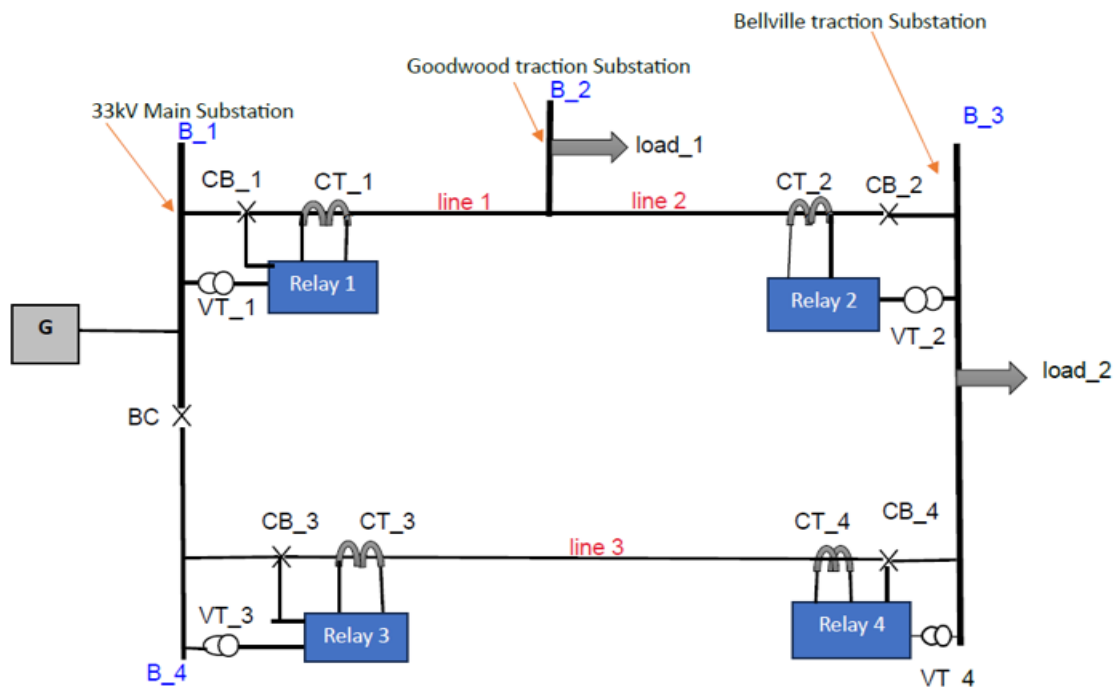


Figure 3.7: System layout

i. Case Study 1:

Case study 1, will present results and analyses of protection settings for Relay 1 and Relay 2 respectively, these two relays are responsible for protecting line 1 and line 2 as indicated in Figure 3.7 above.

ii. Case Study 2:

Case study 2, will present results and analyses of protection settings for Relay 3 and Relay 4 respectively, these two relays are responsible for protecting line 3 as indicated in Figure 3.7 above.

3.8.1 Case Study 1:

As indicated in Figure 3.7, Relay 1 and Relay 2 are protecting Line 1 and Line 2 respectively. Relay 1 is set to protect 80% of line 1 in a forward direction, zone 2 of relay 1, is set to protect 100% of line 1 and 20% of line 2 (120 % of line 1), and lastly, zone 3 of relay 1, is set to cover 100% of line 1 and 100% of line 2.

Depending on the location of the fault, Relay 1, and Relay 2, protect line 1 and line 2 as the main protection and the other as a backup protection. A fault on these lines is seen by both relays.

When one relay is the main protective relay in a particular location, the other relay acts as backup protection. Table 3.15 presents the protection settings for both relays (Relay 1& Relay 2) respectively.

Figure 3.8 below shows the time distance plot for Relay 1 located at the Main substation facing towards the Bellville substation (red graph) and the time distance plot for Relay 2 at the Bellville substation facing backward to the Main substation (green graph).

Table 3.15: Mho distance protection settings for Relay 1 and Relay 2

Parameter name	Set time(s)	Parameter direction	Zone impedance (Primary)	line angle ($\emptyset$) in degrees	Zones
Z1MP	0.02 s	Forward	2.5 ohm	65	Zone 1

Z2MP	0.3 s	Forward	4.7 ohm	65	Zone 2
Z3MP	0.6 s	Forward	6.3 ohm	65	Zone 3
Z1MG	0.02 s	Forward	2.5 ohm	65	Zone 1
Z2MG	0.3 s	Forward	4.7 ohm	65	Zone 2
Z3MG	0.6 s	Forward	6.3 ohm	65	Zone 3

Table 3.15 shows the phase and ground fault settings that are inserted into the relay to protect line 1 and line 2. The designed protection settings consist of three Mho reach zones, zone 1, zone 2, and zone 3 for both phase and earth faults. Reach zones are all designed to protect the line in a forward direction, where zone 1 covers the primary line impedance of 2.5 ohms, zone 2 covers 4.7 ohms, and zone 3 covers the primary line impedance of 6.6 ohms. Figure 3.8 presents phase and ground fault settings in a time distance plot where zone reach is presented graphically.

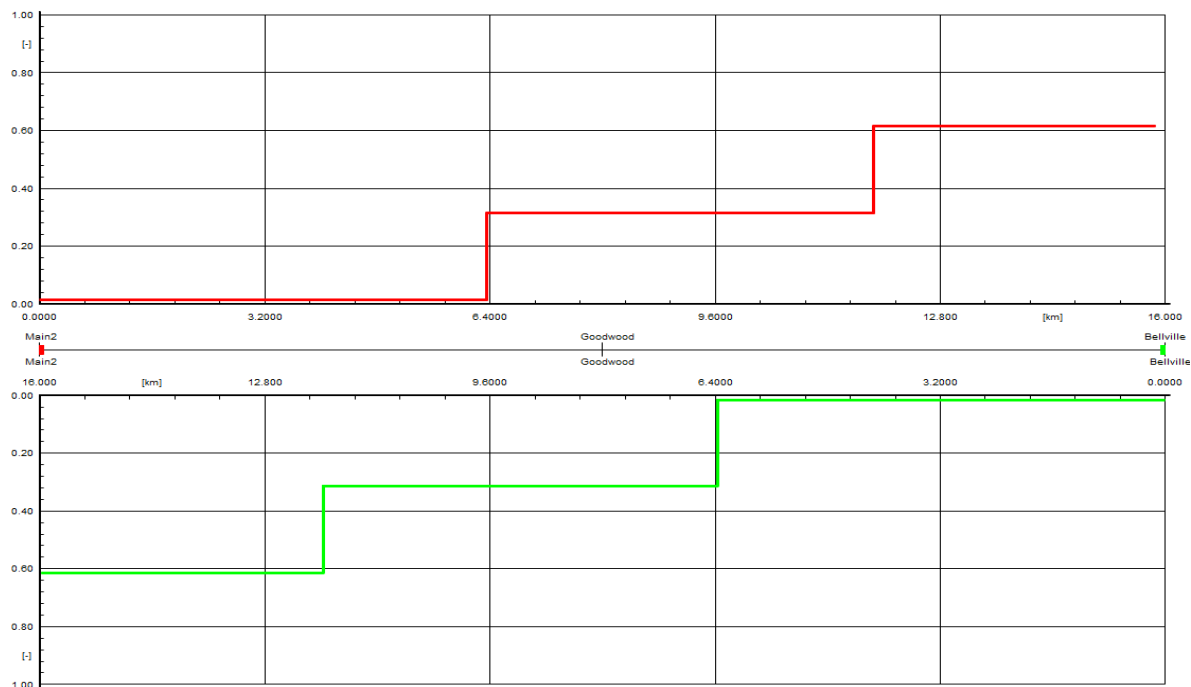


Figure 3.8: Time distance plot for Relay 1 and Relay 2

Figure 3.8 further indicates operating times at each protected zone, and the length covered by each zone is shown.

Table 3.16 provides details indicating fault locations and indicating which relay must clear the fault, and which relay will act as a backup protection for a fault occurring in line 1 or line 2.

Table 3.16: Fault locations and Relays protecting line 1 and line 2.

Fault location [@]	Main protection		Backup protection	
	Relay	Trip zone	Relay	Backup zone
50% of line 1	1	1	2	3
90% of line 1	1 & 2	2	-	-
45% of line 2	2	1	1	2
95 % of line 2	2	1	1	3
19% of line 2	2	2	1	2

Table 3.16 presents the protection system for line 1 and line 2. It must be noted that when the fault occurs between 81% of line 1 and 19% of line 2 both relays will operate at the same time in zone 2. Figure 3.9 shows the Mho characteristic curve of a distance protection relay. This shows tripping zones and the trip time for a simulated three-phase fault in line 1.

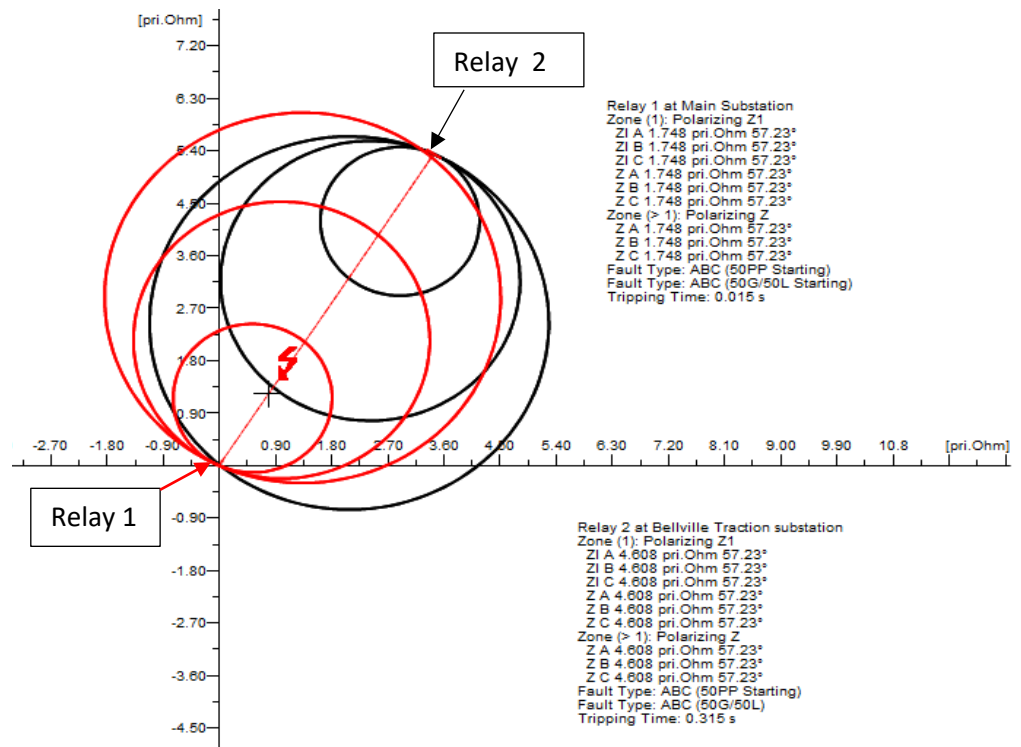


Figure 3.9: Mho results for Relay 1 and Relay 2 for three-phase fault.

Figure 3.9 above shows the behavior of the two relays when a three-phase fault is simulated at 55 % of line 1. Ideally, Relay 1 must operate first to clear the fault since this fault is at zone 1 (red curve) of relay 1 and it is set to operate instantaneously on the zone reach.

In Figure 3.9 it is indeed shown that Relay 1 operated first at 0.015 seconds, while Relay 2 would have cleared the fault at 0.315 seconds as this fault is at zone 2 of Relay 2 (black curve). Table 3.17 further provides the results of the Mho characteristic curve shown in Figure 3.9 in table form.

Table 3.17: Relay 1 and Relay 2 results for a three-phase fault in line 1

Parameter	Relay 1		Relay 2	
	Fault impedance $ Z \Omega$	Line angle(δ) in degrees	Fault impedance $ Z \Omega$	Line angle(δ) in degrees
$ Z $ 'A'	1.75	57.23	4.61	57.23
$ Z $ 'B'	1.75	57.23	4.61	57.23
$ Z $ 'C'	1.75	57.23	4.61	57.23
Fault type	ABC		ABC	

Trip time	0.015 seconds	0.315 seconds
Trip zone	1	2

Figure 3.10 below shows the behavior of the two relays when a single phase to ground fault is simulated at 55 % of line 2. Relay 2 must operate first to clear the fault since this fault is at zone 1 (black curve) of relay 2 and it is set to operate instantaneously in zone 1.

From the results presented in Figure 3.10, it is indeed indicated that Relay 2 operated first at 0.015 seconds while Relay 1 is acting as backup protection for Relay 2, and it will trip after 0.615 seconds as this fault is located at zone 3 of this relay (red curve).

Figure 3.10 shows the Mho characteristic curve when a single phase to ground fault is simulated and verifies which relay responds to the fault.

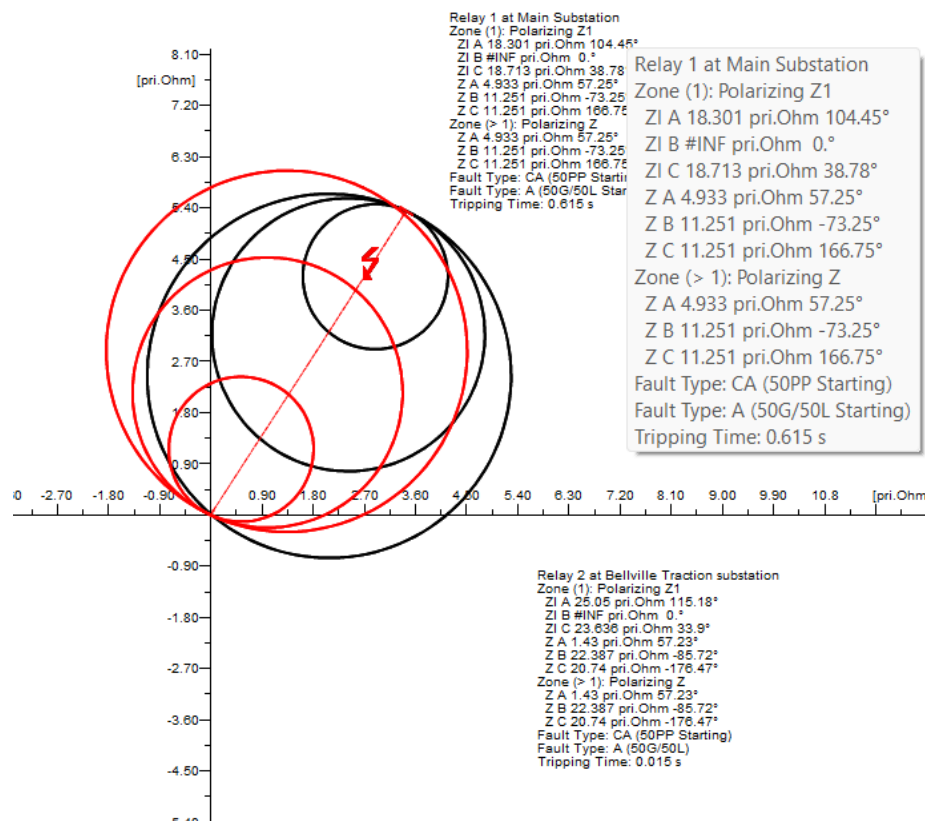


Figure 3.10: Mho results for Relay 1 and Relay 2 for single-phase-ground fault.

Table 3.18 further provides the results presented in Figure 3.10 in table format. This table provides the fault impedance measured by both relays; from the results, it is noticed that phase 'A' (lowest impedance) was the one that was affected by comparing the line impedance of all three phases.

Table 3.18: Relay 1 and Relay 2 results for a single-phase-ground fault in line 2

Parameter	Relay 1		Relay 2	
	Fault impedance $ Z \Omega$	Line angle(δ) in degrees	Fault impedance $ Z \Omega$	Line angle(δ) in degrees
$ Z $ 'A'	4.93	57.23	1.43	57.23
$ Z $ 'B'	11.25	-73.25	22.38	-85.72
$ Z $ 'C'	11.25	166.75	20.74	-176.47
Fault type	AG		AG	
Trip time	0.615 seconds		0.015 seconds	
Trip zone	3		1	

3.8.2 Case Study 2:

In this case study, the relay configuration settings are different from the one in case study one, even though the length of both lines is the same. This is due to the zone reach that is in operation for line 3, where only two zones are activated unlike in case study one, where three zones are activated. Table 3.19 below shows the relay settings of both relays, Relay 3 at the Main substation and Relay 4 at the Bellville traction substation protecting line 3 as indicated in Figure 3.7.

Table 3.19: Mho distance protection settings for relay 3

Parameter name	Set time(s)	Parameter direction	Zone impedance (Primary)	Line angle(ϕ) in degrees	Zones
Z1MP	0.02 s	Forward	5.1 ohm	65	Zone 1
		Forward			

Z2MP	0.3 s		6.4 ohm	65	Zone 2
Z1MG	0.02 s	Forward	5.1 ohm	65	Zone 1
Z2MG	0.3 s	Forward	6.4 ohm	65	Zone 2

Table 3.19 shows the two zones of Mho distance relay settings for phase and ground faults respectively for Relay 3 located at the Main substation and Relay 4 which protects transmission line 3 as indicated in Figure 3.7.

Settings from Table 3.19 are represented on a time distance plot to indicate the length of the line covered by zone elements and the R-X Mho plots show the tripping times of relays for both earth fault and three-phase faults.

Figure 3.11 shows relay settings for Relay 3 and Relay 4 in the time distance plot. Two zones of distance scheme (Mho characteristics) are shown in Figure 3.12 for a three-phase fault and Figure 3.13 presents a Mho characteristic curve when a single line to ground fault is simulated.

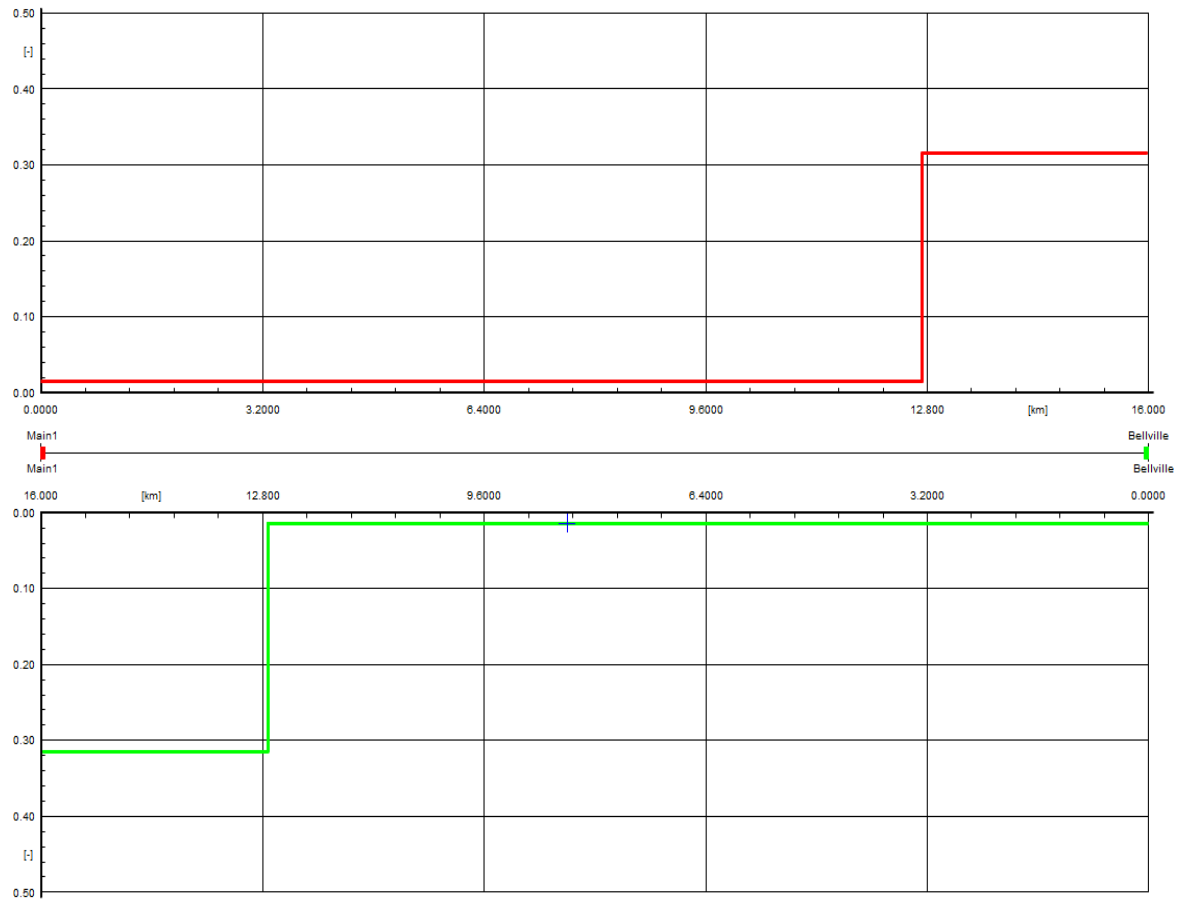


Figure 3.11: Time distance plot for Relay 3 and Relay 4

Figure 3.11 presents the time settings of two zones for both relays, Relay 3, and Relay 4 respectively. The length of the line in kilometers is provided to indicate the length covered by each zone. Zone 1 of both relays is set to cover 12km from both ends of the transmission line and zone 2 of both relays is set to cover 16km (total length) of the line also in opposite directions.

Figure 3.12 provides the Mho characteristic curve for a three-phase fault which is simulated at 50% of line 3 and Figure 3.13 presents the Mho characteristics curve for a single phase to ground fault simulated at 90% of line 3.

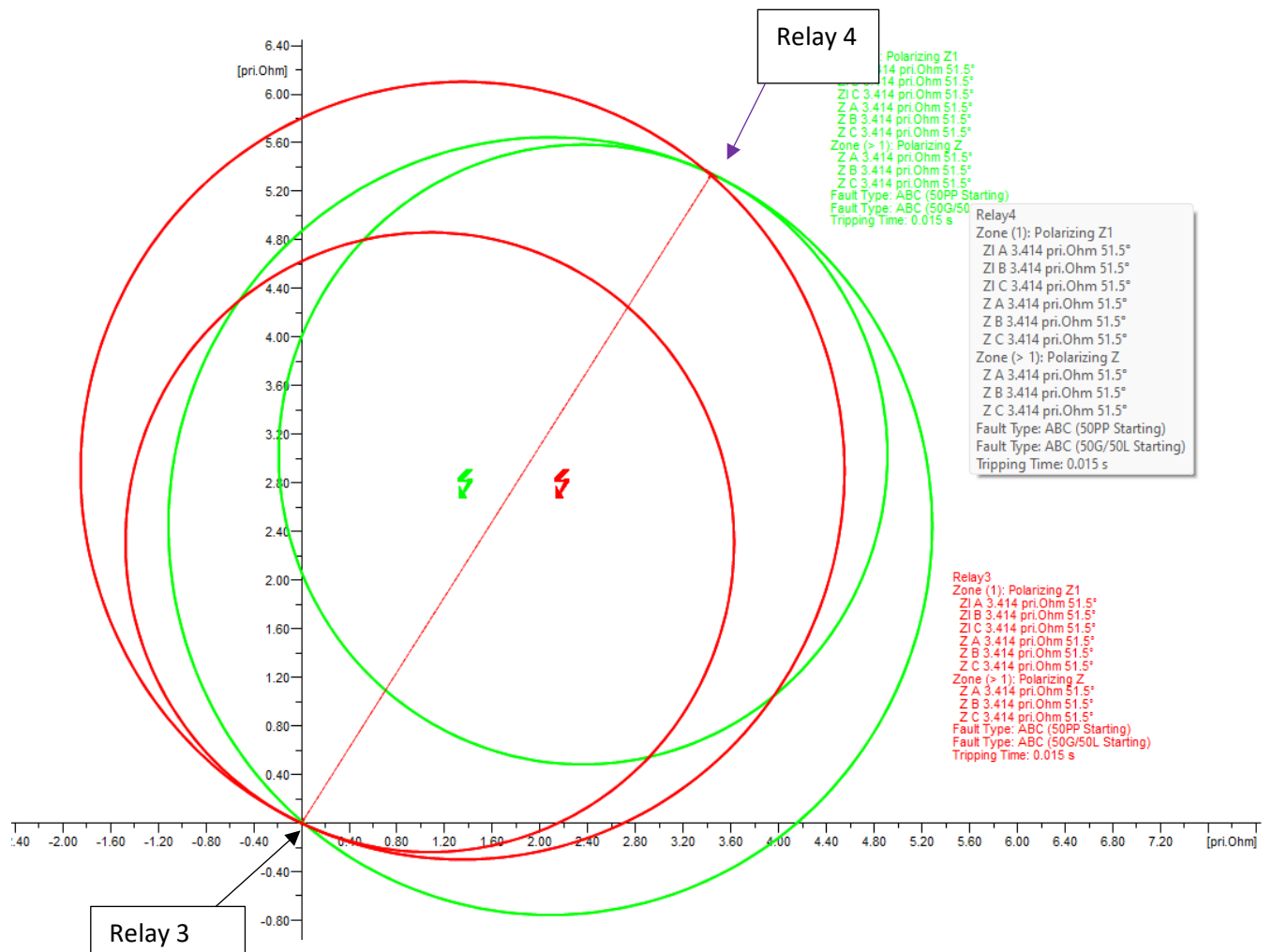


Figure 3.12: Mho characteristics curve for relay 3 and relay 4 for three-phase fault.

Figure 3.12 shows a three-phase fault applied at 50% of line 3, ideally both relays will operate at the same time (0.015 seconds) when a fault occurs in this location as this point is covered by zone 1 of both relays.

Table 3.20 presents the operation of Relay 3 and Relay 4 for a three-phase fault in a table format. In Table 3.20 it is clearly shown that Relay 3 and Relay 4 are measuring the same fault impedance for a fault that is located at 50% of the line. Relays have the same tripping time since this fault is at zone 1 of each relay.

Table 3.20: Relay 3 and Relay 4 results for a three-phase fault in line 3

Parameter	Relay 3		Relay 4	
	Fault impedance $ Z \Omega$	Line angle(δ) in degrees	Fault impedance $ Z \Omega$	Line angle(δ) in degrees
$ Z $ 'A'	3.414	51.5	3.414	51.5
$ Z $ 'B'	3.414	51.5	3.414	51.5
$ Z $ 'C'	3.414	51.5	3.414	51.5
Fault type	ABC		ABC	
Trip time	0.015 seconds		0.015 seconds	
Trip zone	1		1	

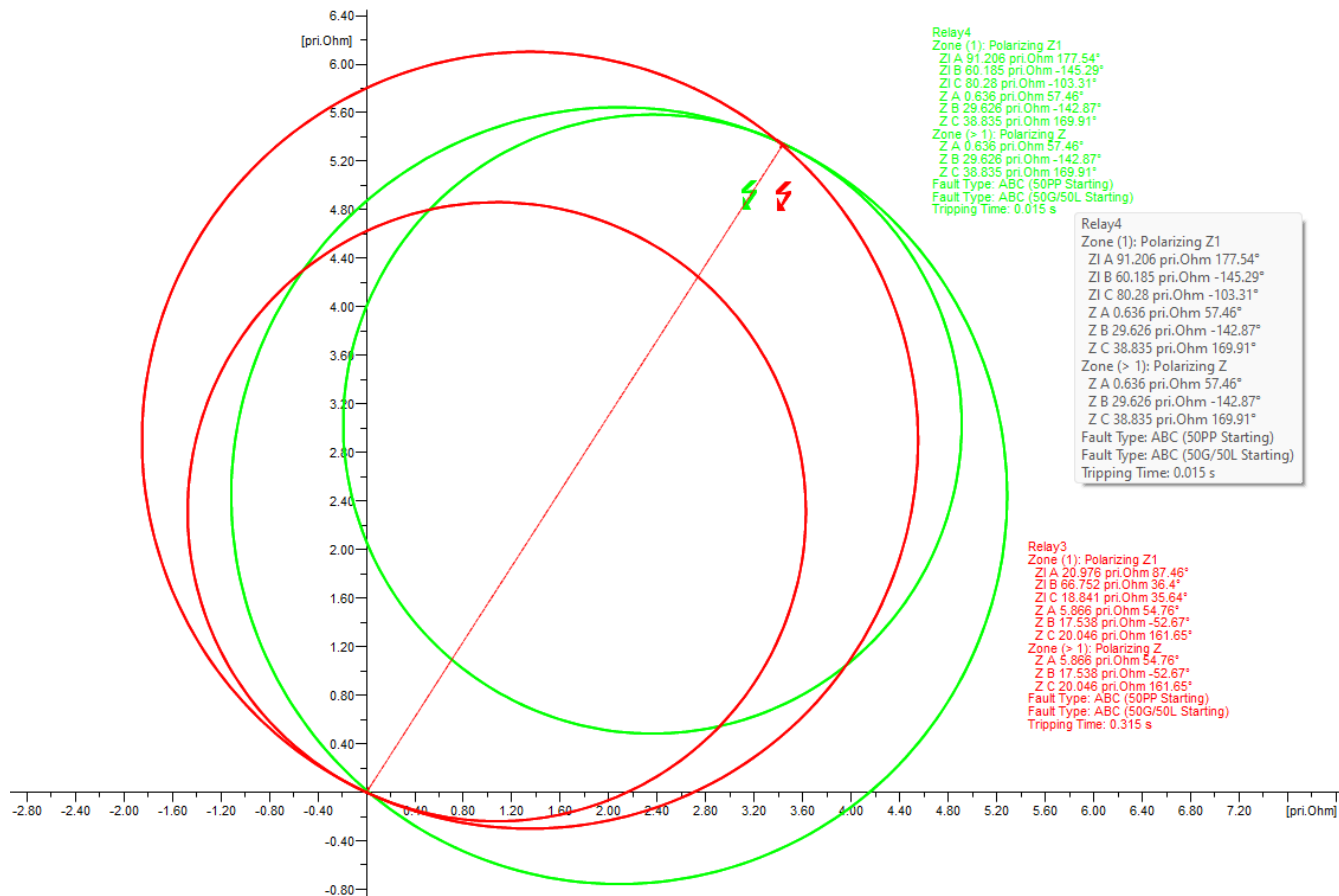


Figure 3.13: Mho curve for relay 3 and relay 4 for single-phase-ground fault.

Figure 3.13 presents the results when the single phase to ground fault is applied at 90% of the location of the transmission line 3. At this point zone 1 of Relay 4 (Green curve) operates instantaneously and zone 2 of Relay 3 will operate after 0.315 seconds as a backup protection. Table 3.21 demonstrates the operation of Relay 3 and Relay 4 for a single-phase-ground fault in a table.

Table 3.21: Relay 3 and Relay 4 results for a single-phase-ground fault in line 3

Parameter	Relay 3		Relay 4	
	Fault impedance $ Z \Omega$	Line angle(δ) in degrees	Fault impedance $ Z \Omega$	Line angle(δ) in degrees
$ Z $ 'A'	5.86	54.76	0.636	57.47
$ Z $ 'B'	17.5	-52.67	29.63	142.87
$ Z $ 'C'	20.04	161.65	83.38	169.91
Fault type	A-G		A-G	
Trip time	0.015 seconds		0.315 seconds	
Trip zone	1		2	

3.9 A comparative analysis of the proposed Mho distance protection scheme with Quadrilateral characteristics

The distance protection scheme is a scheme commonly used to protect power lines where fast clearance of a fault is a priority. (Moyo et al., 2021) performed a study to analyze the distance protection scheme for a Gautrain network in South Africa, where the protection scheme was analyzed, and tested and results are provided.

The study conducted by (Moyo et al., 2021) applies a different distance protection scheme (Quadrilateral distance relay).

The network used as a reference for (Moyo et al., 2021) study it's an AC traction system rated at 25kV. A comparison of results, and protection settings designed from this study and (Moyo et al., 2021) study is provided in Table 3.22 below.

Table 3.22: Comparison of distance protection test results of the Quadrilateral and Mho characteristics

Studies	Protection Zone	Zone Direction	Trip time settings (s)	Rated Voltage system (AC)	Distance relay type
(Moyo et al., 2021)	1	Forward	0.00	25kV	Quadrilateral distance relay
	2	Forward	0.3		
	3	Reverse	1		
Proposed Test results of the Mho distance protection scheme	1	Forward	0.02	33kV	Mho distance relay
	2	Forward	0.3		
	3	Forward	0.6		

3.10 Breaker failure trip logic of the proposed distance protection relay

The SEL-421 protection relay has dedicated circuit breaker failure trip logic. Set SELOGIC control equation BFTR1 (Breaker Failure Trip—BK1) to assert for circuit breaker failure trips from Relay Word bits FBF1, NBF1, LCBF1, and FOBF1. When this SELOGIC control equation asserts, the relay sets Relay Word bit BFTRIP1 (Breaker Failure Trip for Circuit Breaker BK1) to logical 1 until BFTR1 deasserts, timer TDUR3D times out, and an unlatch or reset condition is active. Figure 3.14 below shows the breaker failure trip logic of the SEL 421 relay used in this project.

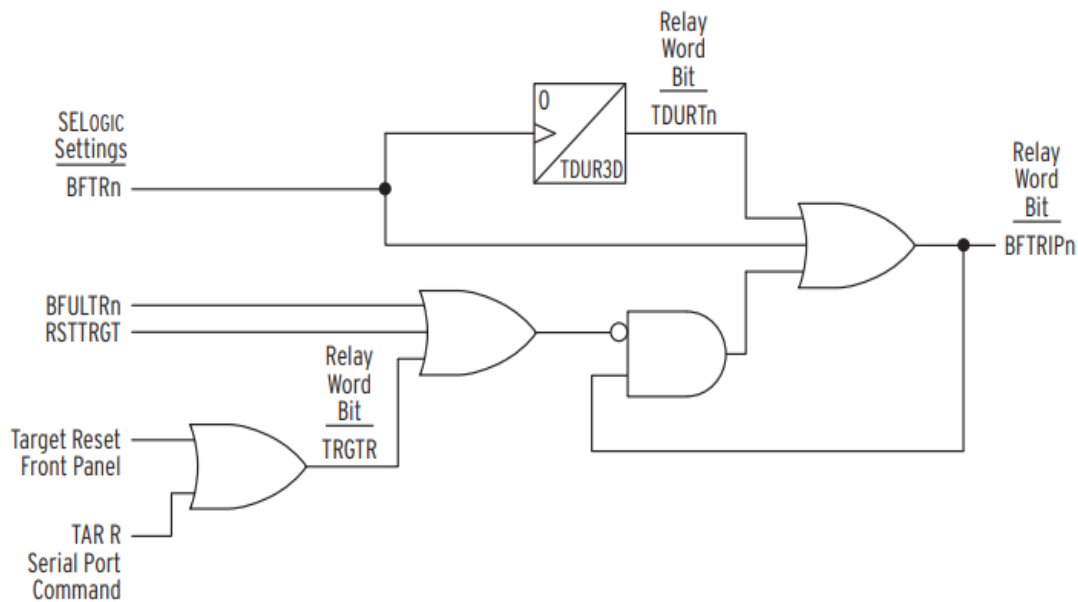


Figure 3.14: SEL 421 Breaker failure trip logic (SEL 2016).

3.11 Discussion of Results

In this study, the focus has been on simulating the 33kV network on a simulation tool that allows the running of load flow and implementation of a distance protection scheme. As the network was simulated from a DigSILENT environment, results were obtained and analyzed to see if the desired results were obtained or not. When running load flow, the obtained results were satisfying, because all obtained results fulfilled most of the power system requirements such as voltage profile limits.

In traditional power systems, protection relays would have been only found at the beginning of the network and only one relay would have been used to protect each transmission line. Referring to Figure 3.2, this means the traditional power system would have only relay 1 and relay 3 protecting the outgoing lines. This chapter introduced and simulated a power system, that has multiple relays protecting the same transmission line, and those relays need to communicate with each other.

Desired distance protection settings have been applied to the simulation, to see the behavior of the relays when different types of faults occur at different locations along the transmission line. Three-phase and single-phase to-ground faults were simulated, and the obtained results were also satisfying because relays were operating in the right zones and responding as per time settings.

3.12 Conclusion

This chapter addressed a distance protection scheme and implemented it on the simulation tool. 33kV network has been used for this study to simulate the load flow and implement a Mho distance protection scheme. The selected network to be protected belongs to one of the state-owned companies that is responsible for operating trains and is known as the Passenger Rail Agency of South Africa (PRASA).

This network is a very critical network that needs to be well protected to avoid malfunctioning of protection relays and avoid unnecessary power supply cut-off to the desired loads. The power flow of the network was simulated, and results were obtained and analyzed. From the simulation results, it is evident that the designed protection settings are suitable for implementation to protect this 33kV network and they can improve malfunction of protection relays.

Implementation of these protection settings would improve the reliability and dependability of the protection devices. The next chapter will discuss the lab-scale implementation of the distance protection scheme.

CHAPTER FOUR

IMPLEMENTATION OF THE LAB SCALE TEST BENCH TO TEST DISTANCE PROTECTION SCHEMES FOR THE 33kV DISTRIBUTION NETWORK.

4.1 Introduction

Transmission and distribution lines are the most important part of the power distribution networks. It is for this reason that great care for network healthiness is critical in power system engineering. Depending on the system voltage level, and line length, those aspects determine what protection scheme is suitable for that network. According to (Agila-Rios et al., 2021a) distance relays are normally used for high-voltage lines due to their advantages over overcurrent protection relays.

Distance protection relays operated based on the measured voltage and measured current on the protected line to calculate the fault impedance. This chapter provides the lab scale test bench to simulate faults on the relay and see how the relay reacts to simulated faults. SEL 421 relay is used to develop the lab scale together with the secondary injection test set (CMC 256 plus). CMC256 plus is used to supply current and voltage signals into the relay and configuration is done on a test universe software for the interface.

The obtained results are compared with the results obtained from the software simulation (DigSilent) from Chapter Four. The first part of this chapter indicates and provides configuration settings for the protection relay. The second part of this chapter illustrates the lab scale for testing relay settings functionality using CMC 256 plus a secondary injection set. Lastly, relay response results are also presented and discussed in the conclusion.

4.2 Protection settings on a numerical distance relay

In this section of chapter five, the lab scale for testing relay functionality is provided and discussed in more detail. Figure 4.1 presents the network under study, and it indicates the locations of protective relays in the system. The layout of the test bench used to test relay settings is provided in Figure 4.2 and Figure 4.3 below. The protection design of this network is divided into two case studies (case study one and case study two).

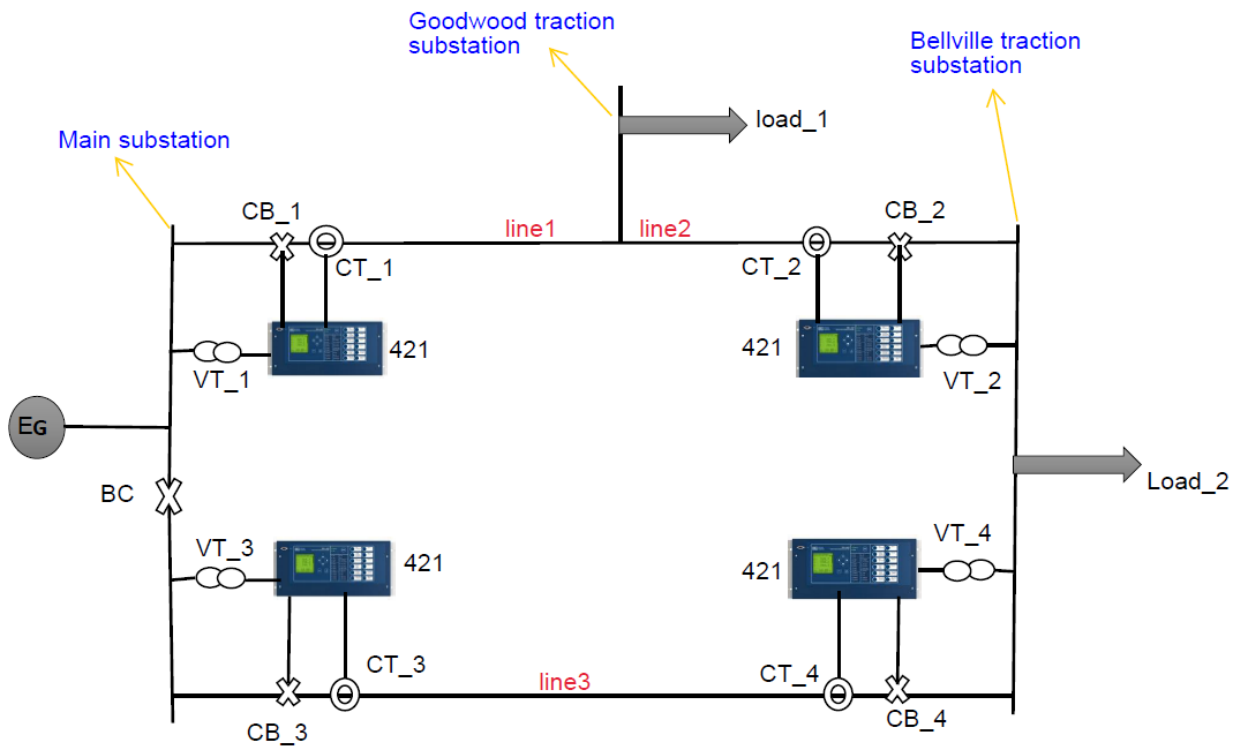


Figure 4.1: Electrical network under study

Figure 4.1 presents the protective devices used in protecting electrical power systems, where VTs and CTs are measuring instruments for voltage and current signals and reduce the signals into values that can be handled by a protective relay. Table 4.1 below provides the technical data for instrument transformers.

Table 4.1: Technical details for instrument transformers

Description	Parameter name	Rating
Current transformer	CT (Primary/ Secondary)	300 A/ 5 A
Voltage transformer	VT (Primary/Secondary)	33000V/110V

Case Study One: This case study presents a design protection scheme for line one and line two as shown in Figure 4.1. These two relays are designed to have three-zone reach protection settings (Zone 1, Zone 2, and Zone 3) for phase and ground faults.

Case Study Two: Case study two presents a design protection scheme for line three of Figure 4.1. Relay 3 and Relay 4 protection settings are designed to have two zones of protection (Zone 1, and Zone 2) for phase and ground faults.

4.2.1 Development of the laboratory test bench

The laboratory test bench has been developed to test relay settings functionality at the laboratory level. Figure 4.2 below shows the lab scale and labels for each device used in testing the relay at the lab.

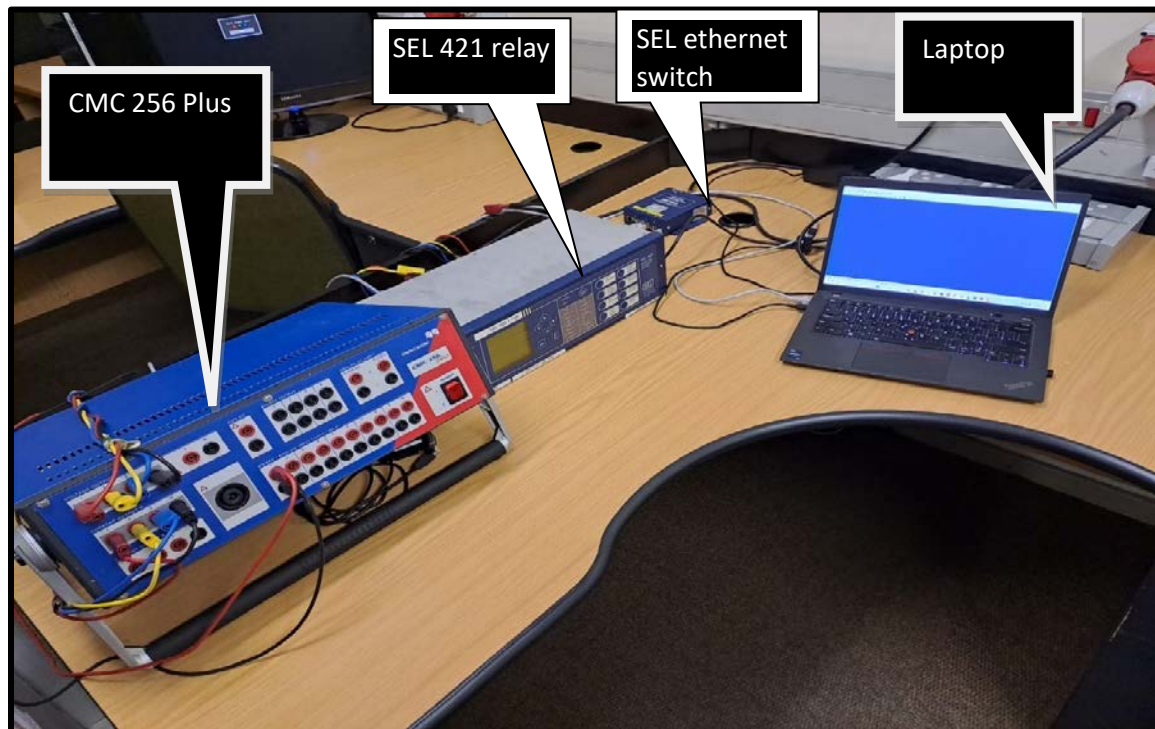


Figure 4.2: Test universe laboratory test setup

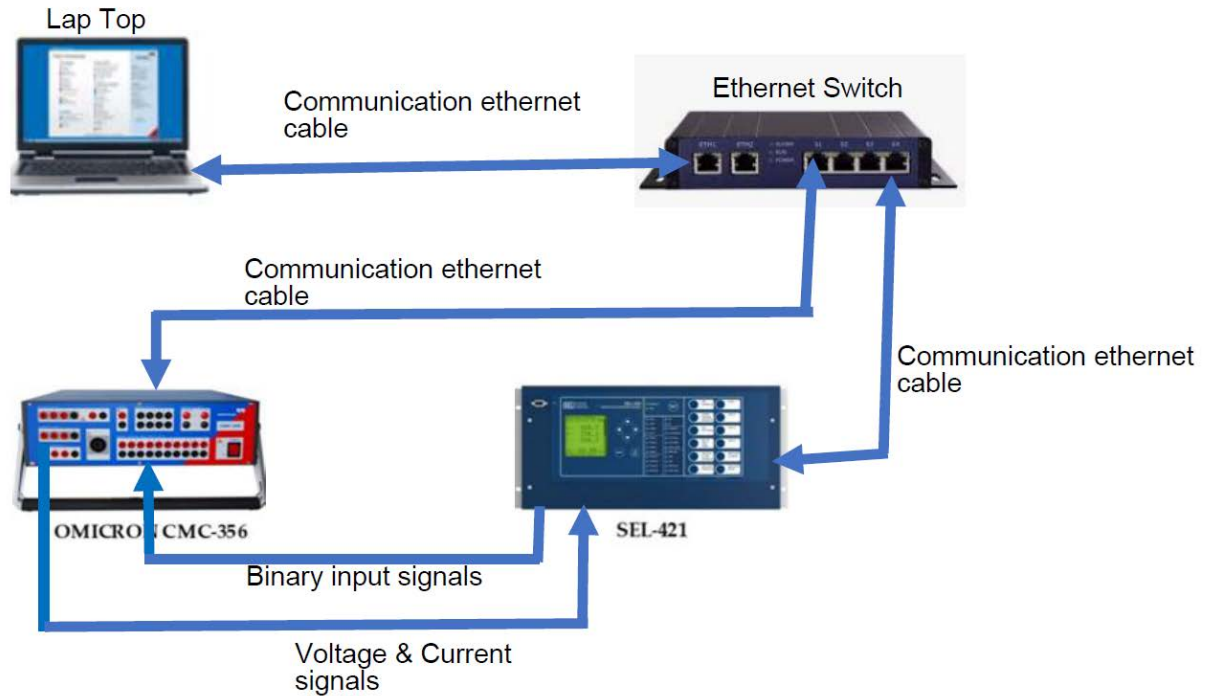


Figure 4.3: Laboratory test setup connections between devices

Figure 4.3 shows the connections between devices presented in Figure 4.2 and communication is achieved using ethernet cable.

4.2.2 Case Study One: line 1 and Line 2 protection design

This case study refers to the line between the Main 33kV substation from bus bar two, and the Bellville traction substation as indicated in Figure 4.2 in chapter four.

Settings for this line are designed to cover three zones for both phase faults and ground faults. Engineering configuration is done using AcSelerator Quickset software. The engineering settings configuration (ESC) of Relay 1 and Relay 2 are presented in Table 4.2 below.

Table 4.2a: General and line configuration data

General Global settings		Line Configuration	
NFRQ	50 Hz	CTR (Current transformer ratio)	60
PHROT	ABC	PTR (Voltage transformer ratio)	300
SID	33kV Traction Main substation	VNOMY (Voltage Nominal)	110 V
RID	SEL 421	Z1MAG (Positive sequence)	1.27 Ω
N/A		Z1 ANG (Positive sequence)	57.2 ⁰
		Z0MAG (Zero sequence)	5.11 Ω
		Z0 ANG (Zero sequence)	76.87 ⁰

Note:

NFRQ: Nominal frequency, PHROT: Phase rotation, SID: Substation identifier, RID: Relay identifier, Z1MAG: Positive sequence impedance magnitude,

Z1ANG: Positive sequence angle, Z0MAG: Zero sequence impedance magnitude, Z0ANG: Zero sequence angle.

$$\text{CTR} = \frac{300}{5} = 60 \quad (4.1)$$

$$\text{VTR} = \frac{33\,000}{110} = 300 \quad (4.2)$$

Table 4.2b: Relay protection setting configurations.

Distance Element	Mho distance Element and set values. (Ω , secondary values)		Zones	Distance time Element (cycles)	Distance time Element (ms)
Phase	Z1P	0.51	3	1	20
	Z2P	0.95		15	300

	Z3P	1.27		30	600
Ground	Z1MG	0.51	3	1	20
	Z2MG	0.95		15	300
	Z3MG	1.27		30	600
Zero sequence compensation factor	K0M1	1.033	N/A	N/A	N/A
	K0A1	25.9 ⁰	N/A	N/A	N/A

Note: k0 is calculated as follows:

$$k0 = \frac{z_0 - z_1}{3z_1} \quad (4.3)$$

Where:

z_0 : is called zero sequence impedance,

z_1 : is called positive sequence impedance.

Table 4.2c: Output and trip logic configuration.

DESCRIPTION	PARAMETERS
Trip Logic (SELOGIC)	M1P OR Z1G OR M2PT OR Z2GT OR M3PT OR Z3GT
OUT101 (MAIN BOARD OUTPUTS)	

Distance relay programming has been done on the following.

- General and Line configurations are presented in Table 4.2a.
- Distance protection elements configuration is provided in Table 4.2b.
- Trip Logic and Main Board OUTPUTS configurations are presented in Table 4.2c.

Figure 4.4 below presents the zone 1 Mho phase distance element trip logic diagrams.

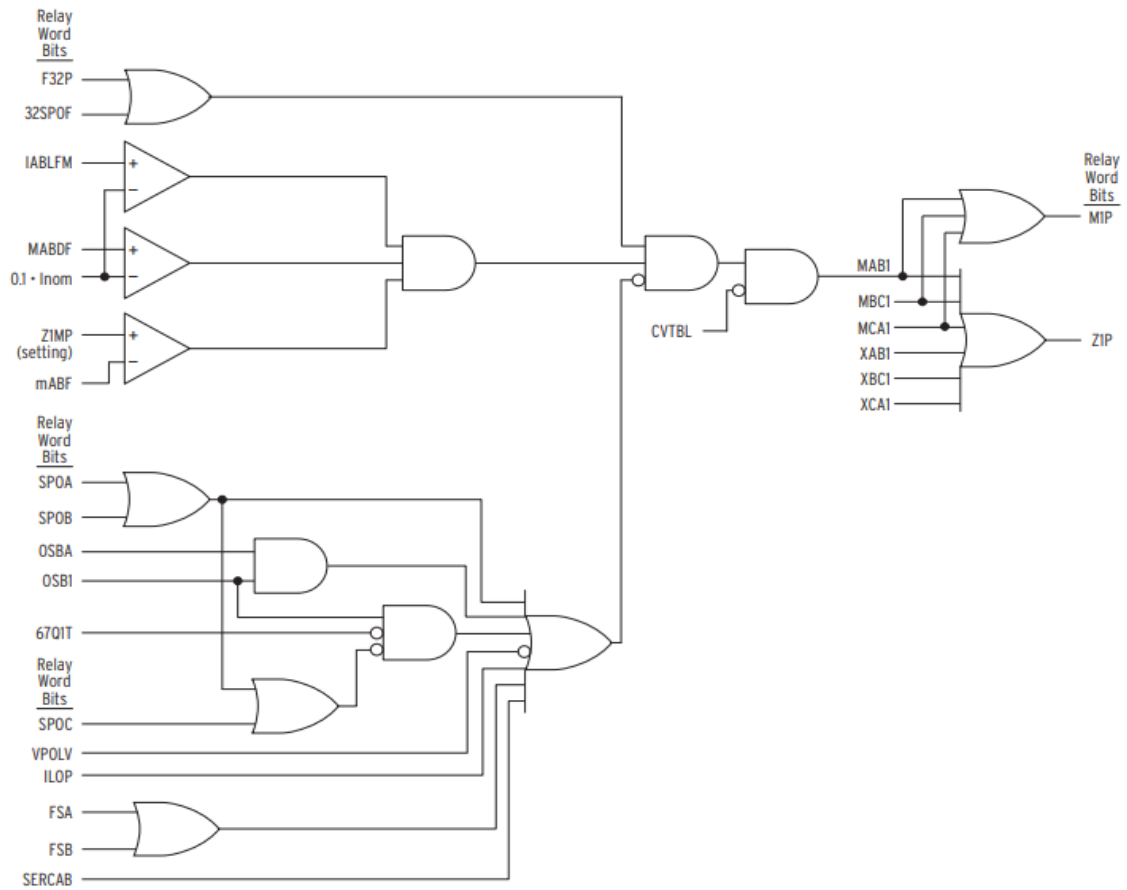


Figure 4.4: Zone 1 Mho phase distance element logic diagram(SEL 2016).

Figure 4.5 below presents a zone 2 Mho phase distance element trip logic diagram.

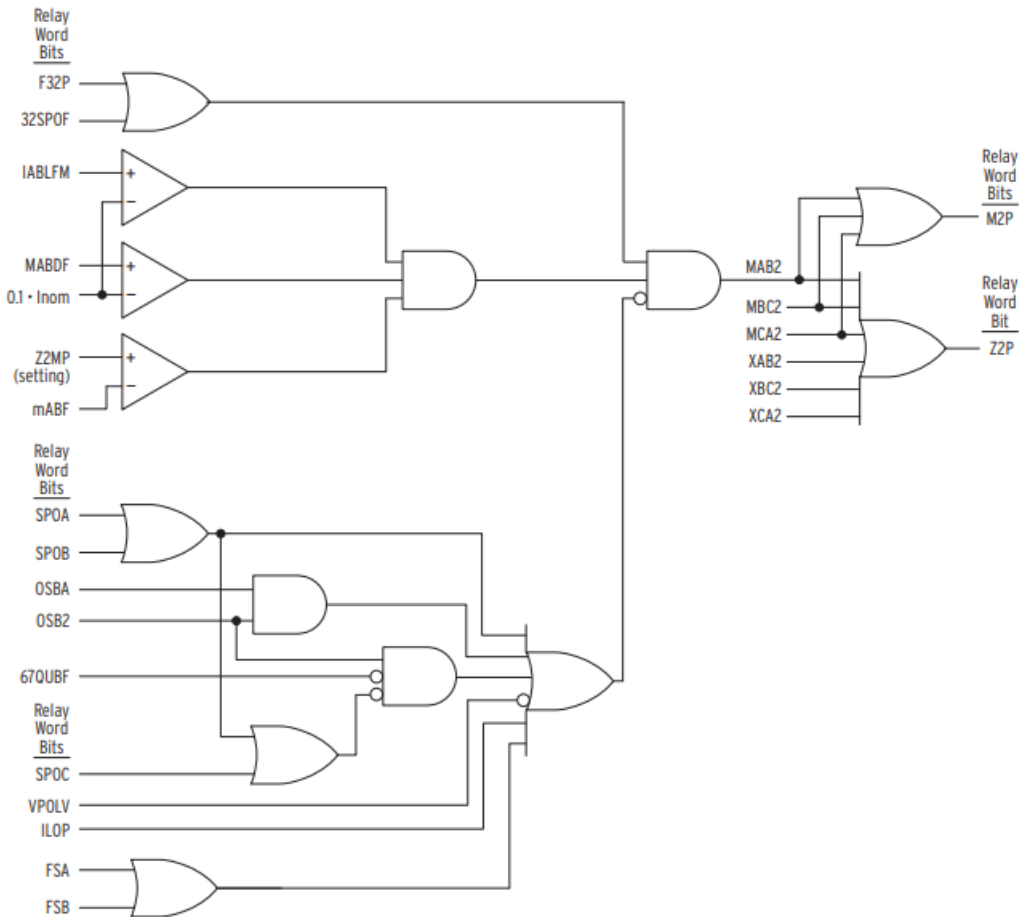


Figure 4.5: Zone 2 Mho phase distance element logic diagram(SEL, 2016).

Design protection settings have three activated zone reach (zone 1, zone 2 & zone 3) for phase fault protection. The high-speed Mho phase distance element only operates on phase-to-phase, phase-to-phase-ground, and three-phase faults.

Tripping logic diagrams for Mho zone 1 and Mho zone 2 elements are presented in Figure 4.4, and Figure 4.5 respectively. Mho phase distance logic diagrams of zone 3, zone 4, and zone 5 are provided in the appendix section. Figure 4.6 and Figure 4.7 below provide trip logic diagrams for Mho ground elements (zone 1 and zone 2).

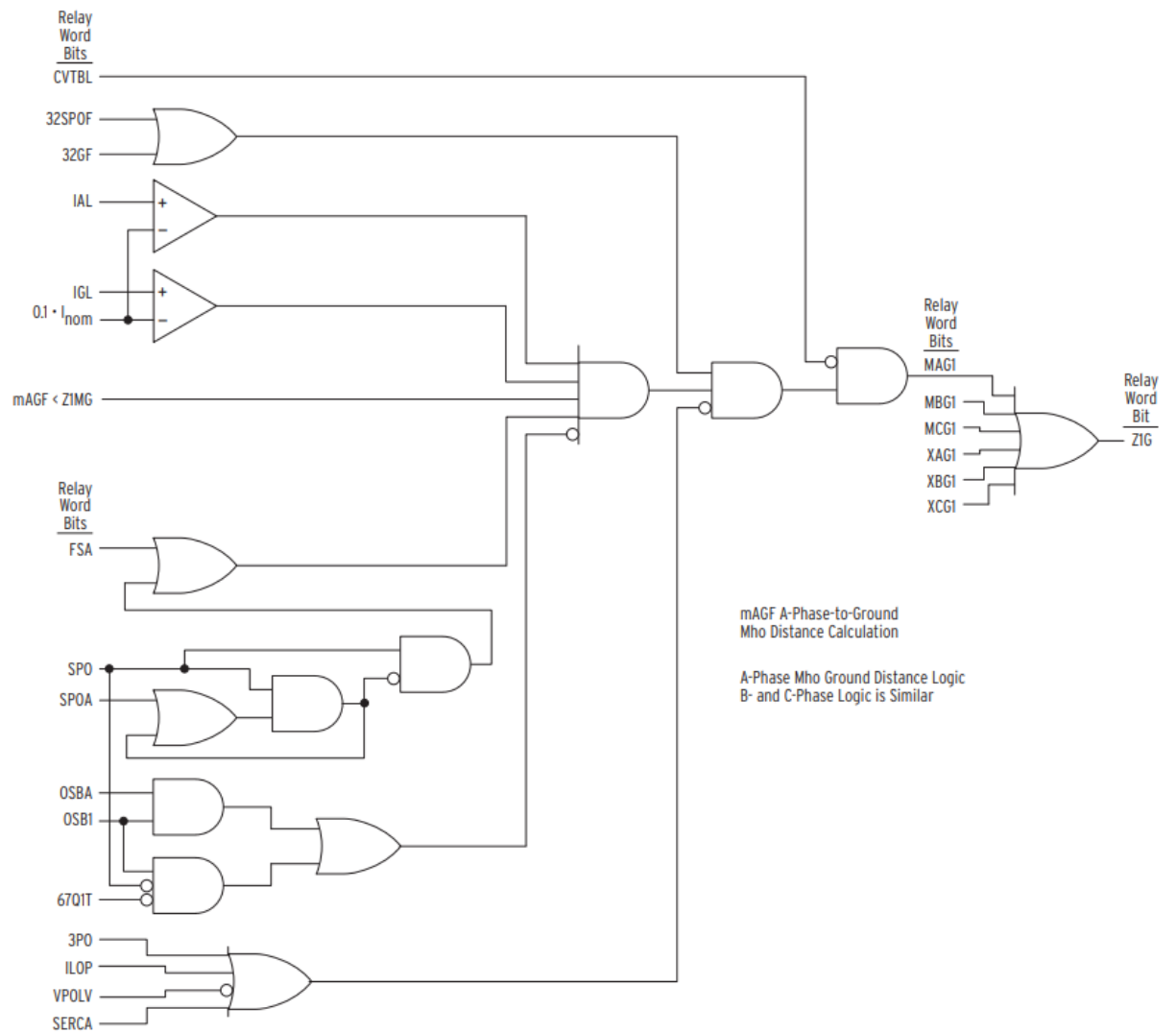


Figure 4.6: Zone 1 Mho ground distance element logic diagram(SEL, 2016).

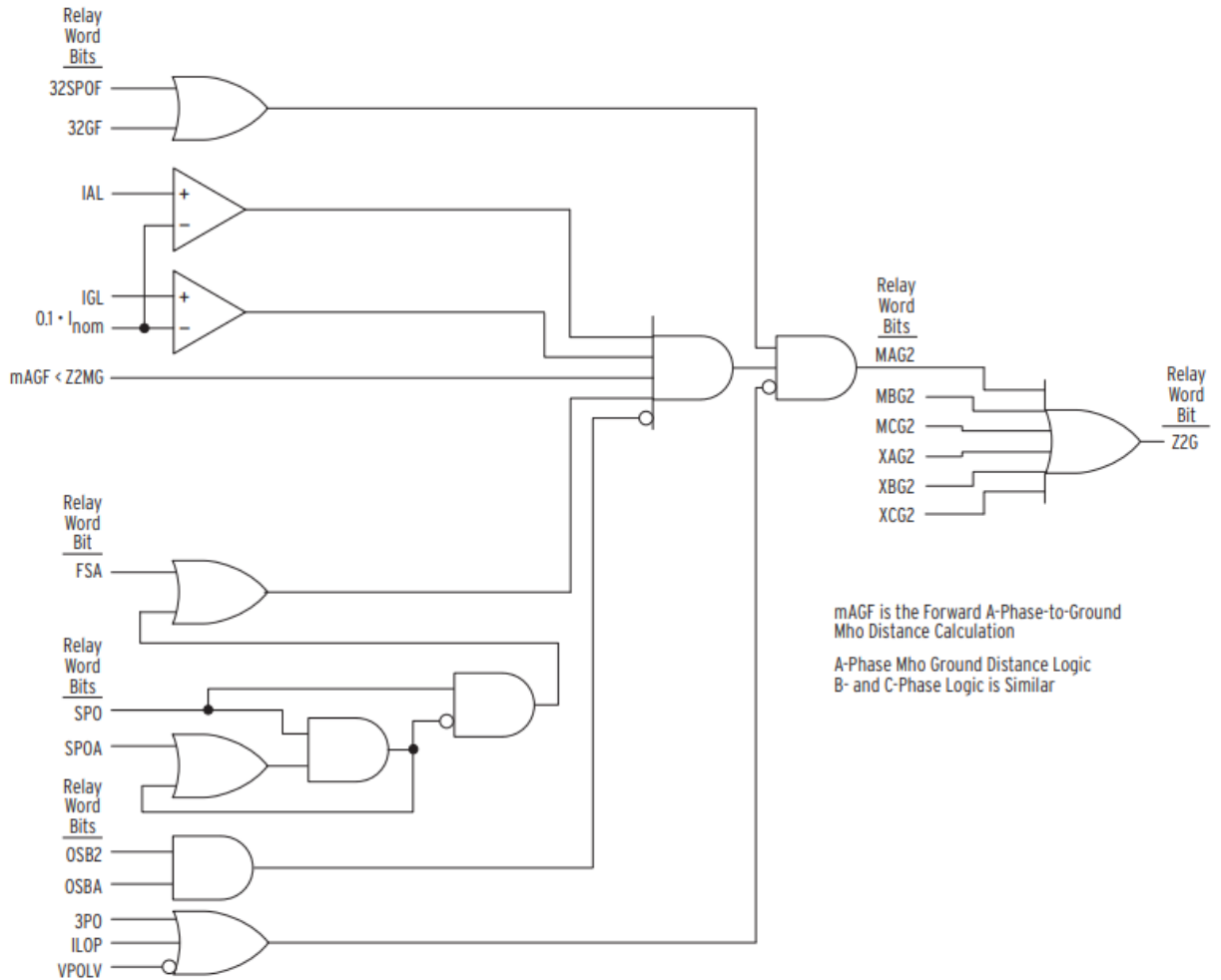


Figure 4.7: Zone 2 Mho ground distance element logic diagram(SEL, 2016).

Mho ground elements only operate for single phase-to-ground faults. Zones are set independently. Zone 1 and zone 2 elements can only be set in a forward direction. The Mho ground element uses positive sequence voltage polarization for security and provides dynamic expansion of Mho characteristic curves.

The first three zones of the ground element have high-speed operating abilities that are less than a cycle. The ground elements are dependent on the zero-sequence compensation factor. Mho ground distance logic diagrams of zone 3, zone 4, and zone 5 are provided in the appendix section.

4.2.2.1 OMICRON test universe setup for testing distance relay

Omicron test universe software provides the ability to configure the test set CMC 256 plus for testing any protection relay. The secondary test set CMC 256 plus was used for supplying current and voltage signals to the protection relay. Test universe software provides a variety of functions that can be used to test different protection schemes, for this thesis advanced distance protection function was used to perform necessary tests. The test bench setup for testing distance protection functionality is provided in Figure 4.8 below.

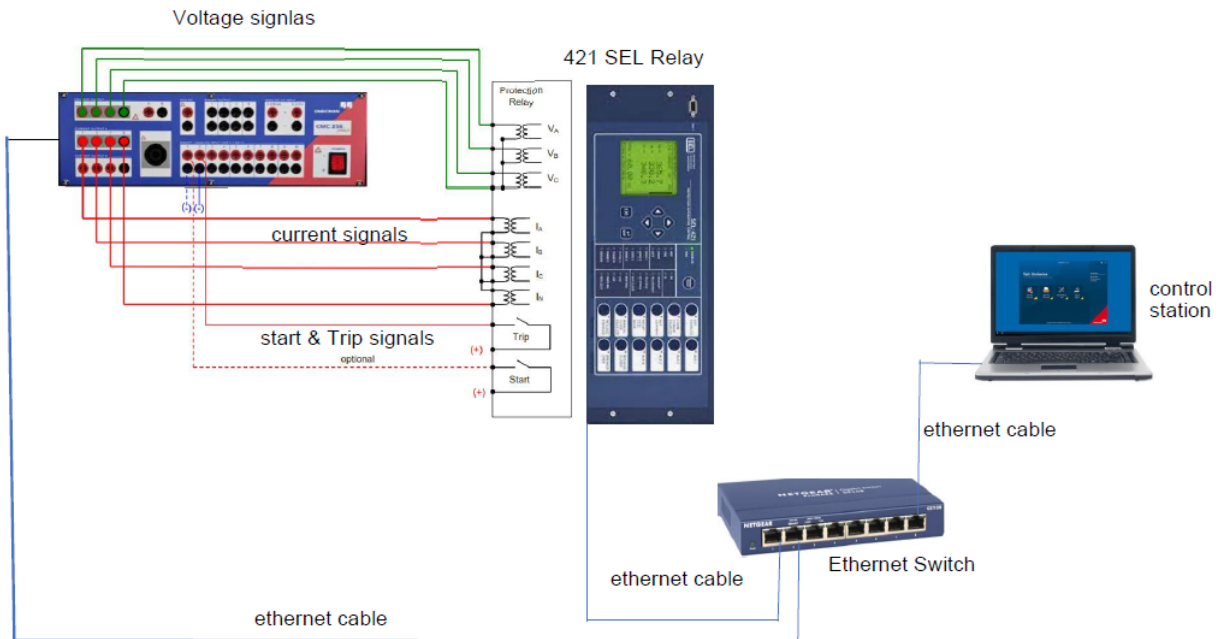


Figure 4.8: Test setup connections for testing distance protection functionality.

4.2.2.2 Configuration of the Test Object

The settings of the SEL 421 relay to undergo testing must be defined in the test object window. This is where the details of the system are inserted/defined and the manufacturer's name can also be provided on this window, Table 4.3 below provides the device settings that are obtained from the test object function on test universe software.

Table 4.3: Device settings for test object function in test universe software

Description	Nominal Values	
	Primary values	Secondary values
System frequency	50 Hz	-
Nominal voltage	33kV (L-L)	110 V (L-L)
	19.1 kV (L-N)	63 V (L-N)
Nominal current	300A	5A

Table 4.3 above indicates the nominal values of the system and the details of the protection relay that is being tested.

4.2.2.3 Mho relay settings for phase and ground faults

Mho Distance relay settings are set on the test universe for three zones of phase and ground faults are presented in Table 4.4 below.

Table 4.4: Relay settings in test universe software

Zone reach	Set time (ms)	Distance element	Set secondary impedance (mΩ)	Angle in degrees
Z1	20.0	Ground	551	57 ⁰
		Phase		
Z2	300	Ground	950	
		Phase		
Z3	600	Ground	1270	
		Phase		
k0	N/A	N/A	1033	25.9 ⁰

4.2.2.4 Practical experiment results

Table 4.5 below summarizes the tests to be carried out on the protection relay for testing relay settings functionality for case study one.

Table 4.5: Relay operation test points summary

Fault loop	Fault location	Trip zone Z	Set time. (ms)	The line covered in (%)
L-G	Line 1	Z1	20	80
	Line 2	Z2	300	120
	Line 2	Z3	600	200
L-L-L	Line 1	Z1	20	80
	Line 2	Z2	300	120
	Line 2	Z3	600	200

a. Single line to ground fault in all zones of the protection scheme

Faults have been simulated to see if the relay will trip or not at different locations, Figure 4.9 presents results when a single line-to-ground fault occurs. Each zone has been tested with a single short test to prove if the settings are working in all zones.

The mho characteristic curve is shown on the right of the test object screen, it must be noted that the relay does not trip when the fault occurs in the protected zones. Test results show that the relay trip was as expected within allowable trip times even though there is a bit of time delay than the set values this is due to the time taken when contacts open.

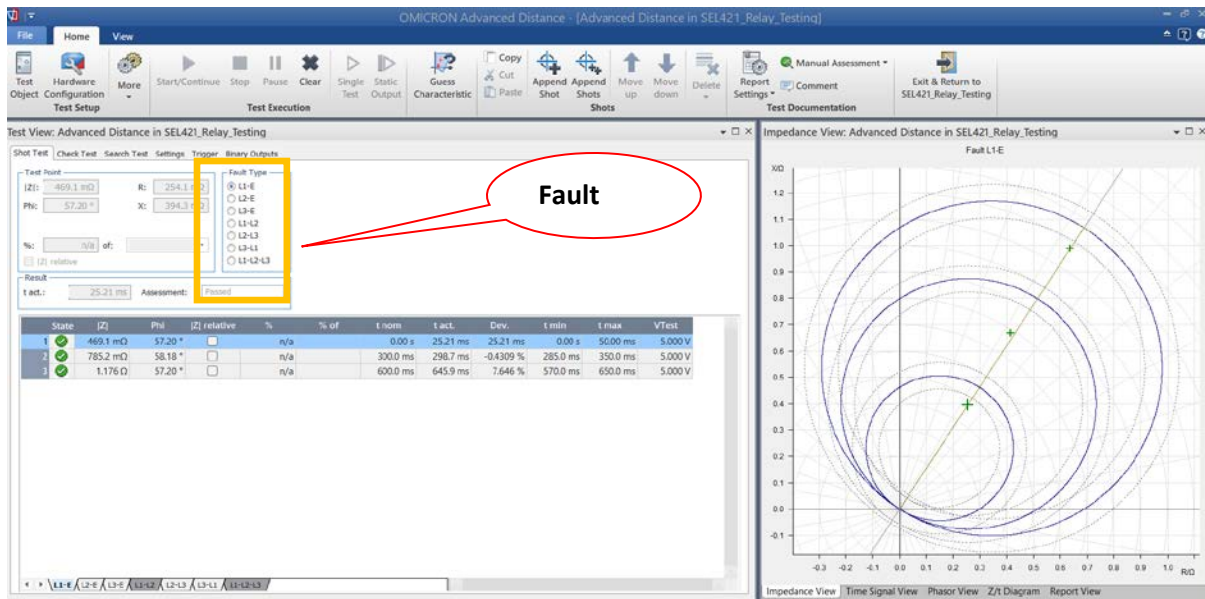


Figure 4.9: Single phase to earth fault test results

Figure 4.9 presents a test view of CMC where shot tests are found to test relays using CMC software. Figure 4.10, figure 4.11, and Figure 4.12 present relay events for each zone.

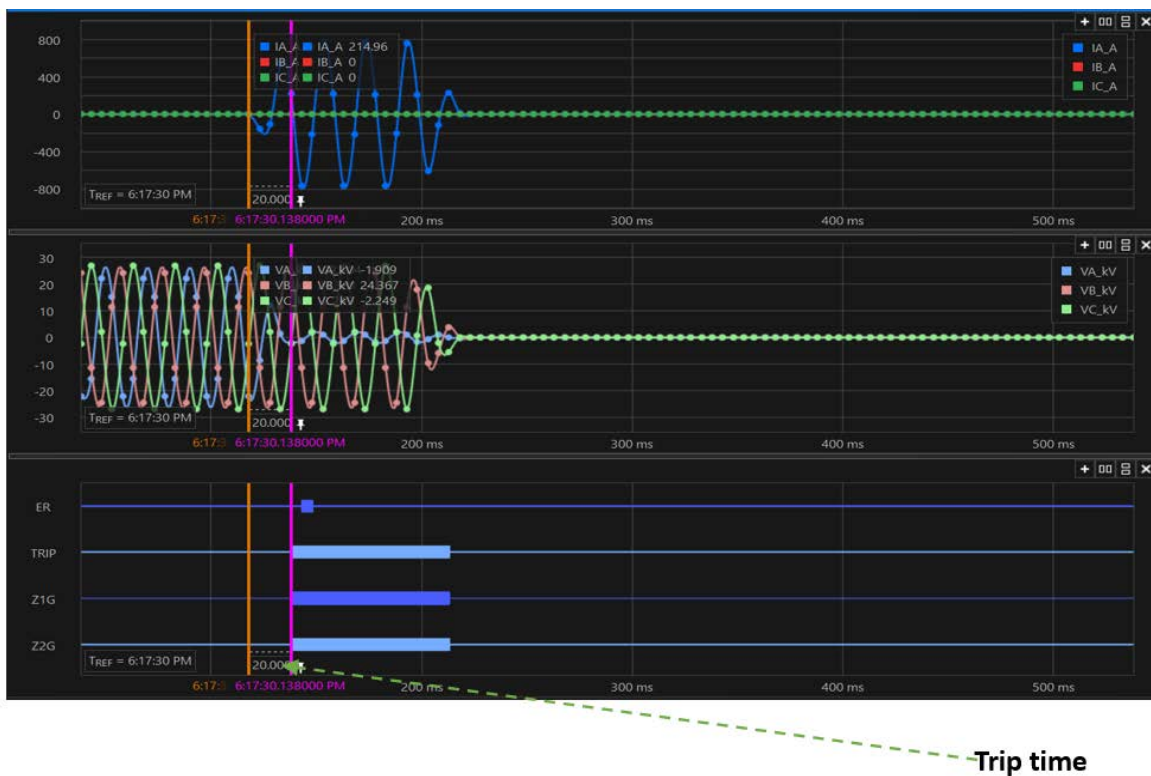


Figure 4.10: Single phase to ground fault events downloaded from the relay for zone 1.

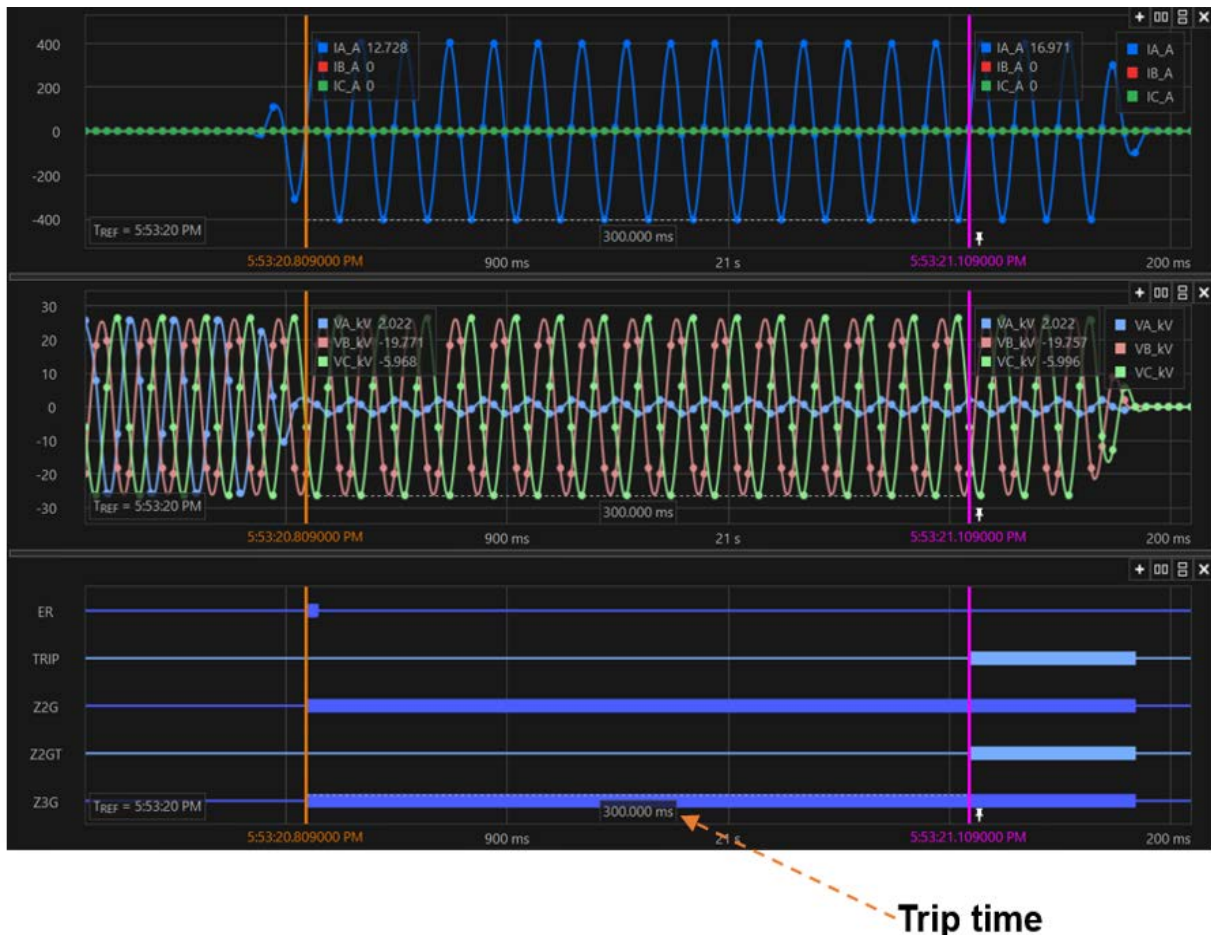
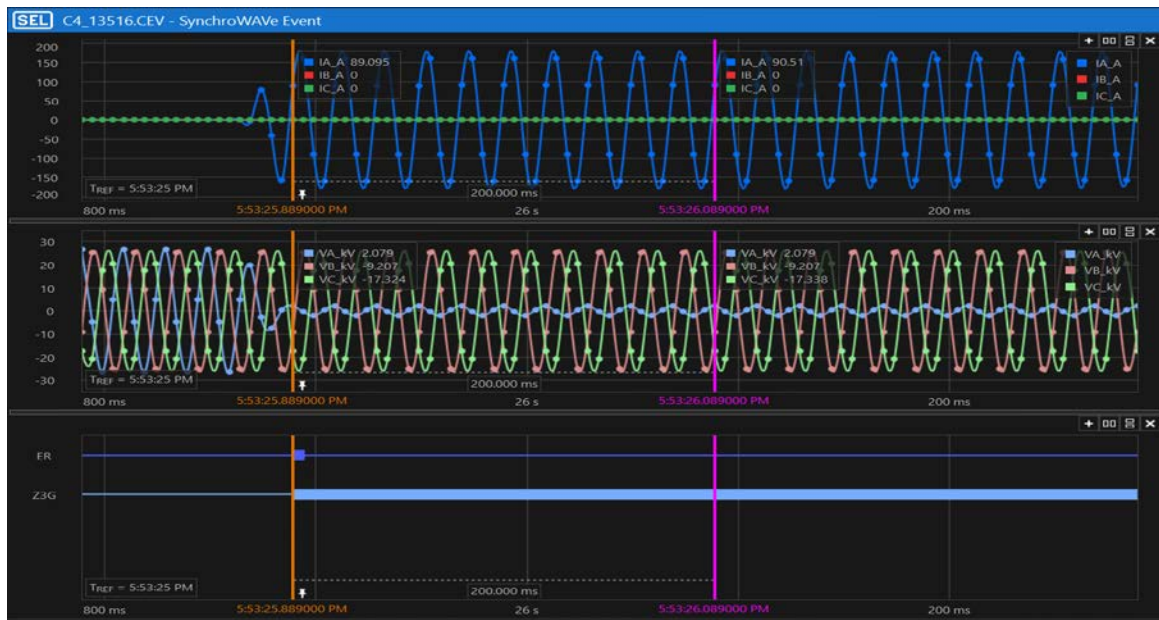


Figure 4.11: Single phase to ground fault events downloaded from the relay for zone 2.





Trip time (5:53:26:487 PM)

Pick up time (5:53:25:889 PM)

Calculated trip time taken by the relay = Trip time – Pick up time = 598 ms

Figure 4.12: Single phase to ground fault events downloaded from the relay for zone 3.

From Figure 4.10, figure 4.11, and Figure 4.12 events reports extracted from the relay are shown, and they all indicate that, before a fault occurs, waveforms are normal and got interrupted during fault time, and after trip time there is no signal shown because the relay has tripped. These results indicate the tripping times taken by the relay for each zone. Obtain results are accepted as they are within the tripping time limits.

b. Three-phase faults in all zones of the protection scheme

Three phase faults have been tested and the obtained results are present. The presented results show the relay has been tested successfully and all zones operated within the time limits. Figure 4.13, Figure 4.14, and Figure 4.15 provide the event reports from the relay to show waveforms and operating times for three-phase faults in all three zones.

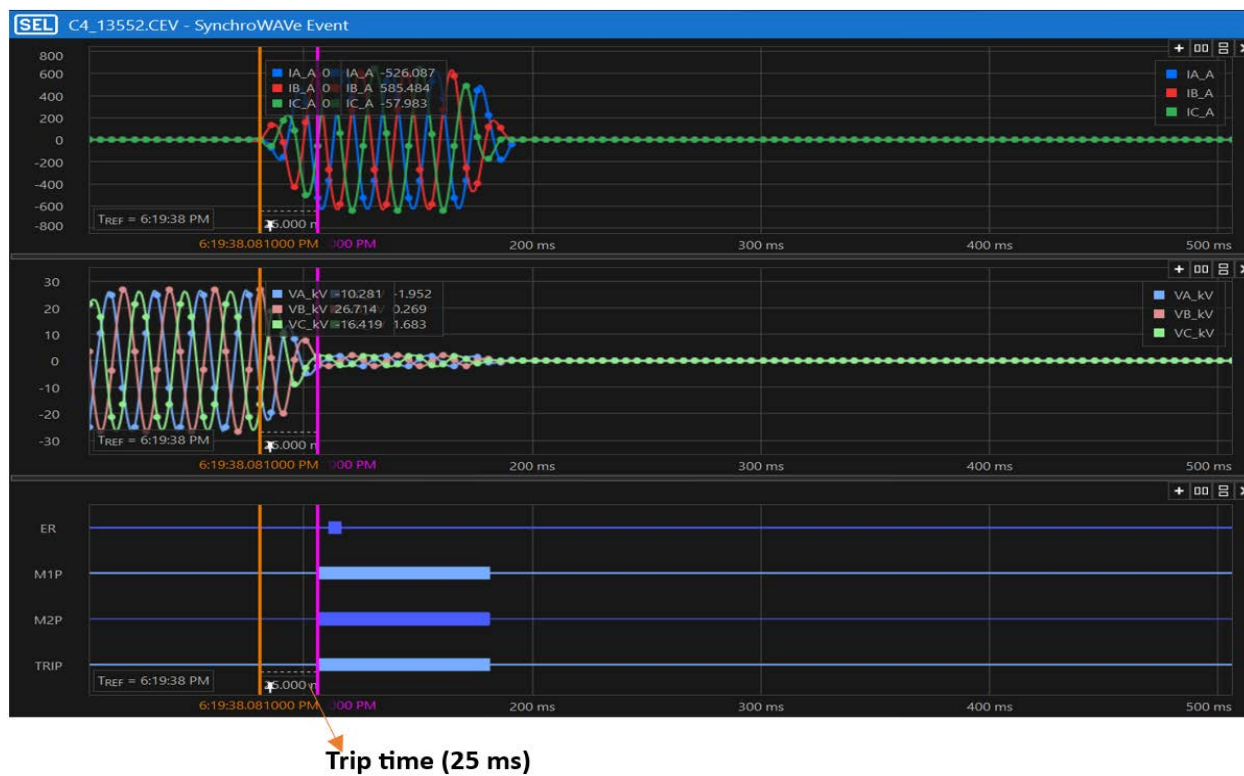


Figure 4.13: Three phase fault events extracted from the relay for zone 1.

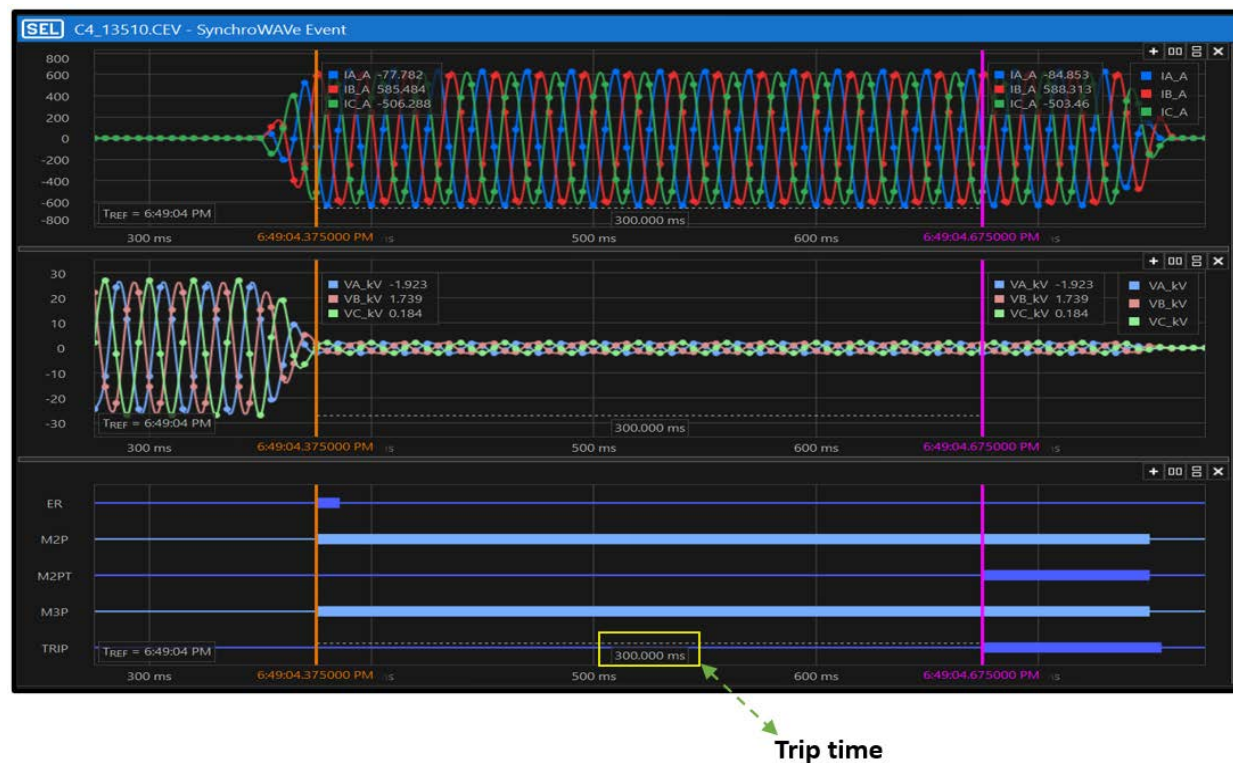
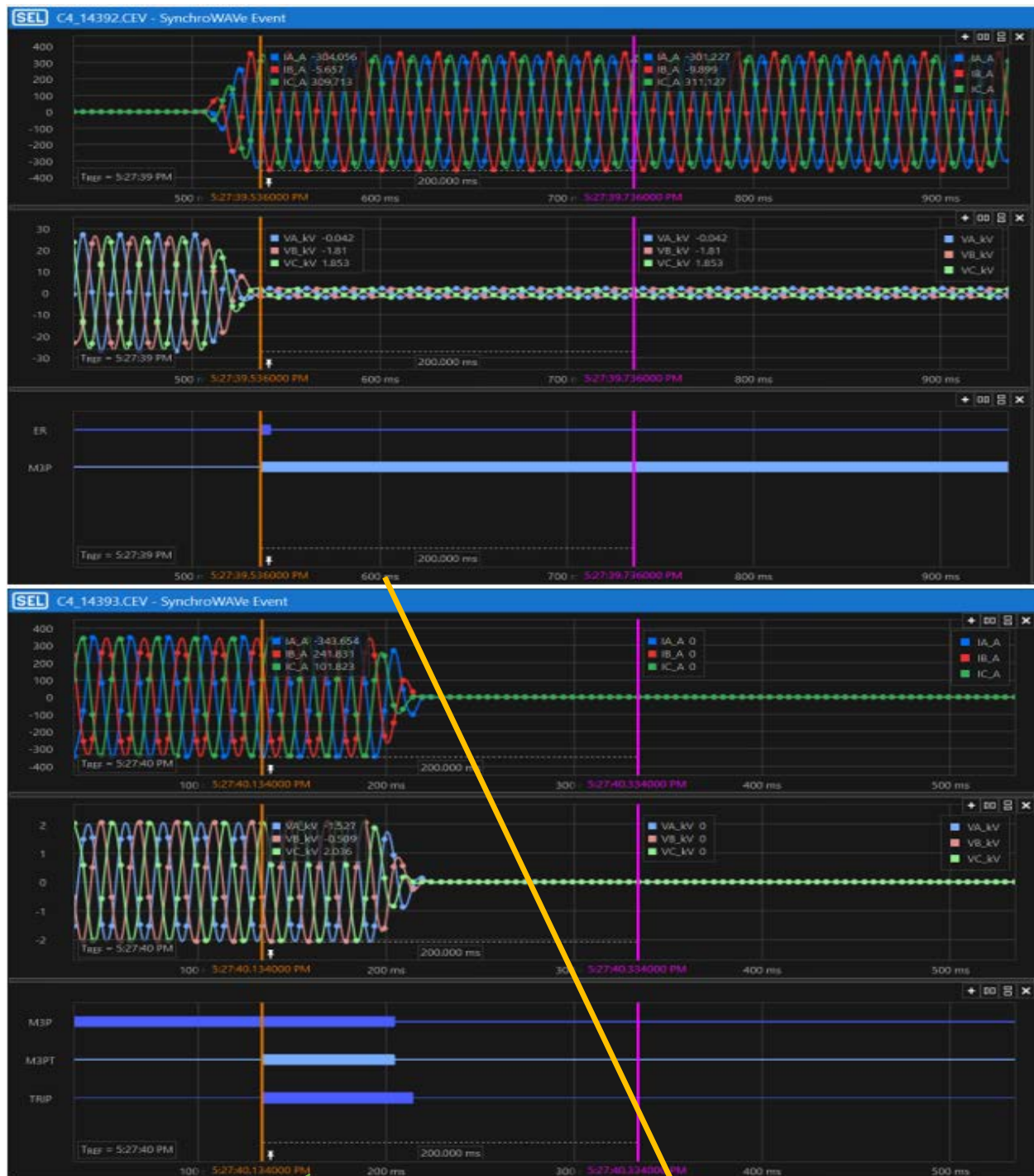


Figure 4.14: Three phase fault events extracted from the relay for zone 2.



Trip time (5:27:40:134 PM)

Pick up time (5:27:39:538 PM)

Calculated trip time taken by the relay = Trip time – Pick up time = 596 ms

Figure 4.15: Three phase fault events downloaded from the relay in zone 3.

The relay was tested successfully, and all desired results were obtained, Figure 4.13, Figure 4.14, and Figure 4.15 present waveforms obtained from the tested relay that provide the current and voltage before, during, and after the fault, operating times of the relay are also provided. Relay operating results for case study one is summarized in Table 5.6 below.

Table 4.6: Relay operation summary for case study one.

Fault Loop	Zone reach Z	Time set. (ms)	Trip time (ms)	Time deviation (%)
L-G	Z1	20	20	0
	Z2	300	300	0
	Z3	600	598	-0.34
L-L-L	Z1	20	25	25
	Z2	300	300	0
	Z3	600	596	-0.67

4.2.3 Case Study Two: line 3 protection design

Case study two focuses on protection design for line three as shown in Figure 4.16 below. Protection settings are designed for the requirement of this line, so they are completely different from the settings in case study one. Case study two provides settings for relay 3 and relay 4 which are at both ends of line 3. Figure 4.16 below presents the layout of the system under study.

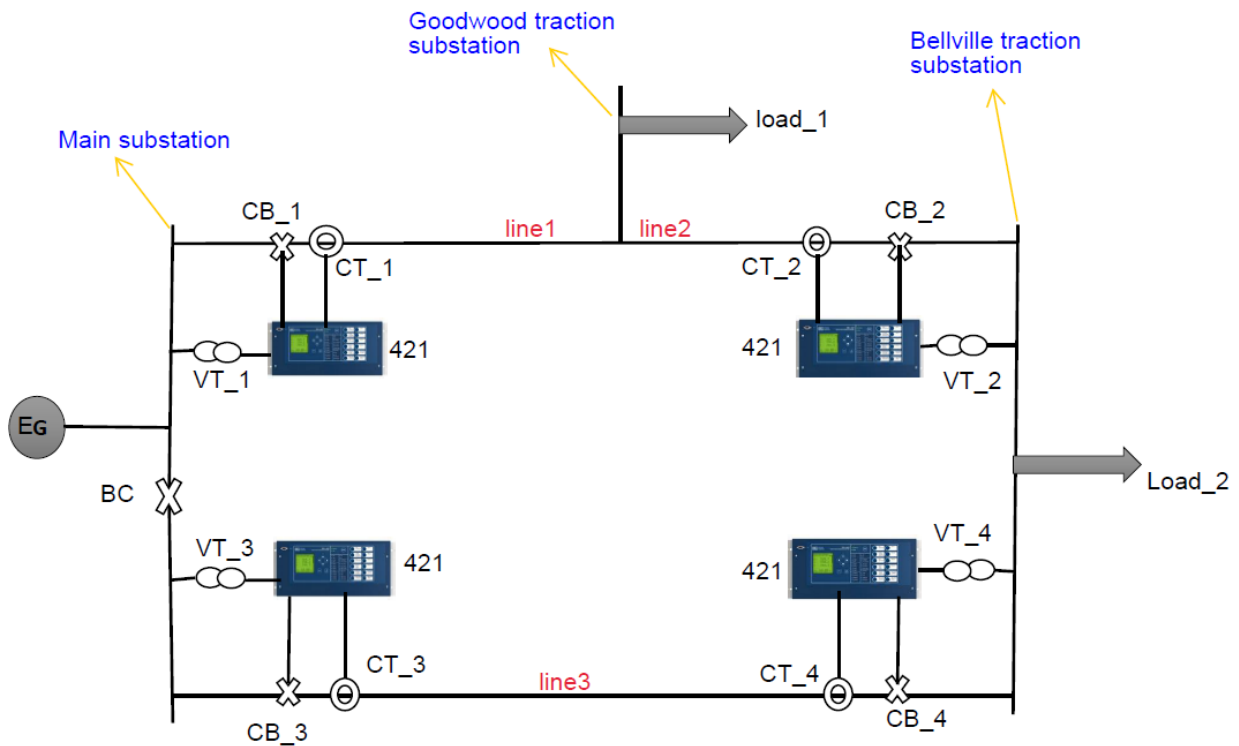


Figure 4.16: Power system network under study for protection design

a. Design settings on AcSELerator software:

Line 3 has no tap-off substation connected to it, therefore the activated zones to protect this line are only two. Zone 1 covers up to 0 to 80% of line 3 and zone 2 covers 100% of line 3. Table 4.5 below shows protection settings configured on AcSELerator software and have been sent to the relay for testing.

Table 4.7: Relay settings configured using AcSELerator software and inserted into the relay.

Distance Element	Mho distance Element and set values. (Ω , secondary values)		Distance time Element (cycles)	Distance time Element (ms)
Phase	Z1P	1.02	1	20
	Z2P	1.28	15	300
	Z1MG	1.02	1	20

Ground	Z2MG	1.28	15	300
Zero sequence compensation factor	K0M1	1.033	N/A	N/A
	K0A1	25.9 ⁰	N/A	N/A

b. Test universe software and protection settings configuration:

Figure 4.6 provides test zone 1 and zone 2 settings for both phase-to-phase faults and phase-to-ground faults.

Table 4.8: Omicron settings configuration using test universe software.

Zone reach	Set time (ms)	Distance element	Set secondary impedance (mΩ)	
Z1	0.0	Ground	1.02	57 ⁰
		Phase		
Z2	300	Ground	1.28	
		Phase		
k0	N/A	Ground	1.033	25.9 ⁰

4.2.3.1 Practical experiment results for case study two

The table below summarizes the tests to be carried out on the protection relay, for testing relay functionality in case study two.

Table 4.9: Relay operation test points summary

Fault loop	Fault location	Trip zone Z	Set time. (ms)	The line covered in (%)
L-G	Line 3	Z1	20	80
		Z2	300	100
L-L-L	Line 3	Z1	20	80
		Z2	300	100

a. Single phase to ground faults in zone 1 and zone 2.

After settings configuration, the relay functionality test was done, and the results obtained are presented in Figure 4.17 below, and Figure 4.18 presents the waveforms extracted from the test universe. Figure 4.17, and figure 4.18 provide the events from the relay to show waveform disturbance and operating times for single phase-to-earth faults in Zone 1 and Zone 2.

Zone 1 and Zone 2 time taken by the relay are indicated in Figure 4.17 and Figure 4.18, the relay tripped at the right time as can be noticed in Zone 1 operation, the operating time is 27.8 ms and the set time on the relay is 20 ms. Zone 2 trip time is 300 ms, and the relay operated at 300 ms.

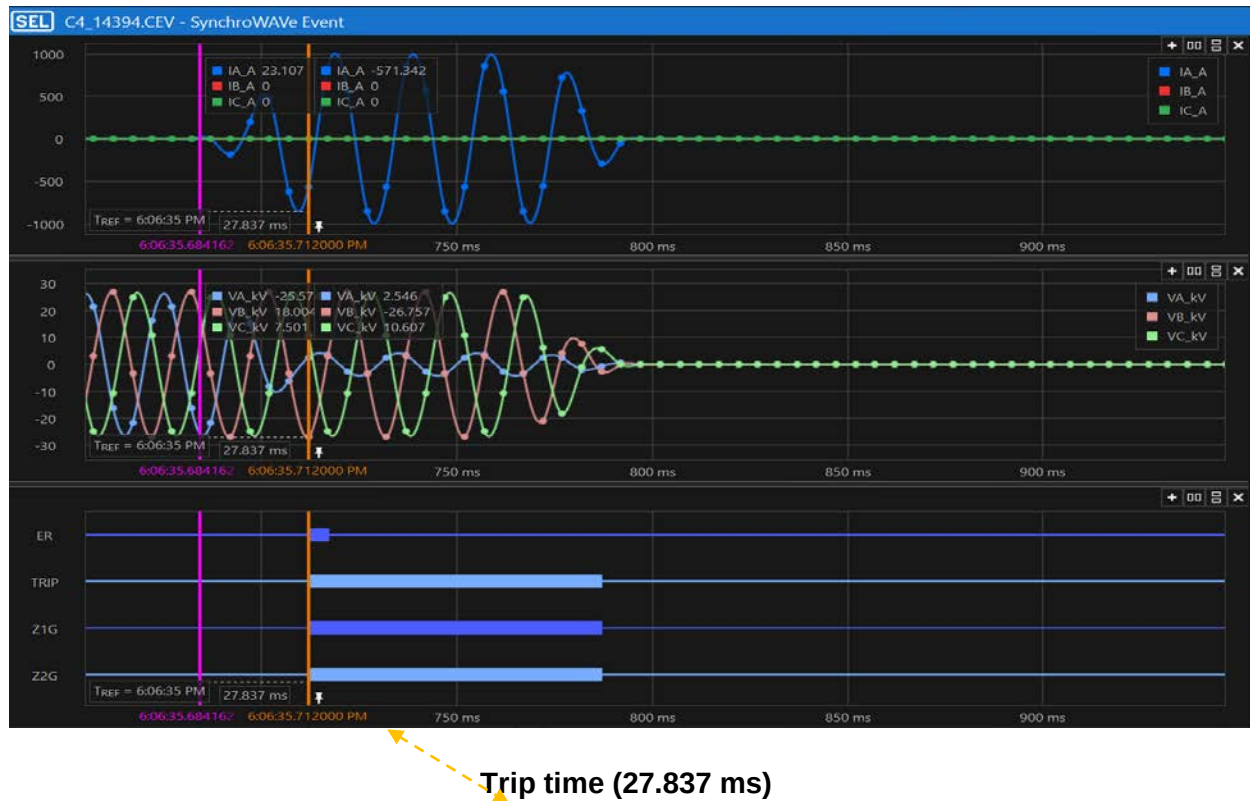


Figure 4.17: Zone 1 phase-to-earth events from the relay.

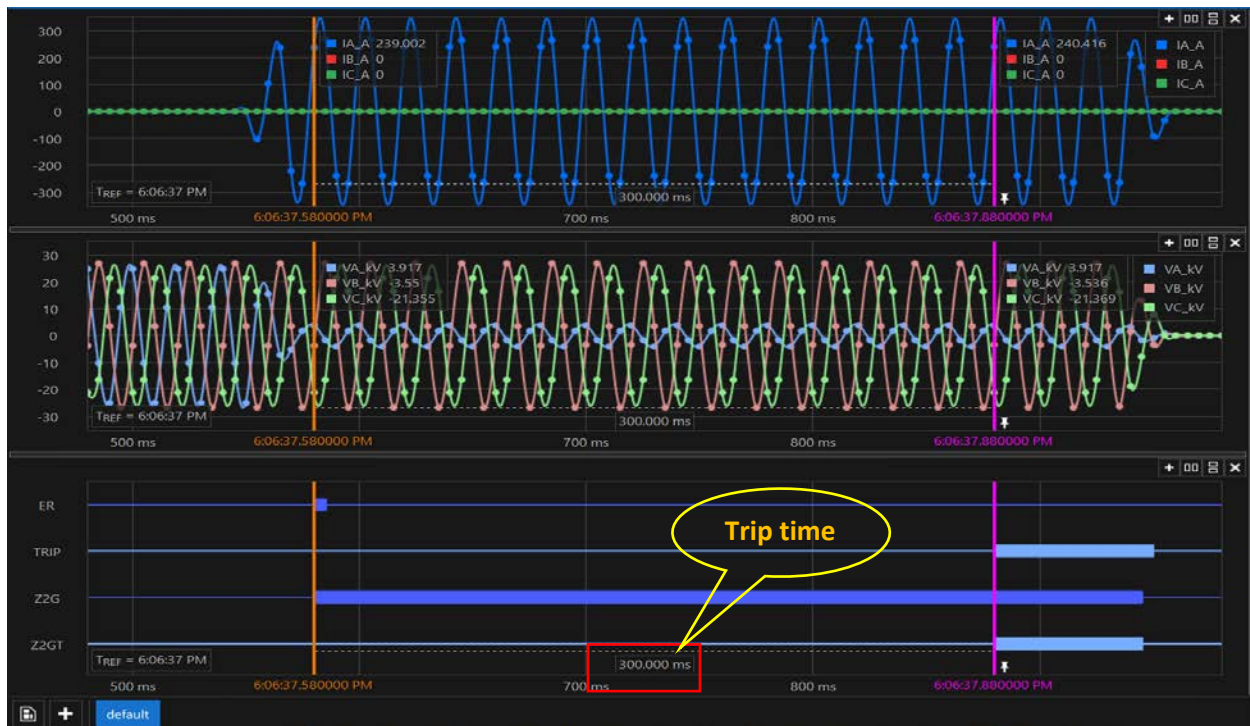


Figure 4.18: Zone 2 phase-to-earth events from the relay.

b. Three phase faults in zone 1 and zone 2.

Figure 4.19 and figure 4.20 provide three-phase fault events that were downloaded from the relay to see how it behaved during fault conditions.



Figure 4.19: Zone 1 three-phase fault events from the relay.



Figure 4.20: Zone 2 three-phase fault events from the relay.

Three-phase faults in Zone 1 and Zone 2 are presented in Figure 4.19 and Figure 4.20 respectively. From the figures it is shown that the relay took 20 and 300 milliseconds to trip respectively after the fault had been detected. Relay operating results for case study one are summarized in Table 4.5 below.

Table 4.10: Relay operation summary for case study two.

Fault Loop	Zone reach [Z]	Time set. (ms)	Trip time (ms)	Time deviation (%)
L-G	Z1	20	27.837	39.19
	Z2	300	300	0
L-L-L	Z1	20	20	0
	Z2	300	300	0

4.2.4 Benchmark table

According to the study done by (Agila-Rios et al., 2021b), distance relay functionality for zone one was tested using CMC 256 PLUS, and the obtained results of this study are used as a benchmark. A comparison between the results obtained by (Agila-Rios et al., 2021b) and the

results obtained in this chapter is shown in Table 4.11 below to compare time deviation on the tested relays.

Table 4.11: Comparison of distance relay time tripping comparison for two relays of different studies

Study by	Fault Loop	Case study	Time set. (ms)	Trip time (ms)	Time deviation (%)
(Agila-Rios et al., 2021b)	L-G	1	35	74.06	111.6
		2		28.76	-17.83
Obtained results in Chapter Four	L-G	1	20	20	0
		2		27.837	39.2

Table 4.11 indicates that the time deviation of the relay tested in the CPUT lab is much better than the relay tested by (Agila-Rios et al., 2021b) for trip functions in zone one when a single phase to ground fault occurs. Analysing the results obtained; the proposed protection system would be more appropriate for this network and the relay used is faster to clear electrical faults.

4.3 Conclusion

This chapter provides the 33kV electrical distribution network that is being investigated. Chapter Five provided engineering configuration settings for distance protection relays (SEL 421). The designed and detailed protection settings are provided for two case study scenarios. The Omicron CMC test set and SEL 421 relay are used for laboratory-scale development where relay functionality is tested.

Obtained test results for both case studies are presented, and different fault loops were tested in the relay. Desired test results were indeed obtained for both case studies and were compared with the results of other studies in the literature.

Chapter five illustrates the implementation of the hardware in the loop (HIL) in the RTDS environment for testing the functionality of distance relays in a closed-loop system

CHAPTER FIVE

IMPLEMENTATION OF THE HARDWARE-IN-THE-LOOP TESTING OF A DISTANCE PROTECTION SCHEME FOR A 33KV TRACTION NETWORK

5.1 Introduction

Protection of power lines in an electrical system is achieved by using protective devices called relays/ intelligent electronic devices (IEDs). These devices control the circuit breaker status, when there is an electrical fault on the distribution line, the protective device sends a trip signal to the circuit breaker to open and isolate the electrical network from the fault part of the system.

The process of isolating faulty parts of an electrical network is required to happen as fast as possible to protect the system from high fault currents. One of the key elements that a protective device should provide is to be able to react to a fault as quickly as possible. To identify these capabilities on protective devices, these devices must be tested on a laboratory scale setup before they are applied to the real electrical network.

Hardware-in-the-loop (HIL) testing is an important test technique that is used to test the hardware devices before implementing them on a real system and process. HIL is useful for training and understanding how the system works and operates on real power system networks.

This chapter provides the modeling of the 3-bus PRASA electrical network. It provides a hardware-in-the-loop simulation technique for testing the functionality of the distance relays (SEL 421) using the real-time digital simulator (RTDS) and RSCAD modeling software. A distance protective relay has been tested to identify how fast they can react to a fault occurring in zone 1 for a 33kV traction distribution network.

Distribution network faults can be classified into two categories, symmetrical and unsymmetrical faults, where unsymmetrical faults are known as common types of electrical faults. These faults, both symmetrical and unsymmetrical, are studied and analyzed in this chapter.

This chapter provides a power system network where the distance protection scheme is evaluated using the hardware-in-the-loop testing technique. Two SEL 421 relays are used in the HIL simulation, and a signal amplifier and RTDS simulator are used in developing a test bench. Section 5.2 defines the RSCAD software, section 5.3 describes the RTDS simulator, section 5.4 provides a model of a three-bus network on RSCAD, section 5.5 provides the implementation of

HIL simulation, section 5.6 discusses the simulation results and section 5.7 provides the conclusion of chapter five.

5.2 RSCAD Software for Network Modelling

RSCAD is a modeling and interfacing software used to model and simulate electrical power systems. This software provides capabilities such as system design, system simulation, and system control and performs hardware-in-the-loop studies(Luitel & Venayagamoorthy, 2013).

5.3 Real-time digital simulator (RTDS)

RTDS is a system or tool used to implement and study real-time simulations for power and control systems. The power system conditions can be easily studied and analyzed using the RTDS and RSCAD software to address the dynamic conditions of the electrical power system.

Real-time digital simulation is a computer modeling interfacing of the hardware and software tools to enable the real-time simulation of a power system(Luitel & Venayagamoorthy, 2013). Advanced electronic cards are used in RTDS to make it possible to interface hardware and software tools, some of the cards found in RTDS are as follows but not limited to:

- i. GTO: Gigabit transceiver processor output card
- ii. GTAO: Gigabit transceiver twelve-channel analogue output card
- iii. GTNET: Gigabit transceiver network interface
- iv. GTWIF: Gigabit transceiver workstation interface card
- v. GTFPI: Gigabit transceiver front panel interface card

For this study, the RTDS is used to perform HIL for testing distance protection schemes and RTDS cards such as GTO, GTAO, and GTFPI were used in this project. Figure 5.1 Below presents the RTDS hardware in the CSAEMS lab at Cape Peninsula University of Technology used for practical components to test the distance protection functionality using HIL simulation.

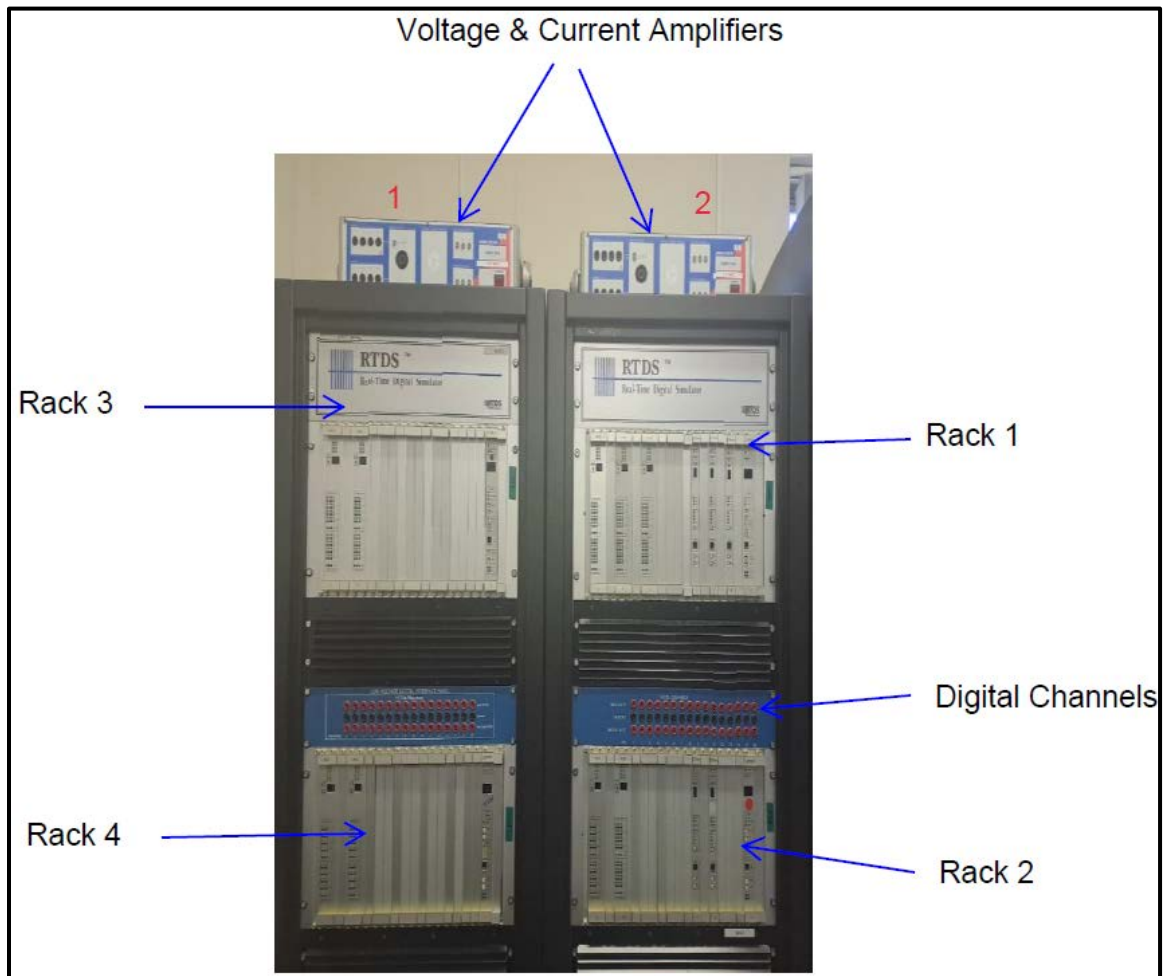


Figure 5.1: RTDS hardware in CSAEMS lab at Cape Peninsula University of Technology

Figure 5.1 provides the real-time digital simulator (RTDS) found in the Centre for Substation Automation and Energy Management System (CSAEMS) at the Cape Peninsula University of Technology. The RTDS can perform the following functions and applications:

- High-speed simulations.
- Closed-loop testing of protective devices (relays/IEDs).
- Closed-loop testing of control devices (voltage regulator, power system stabilizer, etc).
- Hardware in-the-loop applications.

In this project, Closed-loop testing of distance protective functionality is performed.

5.4 PRASA Three-Bus network modeled on RSCAD software.

The PRASA Three-bus system has been modelled on RTDS software to identify load flow data and results are provided in Table 5.1. This system consists of 3-distribution lines distributing power from the 33kV main traction substation and these three lines supply power to two 3kV DC traction substations (Goodwood and Bellville traction substation) where the loads are connected. The study is conducted to test the distance protection relay functionality on those distribution lines. Figure 5.2 below shows the modeled network with two loads connected in Goodwood and Bellville 3kV DC traction substations.

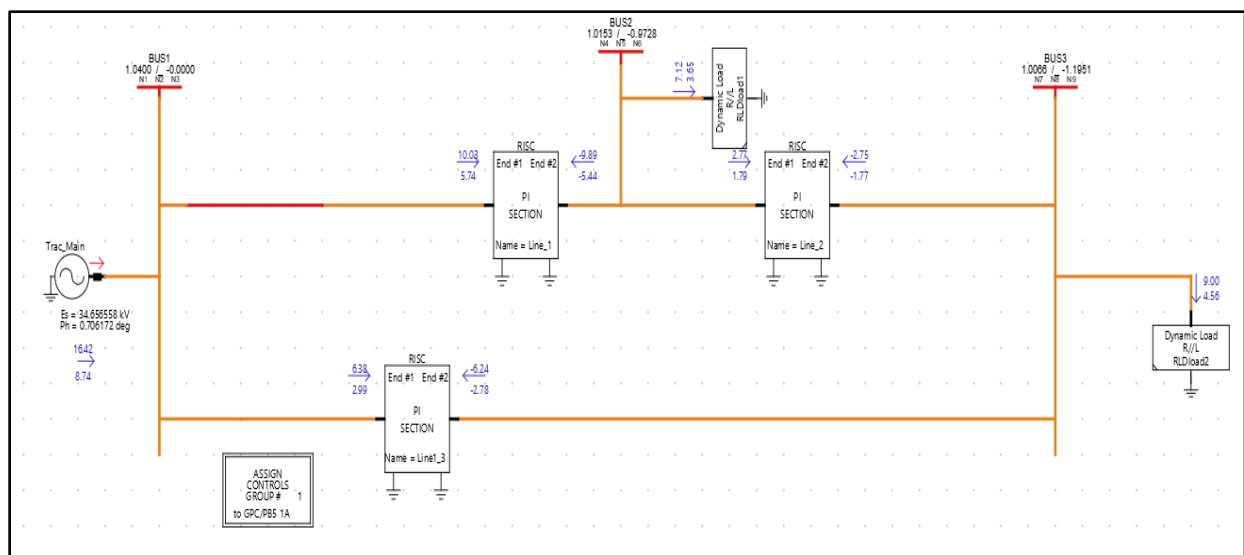


Figure 5.2: PRASA Three-Bus system modeled in RSCAD software.

From Figure 5.2, instrument transformers are indicated on one branch of the network, this was done to perform a functional test of the applied principle, assuming that the same principle will be applied to protect the other branch of the network.

The load flow results of the simulated network are presented in Table 5.1 below and compared to the load flow results obtained on the DigSilent simulation performed in Table 3.6, Table 3.8, and Table 3.10 from Chapter Three.

Table 5.1: Load flow results for both RSCAD and DigSilent simulations.

Parameter Description (Power)		RSCAD load flow results	DigSilent load flow results
Grid	MW	16.42	16.6
	MVAR	5.05	8.4
Goodwood 3kV DC substation	MW	7.12	7.2
	MVAR	3.65	3.5
Bellville 3kV DC substation	MW	9.0	9.0
	MVAR	4.56	4.4

Table 5.1 provides the load flow data, where it is evident that the results are pretty much the same when comparing load flows from two different software. Obtaining these results proves the accuracy of the used software for modeling the network.

5.5 Implementation of the developed protection scheme in RTDS Hardware in the loop (HIL)

Real-time data in modern power systems is a priority, RTDS provides a platform for achieving the implementation of real-time simulation and testing of protection devices before they are applied to the real power system. Testing relays' protection function is important to guarantee an adequate and dependable protection system(Camarillo-Penaranda et al., 2021).

Hardware in the loop protective relay simulation is one of the testing techniques where analysis is very close to real-time scenarios. For this study, hardware in the loop is implemented to test the distance relay functionality in zone 1 of the protected line to identify the protection speed of the relay for a fault in zone 1. Figure 5.3 provides the single-line diagram of the power system where the tested zone operation is indicated.

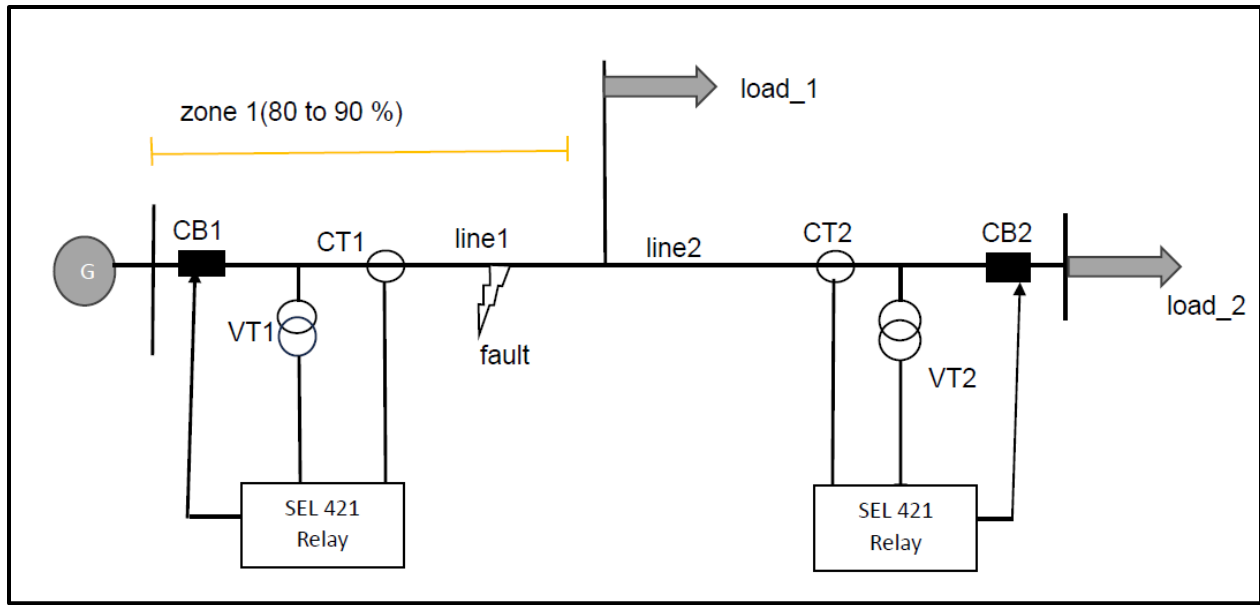


Figure 5.3: Single-line diagram of a power system

Figure 5.3 presents the single-line diagram that indicates zone 1 relay settings, in the diagram zone 1 protects 80 to 90% of the line, and the trip time is instantaneous. In this chapter, the distance protection relay is tested using HIL simulation for symmetrical and unsymmetrical faults occurring in zone 1 of the lines as indicated in Figure 5.3.

5.5.1 Instrument Transformers (VT and CT)

5.5.1.1 Current Transformer (CT)

The current Transformer is an electromagnetic component that is used for monitoring and current transformation from high current magnitude to lower current values that can be handled by the protective relays.

Table 5.2 below presents the ratio current transformer used in the HIL simulation.

Table 5.2: Current transformer data

Description	Parameter name	Rating
Current transformer	CT (Primary/ Secondary)	300 A/ 5 A

To ensure that the current supplied into the relay is equal to the simulation current, the following equation was used to calculate the current scaling factor.

$$\frac{5 \text{ (Volts out)}}{S_x \text{ (Amp in)}} \times 5 \frac{\text{ (Volts out)}}{\text{ (Amp in)}} = 1 \quad (5.1)$$

$$S_x = 25$$

Where:

S_x : Current scaling value

5.5.1.2 Voltage Transformer (VT)

These measuring instruments are known as key elements in the power grid for voltage measurement, voltage monitoring, and protection purposes. The voltage transformer (VT) works by the electromagnetic principle in transforming the high voltage signals into low voltage that can be handled by measuring and protective devices (Ge et al., 2020). VT operation principle can be described as follows:

- Primary windings of VT are connected to an alternating source of supply
- Primary current (I_p) is then flowing through the primary windings of a VT
- This flowing current on primary windings, produces magnetic flux around/ across the core
- The existing or produced flux will extend to the secondary windings of the VT

Due to the flux being extended to secondary windings, there will be induced EMF across the secondary windings which is proportional to the voltage on the primary winding. Table 5.3 below presents the ratio current transformer used in the HIL simulation.

Table 5.3: Voltage transformer data

Description	Parameter name	Rating
Voltage transformer	VT (Primary/Secondary)	33000V/110V

To ensure that the current supplied into the relay is equal to the simulation voltage, the following equation was used to calculate the current scaling factor.

$$\frac{5 \text{ (Volts out)}}{S_z \text{ (Volts in)}} \times 50 \frac{\text{(Volts out)}}{\text{(Volts in)}} = 1 \quad (5.2)$$

$$S_z = 250$$

Where:

S_z : Voltage scaling value

5.5.1.3 Distance Protective Relay

Protective relays are devices that are used to send trip signals to the circuit breaker when the measured current, voltage, or impedance is less or higher than the preset values. These devices are programmable devices that can be programmed to meet the needs of the protected system. Figure 5.4 below presents the engineering configuration for the two distance relays presented in Figure 5.3.

```

Group 1
Line Configuration
CTRW := 60    CTRX := 400    PTRY := 300    VNOMY := 110
PTRZ := 2000  VNOMZ := 115    Z1MAG := 1.27    Z1ANG := 57.20
Z0MAG := 5.11    Z0ANG := 76.87    EFLOC := Y    LL := 16.00
Relay Configuration
E21P := 1    E21MG := 1    E21XG := N    ECVT := N
ESERCMP := N    ECDTD := N    ESOTF := N    EOOS := N
ELOAD := N    E50P := N    E50G := N    E50Q := N
E51S := N    E32 := AUTO    ECOMM := N    EBFL1 := N
E25BK1 := N    E79 := N    EMANCL := N    ELOP := Y1
EDEM := N    EADVS := N
Mho Phase Distance Element Reach
Z1P := 0.51
Mho Phase Distance Element Time Delay
Z1PD := 1.000
Mho Ground Distance Element Reach
Z1MG := 0.51
Zero-Sequence Compensation Factor
k0M1 := 1.033    k0A1 := 25.90
Ground Distance Element Time Delay
Z1GD := 1.000
Directional Control Element
ORDER := "QV"
S0FP := 0.60    S0RP := 0.40    Z2F := 0.63    Z2R := 0.74
a2 := 0.10    k2 := 0.20    Z0F := 2.56    Z0R := 2.65
a0 := 0.10
E32IV := 1
Pole Open Detection
EPO := 52    SPOD := 0.500    3POD := 0.500
Trip Logic
TR := M1P OR Z1G OR M2PT OR Z2GT OR M3PT OR Z3GT OR M4PT OR Z4GT

```

Figure 5.4: SEL 421 Engineering configuration

Figure 5.4 provides engineering configurations where the line length, protection settings, and time delay are indicated. Referring to Figure 5.4 only zone 1 is activated for testing relay functionality for a fault in zone 1 of the line.

5.5.2 Lab-scale setup for HIL implementation

Hardware-in-the-loop testing techniques are used to interface engineering software with the hardware simulator for testing the physical protective relays to identify and understand the dynamic behavior of the relay in real-time conditions.

In this study, a lab setup for performing the HIL has been developed and Figure 5.5 below presents the single-line diagram of the power system network that has been developed for this project. Furthermore, Figure 5.6 presents the physical lab-scale setup for the network presented in Figure 5.5. In Figure 5.6 all used devices are indicated and the link between devices is also provided. In this chapter, two protective relays were connected in the HIL setup to evaluate their functionality as indicated in Figure 5.5 and Figure 5.6 below, and the simulated network was done on RSCAD software on the laptop shown in Figure 5.6.

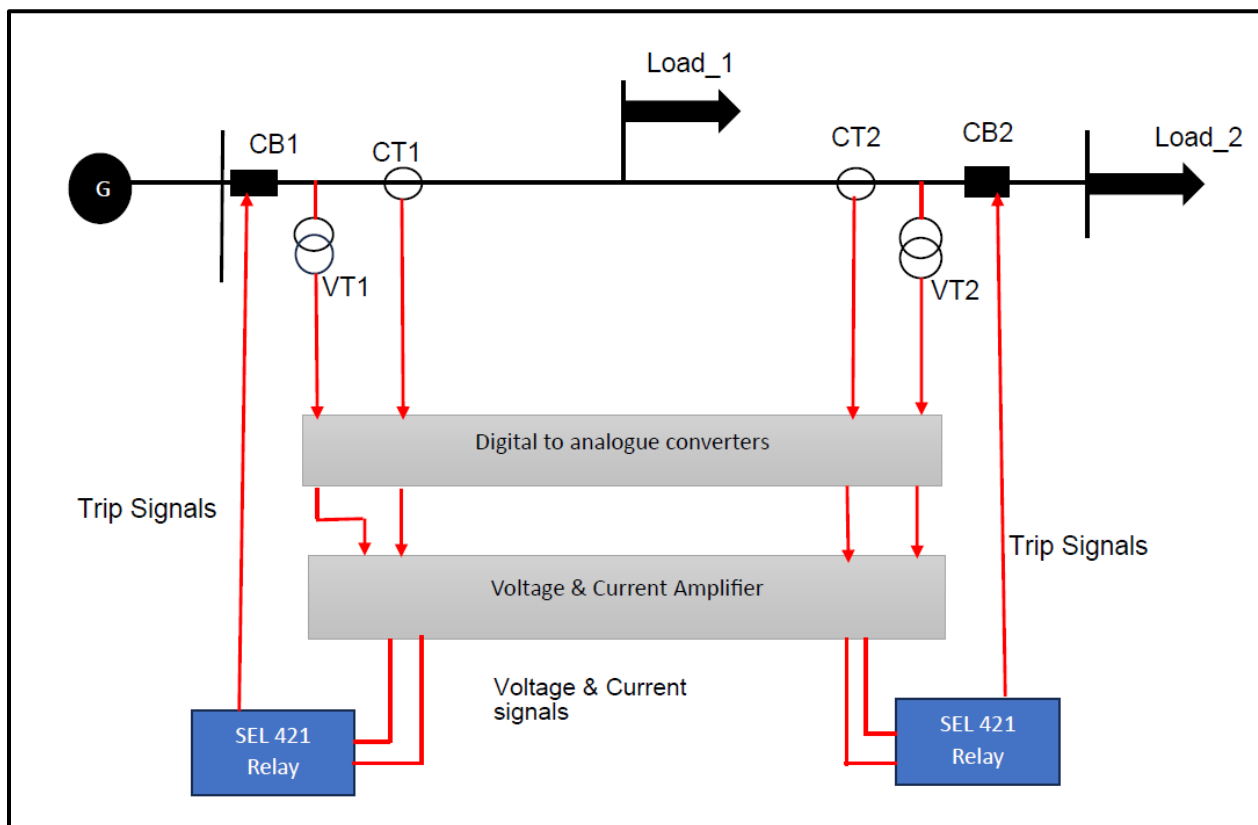


Figure 5.5: Single-line diagram of power system for a simulated network in RSCAD

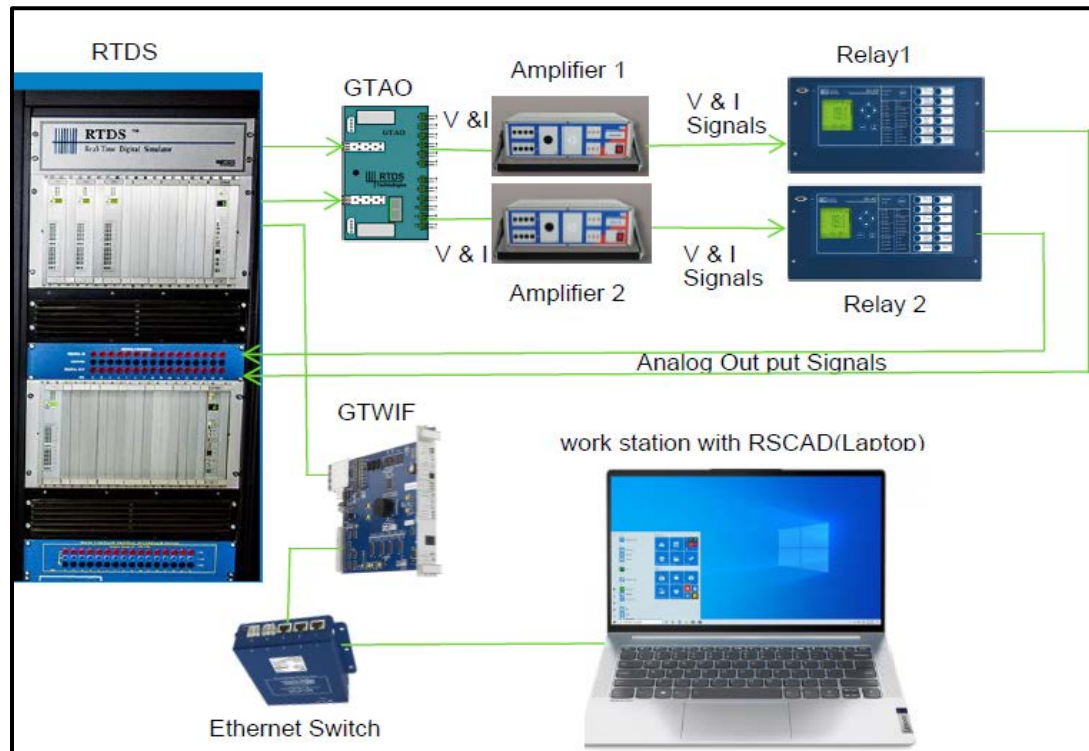


Figure 5.6: Hardware-in-the-loop lab-scale setup for testing distance protection relays

To understand Figure 5.5 and Figure 5.6, the following comments are important:

- The network presented in Figure 5.5 is modeled on the computer with RSCAD software simulation.
- Measuring instruments such as voltage and current transformers are also modeled and configured in a software (RSCAD) tool as well.
- The fault indicated in Figure 5.5 is simulated on the software and trips the physical relay.
- The circuit breaker shown in Figure 5.5 is a software-modelled circuit breaker that is controlled by signals sent by the physical relay.
- Laptop with RSCAD simulated network interface with the RTDS simulator through an ethernet switch and GTWIF card.
- GTAO card converts the voltage and current digital signals to analogue signals and sends the signals to the voltage and current amplifier.
- Amplified voltage and current signals are sent to the physical SEL 421 relays.
- When there is a fault in the power system modeled in the RSCAD software will transfer the fault current signals to the physical relays via amplifiers. Then the physical relay will trip and

send trip signals to the software circuit breaker modelled in RSCAD via digital channels and GTFPI card.

5.5.2.1 GTAO card

GTAO card is a component found in the RSCAD software library and in the RTDS simulator, this card is a 12-channel card for voltage and current signals. A GTAO card interfaces between RTDS hardware and the analogue signal amplifier (voltage & current). The card is designed to have an approximate ± 10 V output. The output of the GTAO card is directly connected to the analogue signal amplifier. The amplifier scales up voltage and current signal to values that can be recognized by the relays. Figure 5.7 below presents the GTAO card used for this study.

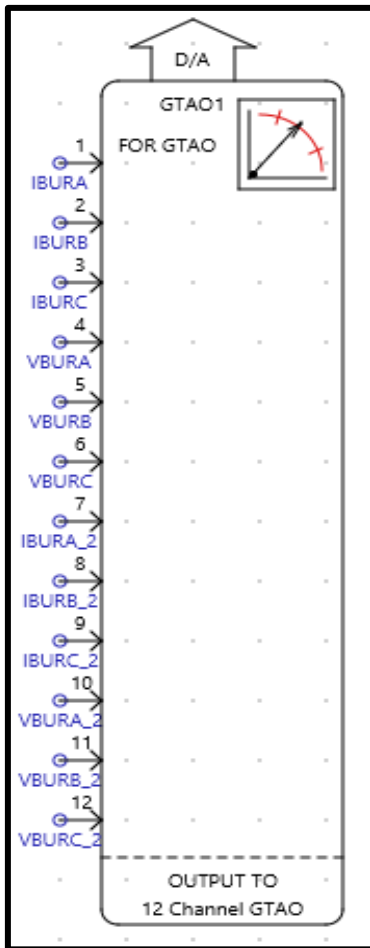


Figure 5.7: GTAO card used in RTDS simulator and RSCAD software for HIL testing.

Table 5.4 below provides the parameter description of the GTAO card.

Table 5.4: GTAO parameter description

Parameter	Description
IBURA	Phase A Current measured by CT 1
IBURB	Phase B Current measured by CT 1
IBURC	Phase C Current measured by CT 1
VBURA	Phase A to neutral Voltage measured by VT 1
VBURB	Phase B to neutral Voltage measured by VT 1
VBURC	Phase C to neutral Voltage measured by VT 1
IBURA_2	Phase A Current measured by CT 2
IBUR B_2	Phase B Current measured by CT 2
IBURC_2	Phase C Current measured by CT 2
VBUR A_2	Phase A to neutral Voltage measured by VT 2
VBUR B_2	Phase B to neutral Voltage measured by VT 2
VBUR C_2	Phase C to neutral Voltage measured by VT 2

5.5.2.2 GTFPI card

Distance relay trip signals are sent to the RDTS simulator through digital inputs, these signals are sent to the circuit breaker of the RSCAD simulated network with the aid of a GTFPI card and Figure 5.8 below is the front panel of the GTFPI card and trip signals sent by the relays.

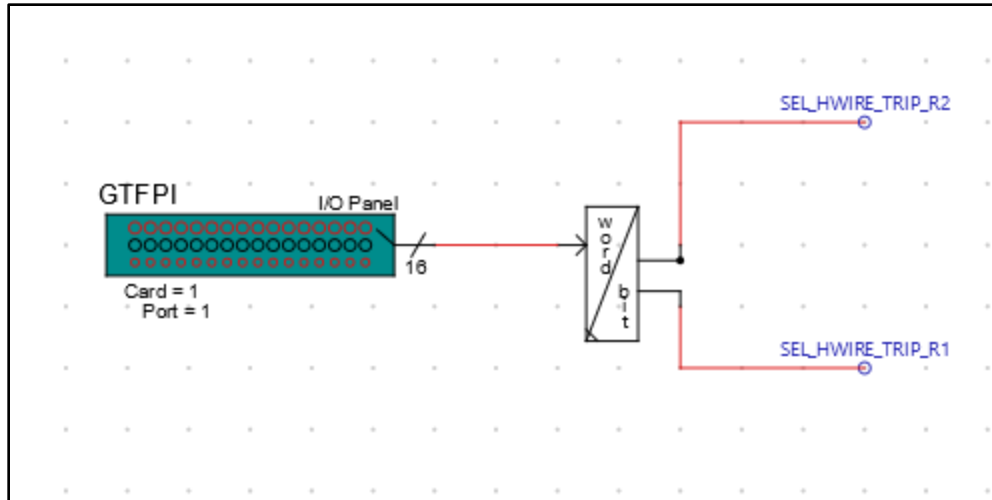


Figure 5.8: GTFPI card used in RTDS simulator and RSCAD software for HIL testing.

Relay 1 and Relay 2 send trip signals to the digital input channels and those signals are sent to the respective software circuit breaker via the GTFPI card presented in Figure 5.8.

The detailed fault control logic is presented in Figure 5.13, where the trip signal from relay 1 is connected to the signal block named “SEL_HWIRE_TRIP_R1” and the trip signal from the relay is connected to the signal block named “SEL_HWIRE_TRIP_R2”.

5.5.2.3 Modelling and configuration of fault logic control circuit

The power distribution line of any power system network often experiences fault conditions. The most common faults occurring on the network are those involving single-phase-to-earth faults. To simulate faults in the RSCAD environment, fault logic must be designed and configured to control the faults in the software.

Different components found in the RSCAD library are used to build these fault logics. Even though common faults are single-phase to ground faults, double-phase, and three-phase faults have been simulated in this study. Figure 5.9 below presents a typical single phase-to-ground fault logic designed to simulate and control single phase-to-ground fault in this project.

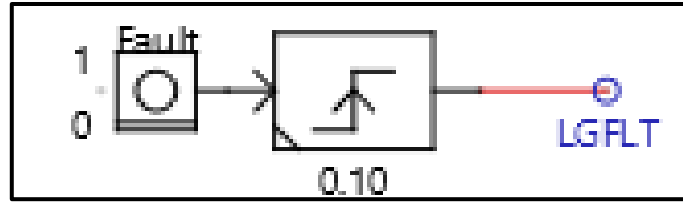


Figure 5.9: Single phase to ground fault logic.

Figure 5.9 provides a fault logic circuit used to simulate and control single-phase to-ground faults on the system. These types of faults are very common (ranging from 70-90% of faults) in power system engineering. Figure 5.10 below shows a single phase-to-earth fault logic configuration.

Component Parameters for rtds_sharc_sld_FAULT

rtds_sharc_sld_FAULT

CONFIGURATION	Name	Description	Value	Unit	Min	Max
L-G PARAMETERS	Agnam	A Phase - Ground Fault Name	AG			
	AgRon	A Phase - Ground Fault Resistance	0.1	ohm	1E-9	
A Phase - Ground Fault Branch Data	Agholdi	Extinguish Arc for abs(I) at or below:	0.0	kA	0.0	10.0
AUTO-NAMING SETTINGS	Asig	Signal Name to control fault	LGFLT			
	Abit	Active bit number in Asig to trigger fault	1		1	32
	Amon	Monitor fault current	Yes			
	IAgnam	Fault Current Signal Name	Iag			

Figure 5.10: Single phase to ground fault logic configuration and settings.

Fault logic configuration settings show that only phase A of the system is configured to fault 0.1 ohm as indicated in Figure 5.10 above. Figure 5.11 below shows the double line and three-phase faults logic circuits.

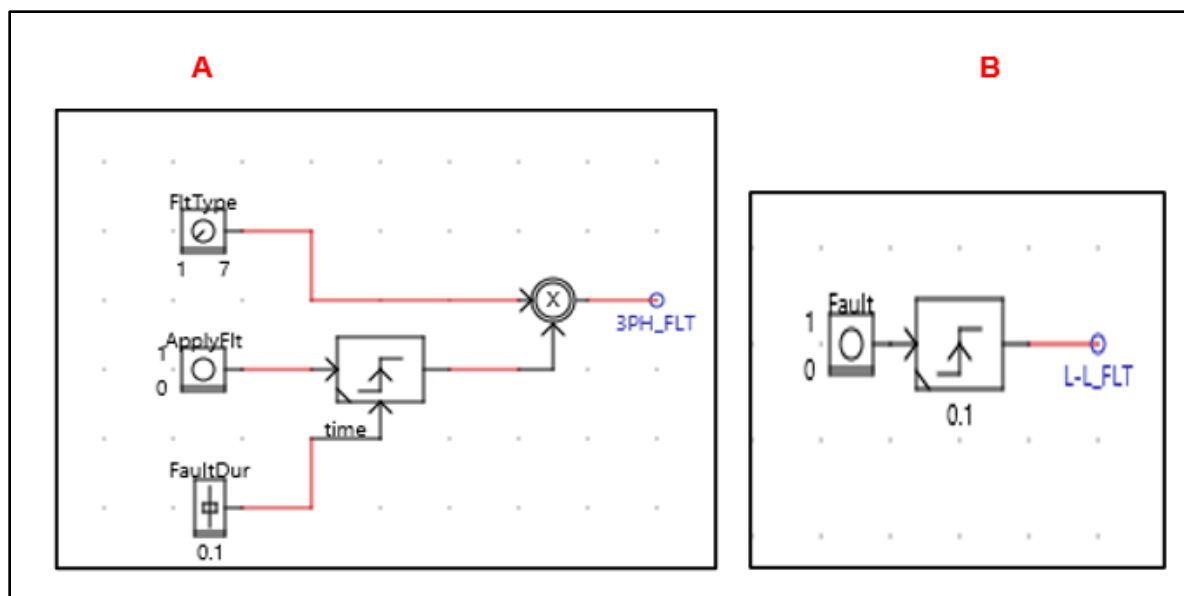


Figure 5.11: Three-phase (A) and Double-phase (B) design fault logic

Figure 5.11 provides the fault control logic for a three-phase fault (A) and phase-to-phase (B) faults simulated on the RSCAD system. The fault duration element in the logic circuit measures the duration of the fault current.

Figure 5.12 below illustrates the fault logic setting for double-phase faults.

Component Parameters for rtds_sharc_sld_FAULT						
rtds_sharc_sld_FAULT						
CONFIGURATION	Name	Description	Value	Unit	Min	Max
L-L PARAMETERS	ABnam	A-B Line Fault Name	A-B			
	ABRon	A-B Line - Line Fault Resistance	0.1	ohm	1E-9	
A-B Line - Line Fault Branch Data	ABholdt	Extinguish Arc for abs(I) at or below:	0.0	kA	0.0	10.0
AUTO-NAMING SETTINGS	ABsig	Signal Name to control fault	L-L_FLT			
	ABbit	Active bit number in Asig to trigger fault	1		1	32
	ABmon	Monitor fault current	No			
	IABnam	Fault Current Signal Name	Iag			

Figure 5.12: Double-phase fault logic configuration

The simulated fault for double phase fault affects phase 'A' and phase 'B' of the distribution network.

5.5.2.4 Modelling and configuration of circuit breaker logic

The purpose of a circuit breaker logic circuit is to control the software breaker status modeled in RSCAD; this logic controls the opening of the circuit breaker during fault conditions.

During fault conditions, the relay sends trip signals to the front panel of the RTDS hardware, and trip signals are sent to the software breaker via GTFPI card in the runtime of RSCAD to open the circuit breaker. Figure 5.13 below provides the circuit breaker control logic used to control breaker status on the modeled network presented in Figure 5.3 above.

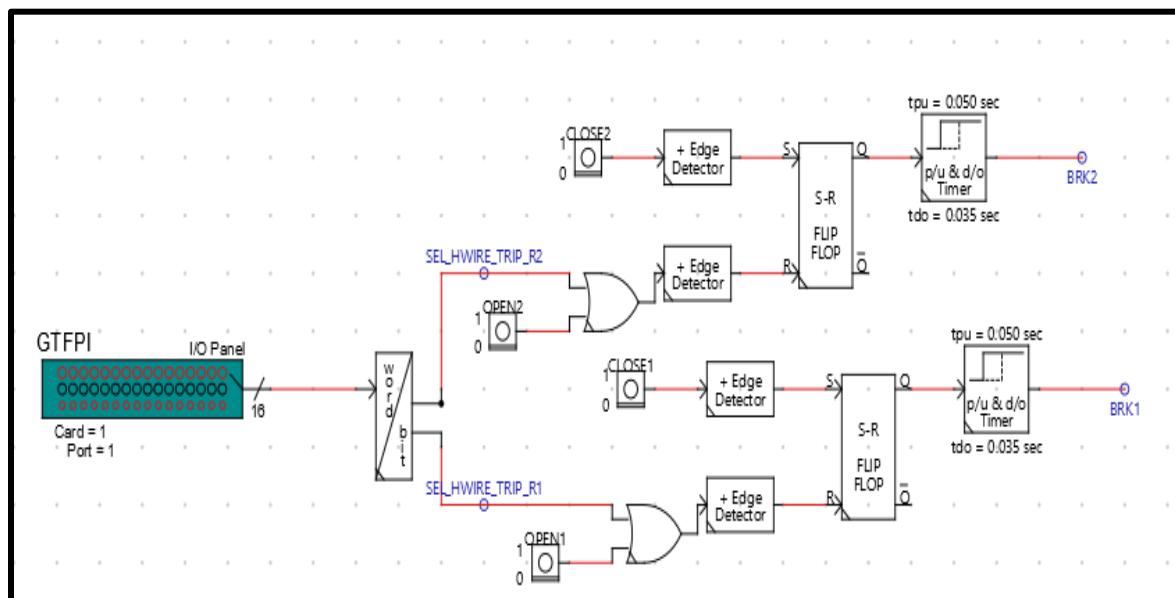


Figure 5.13: Circuit breaker control logic to control circuit breaker 1 and circuit breaker 2 status.

To understand Figure 5.13 Table 5.5 is provided to describe the building block components used for circuit breaker control logic.

Table 5.5: Description of components used to build circuit breaker control logic.

Abbreviation	Description of the control component used to build the circuit breaker control logic
SEL_HWIRE_TRIP_R1	The physical wire connecting trip contacts of relay 1 to the digital input channel of the RTDS simulator

SEL_HWRE_TRIP_R2	The physical wire connecting trip contacts of relay 2 to the digital input channel of the RTDS simulator
OPEN 1/CLOSE 1 OPEN 2/CLOSE 2	The push button opens/closes the circuit breaker 1 The push button opens/closes the circuit breaker 2
BRK 1	The control signal to represent circuit breaker 1 in the RTDS simulation
BRK 2	The control signal to represent circuit breaker 2 in the RTDS simulation

Two pushbuttons are indicated for each circuit breaker for breaker status control, each breaker has an open and close pushbutton as indicated in Figure 5.13. The trip signals from each protection relay (external SEL 421 relays) are indicated to send signals from the tripping contacts (binary outputs) of the relays to the front panel of the RTDS simulator. During fault conditions, the relays trip and send trip signals to the RSCAD modeled circuit breaker, and then the pole of the breaker contacts open to clear the fault current in the simulated power system network.

5.5.3 HIL simulation results for Phase-to-ground fault occurring in zone 1 of relay 1.

Hardware in the loop test has been developed to test the distance protection scheme and relay functionality. Electrical faults such as single phase to ground faults are common in power systems and these faults have been discussed and analyzed in this study. Figure 5.14 shows an electrical network simulated and modeled in RSCAD software. From Figure 5.14 two current transformers and two voltage transformers are indicated to measure the current and voltage of the network.

Three case studies are presented for testing protection functionality in the HIL simulation.

Case study 1: This case study presents an analysis of a steady system where there is no fault.

Case study 2: This case study presents an analysis of a single-phase to-ground fault occurring in zone 1(85% of line 1) of relay 1.

Case study 3: This case study presents an analysis of a double-phase to-ground fault occurring in zone 1(85% of line 1) of relay 1.

Case study 4: This case study presents an analysis of a three-phase to-ground fault occurring in zone 1(85% of line 1) of relay 1.

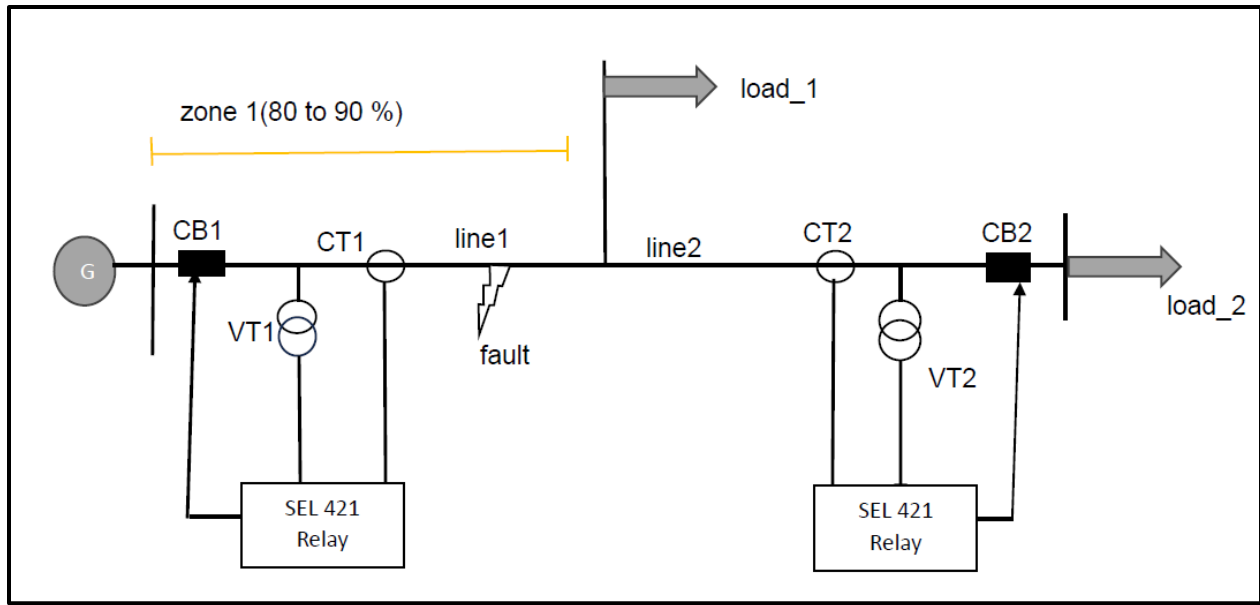


Figure 5.14: Power system in RSCAD software

From Figure 5.14, electrical faults are simulated in zone 1 of line 1, as indicated.

5.5.3.1 Case Study 1: Voltage and current measurements during normal conditions:

During normal conditions, the current and voltage transformer are measuring the signals as provided in Figure 5.15. The current and voltage waveforms are presented in Figure 5.16 and Figure 5.17 respectively.

Figure 5.15 provides the measured voltage and current at the relaying point. Measured current and voltage values are for both primary and secondary values as indicated. The measured voltage is the line-to-neutral (RMS) value for the system voltage 33kV network.

Figure 5.16 presents voltage waveforms measured by VT1. The CT1 measures current waveform and primary current values are provided in Figure 5.17.

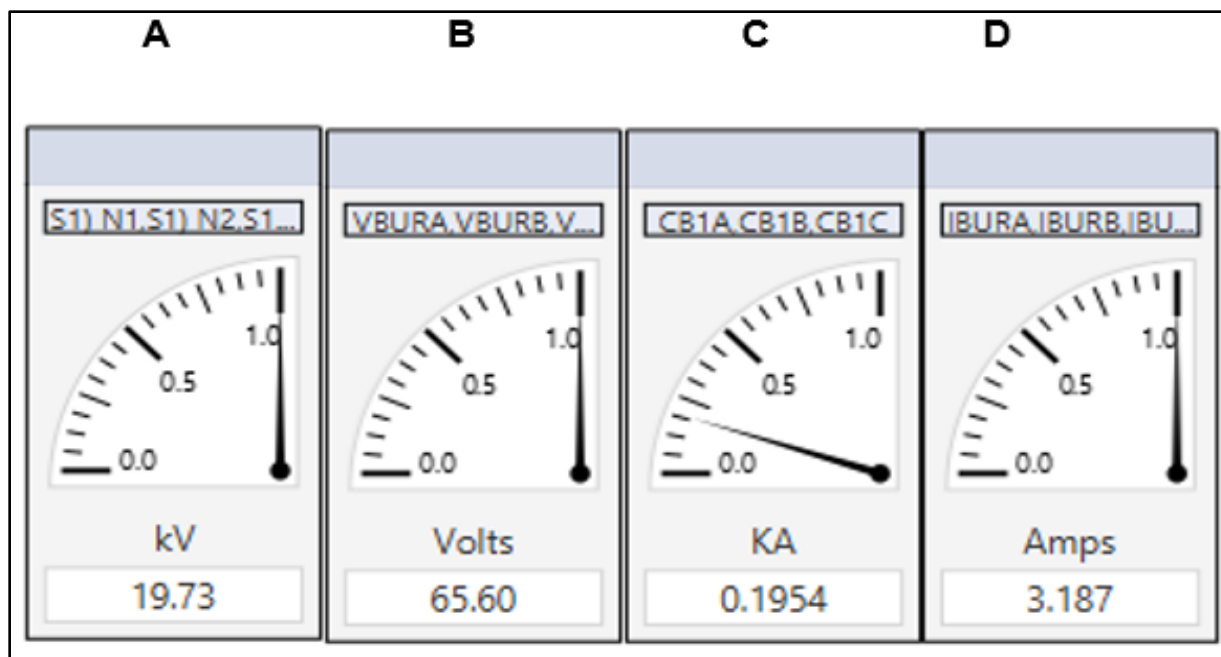


Figure 5.15: The power system measured voltage and current by VT1 and CT1 respectively.

Where:

A: Line to line primary voltage

B: Line to line secondary voltage

C: Primary current

D: Secondary current

The node voltage and primary currents are mapped with VT1 & CT1 as indicated in Table 5.6 below.

Table 5.6: Node Voltage and primary current mapping with the VT1 & CT1 in RSCAD

Parameter	Node Mapping
Phase "A" Voltage	N1
Phase "B" Voltage	N2
Phase "C" Voltage	N3
Phase "A" Current	CB1
Phase "B" Current	CB2
Phase "C" Current	CB3

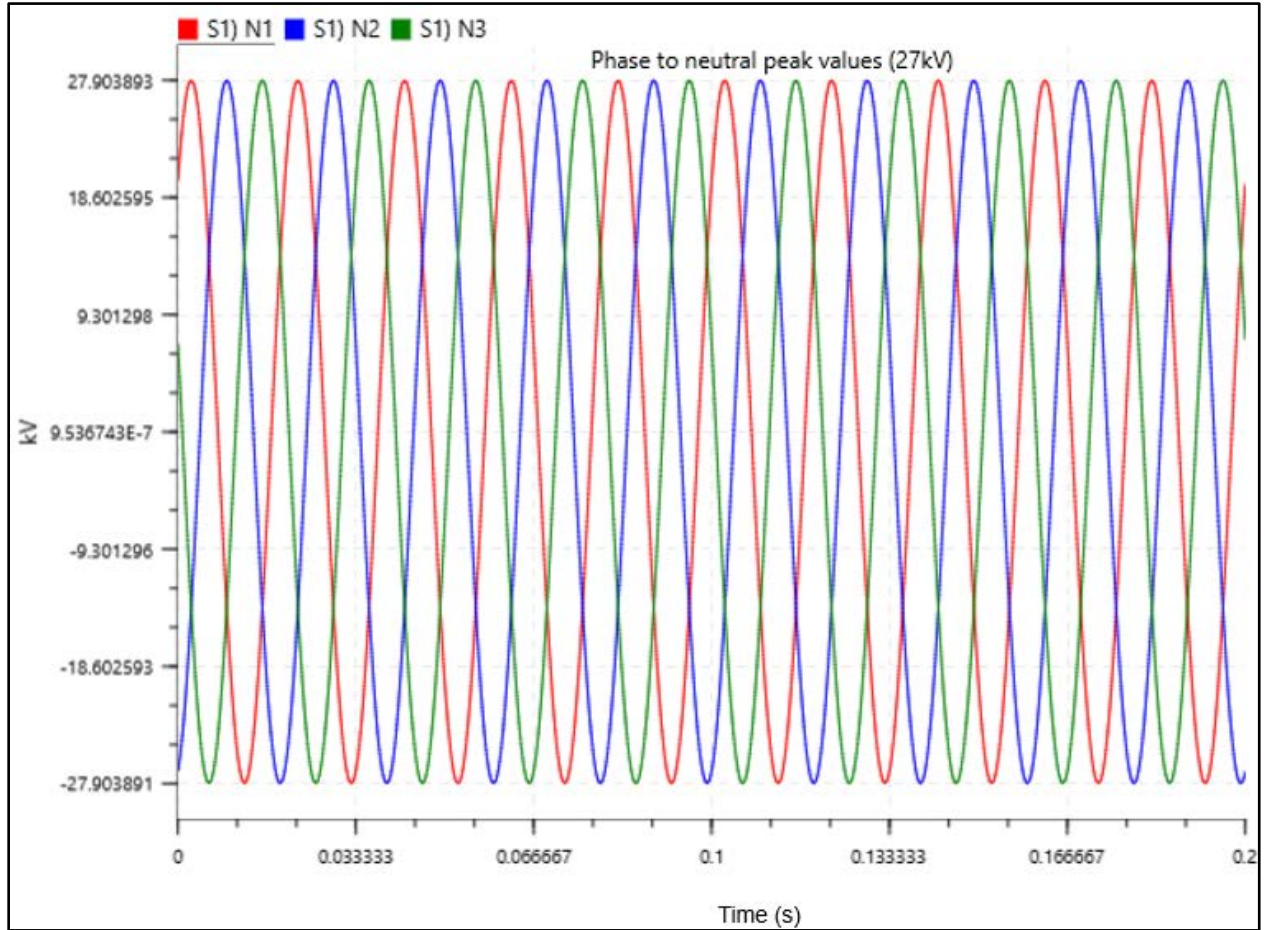


Figure 5.16: The voltage measured waveforms by VT1 during normal state.

Figure 5.16 provides the system voltage during normal conditions, where 27.8 kV is indicated. This is the peak phase to neutral voltage measured by the voltage transformer and this value can be determined as follows.

$$\frac{33\text{kV}}{\sqrt{3}} = 19.05 \text{ kV}$$

Therefore 19.0kV is the phase to neutral voltage (RSM).

$$19.05 \text{ kV} \times \sqrt{2} = 27.0 \text{ kV}$$

Therefore 27 kV is the phase to neutral voltage (Peak value).

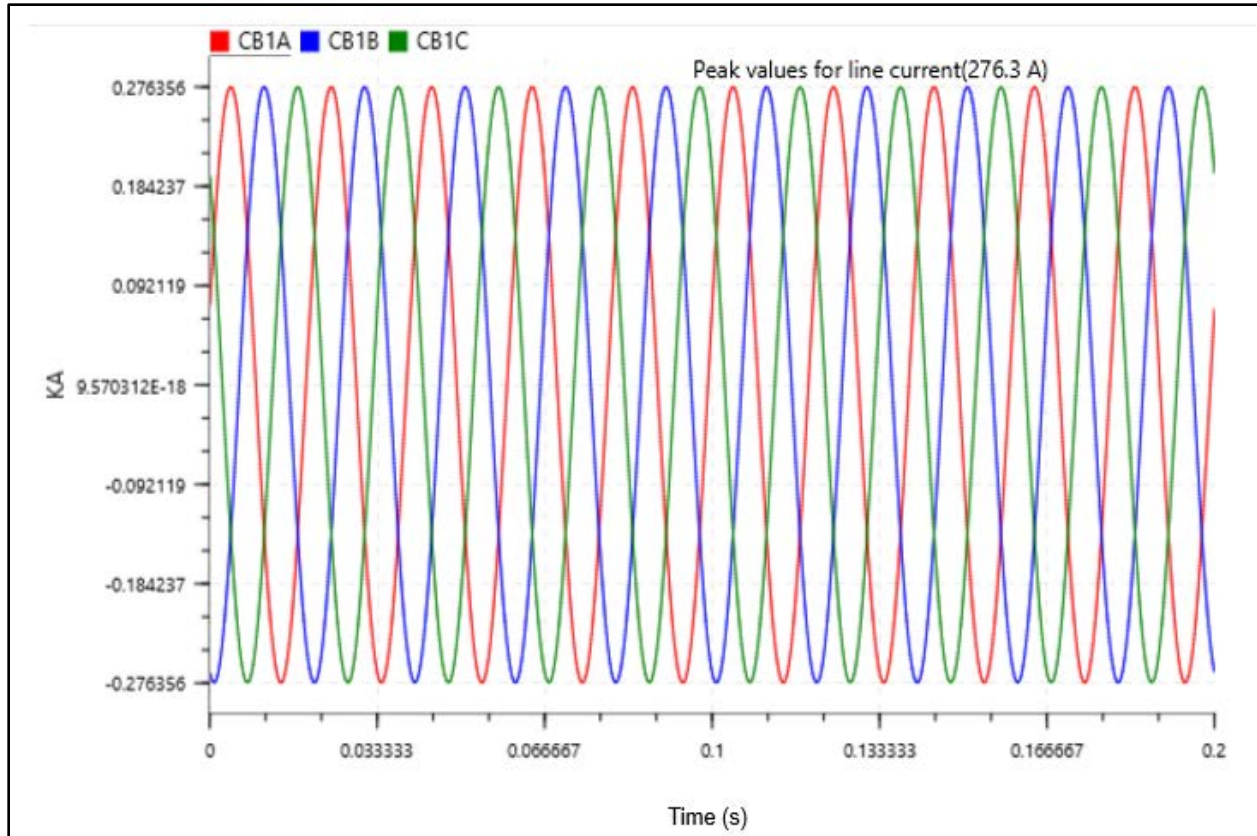


Figure 5.17: The current measured waveforms by CT1 during normal state.

The current flow through the network is presented in Figure 5.15 and Figure 5.17. Figure 5.15 shows both the primary and secondary measured currents, Figure 5.17 provides the sinusoidal representation of the primary current.

Figure 5.17 provides the system current during normal conditions (peak value), where 276.35 A is indicated. This is the peak phase to the neutral current measured by the current transformer and this value can be determined as follows.

$$\frac{276.35 \text{ A}}{\sqrt{2}} = 195.16 \text{ A}$$

Therefore 195.16 A is the phase to neutral current (RSM).

5.5.3.2 Case Study 2: Voltage and current measurements during single phase to ground fault conditions.

This section provides the simulation results for the single-phase-to-ground fault on phase “A”. Figure 5.18 presents single-phase-to-ground fault results, it is noticeable that the red phase had

experienced abnormal conditions by looking at the measured current and voltage for this phase. Figure 5.18 below presents the voltage waveform during the single line-to-ground fault.

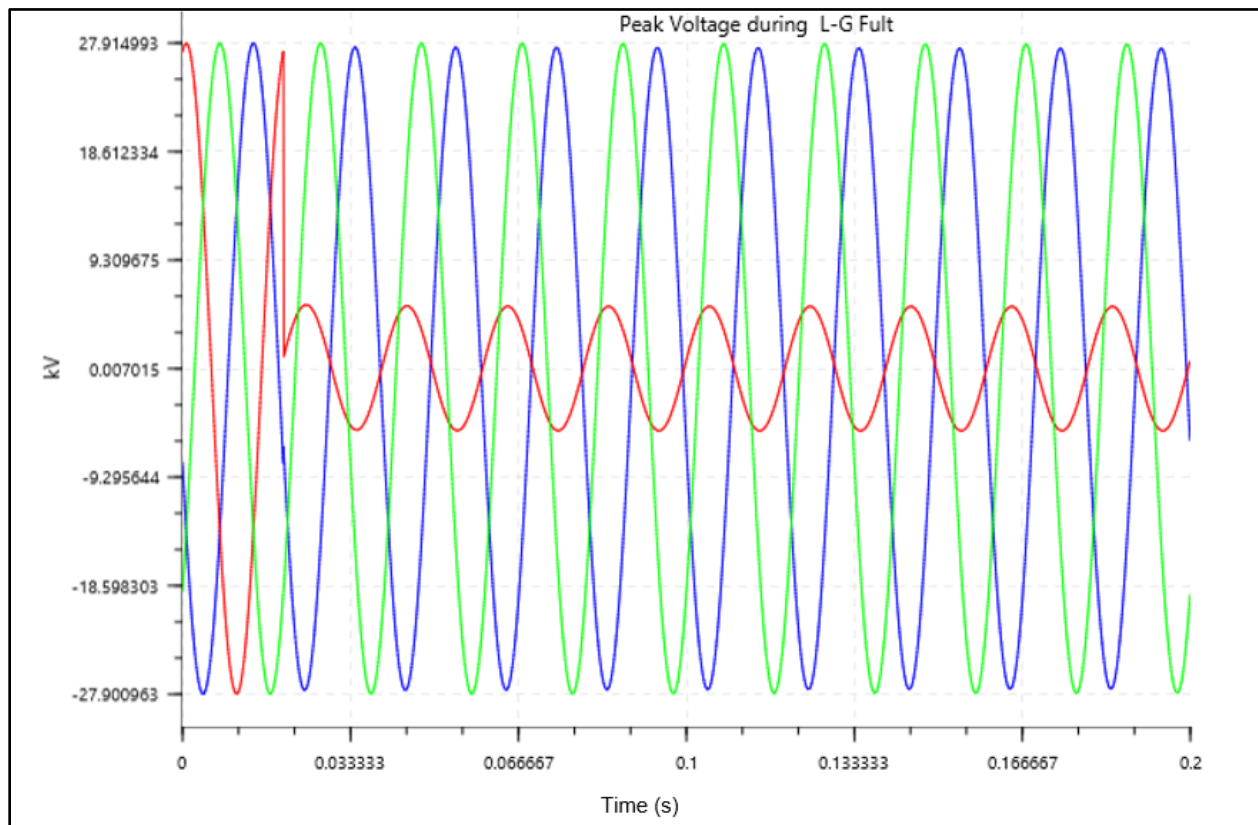


Figure 5.18: Voltage during single-phase fault in zone 1 of the line 1

Figure 5.18 provides the voltage during a single phase-to-ground fault where the red phase voltage has collapsed since there is a high fault current flowing through this phase. Figure 5.19 below presents the red phase fault current.

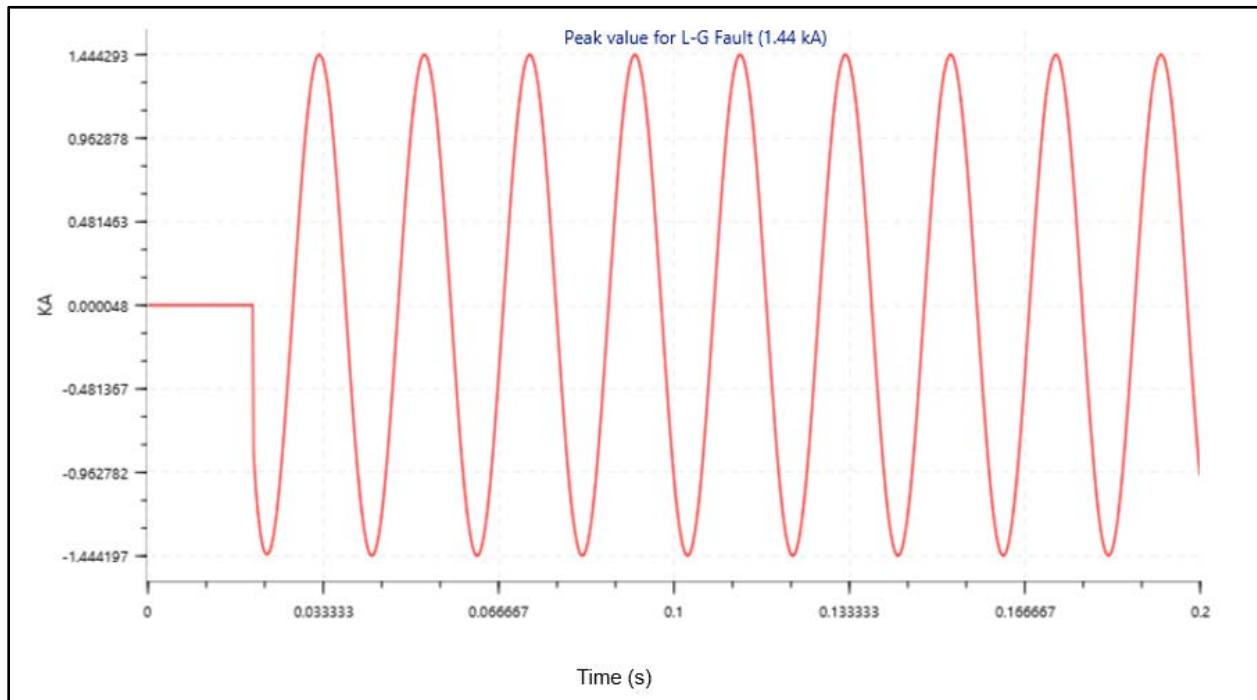


Figure 5.19: Single-phase fault current results in zone 1 of the line 1

A fault current of 1.44 kA is indicated in Figure 5.19 and this value is the peak value of the fault current. The RMS value is calculated as follows.

$$\frac{1.44 \text{ kA}}{\sqrt{2}} = 1018 \text{ A}$$

Therefore, the RMS value for single phase to ground fault is 1018 A as indicated in Figure 5.20 as well.

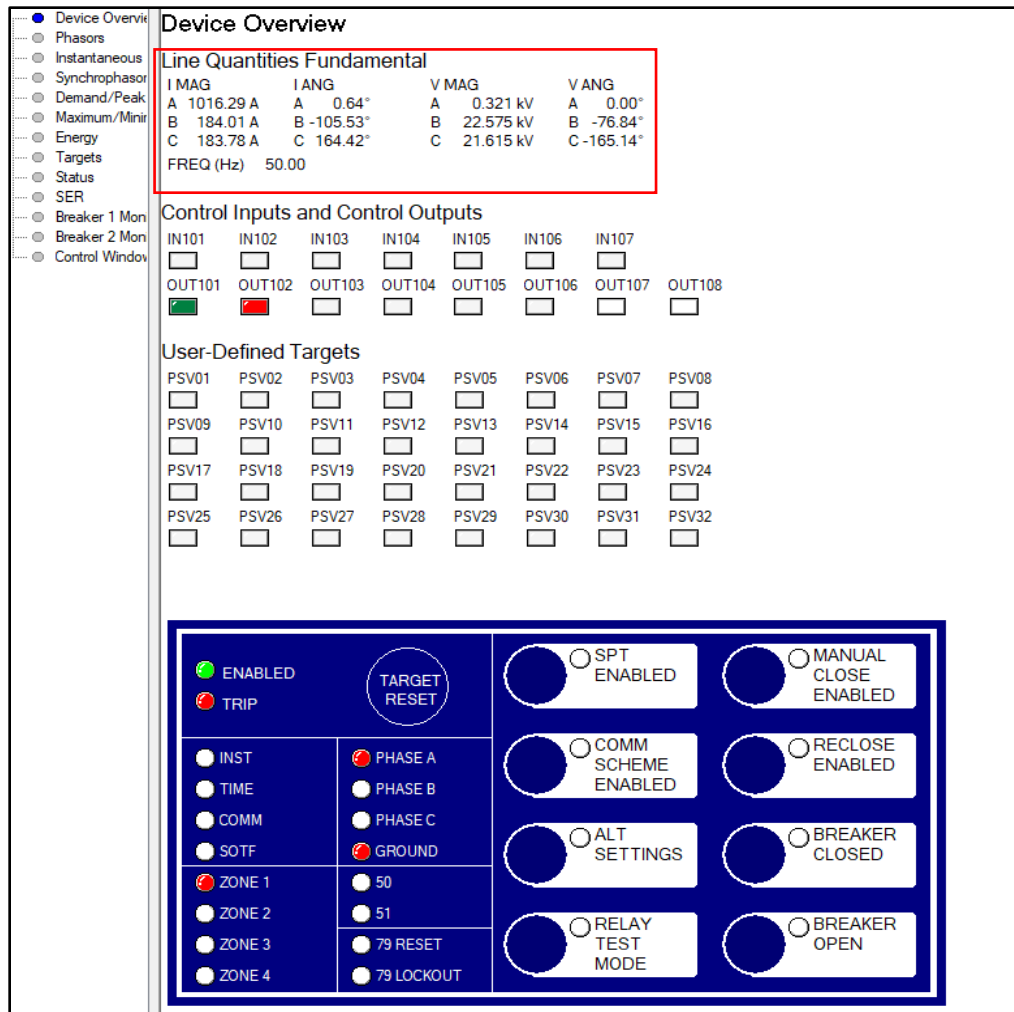


Figure 5.20: SEL 421 HMI view indicating single phase to ground fault trip.

Figure 5.20 provides the line quantities of fundamental data captured by the relay during the fault conditions. The trip zone and the fault type that tripped the relay are indicated.

Event reports of the relay have been extracted to see how the relay reacted to this kind of fault and results are presented in Figure 5.21 below.

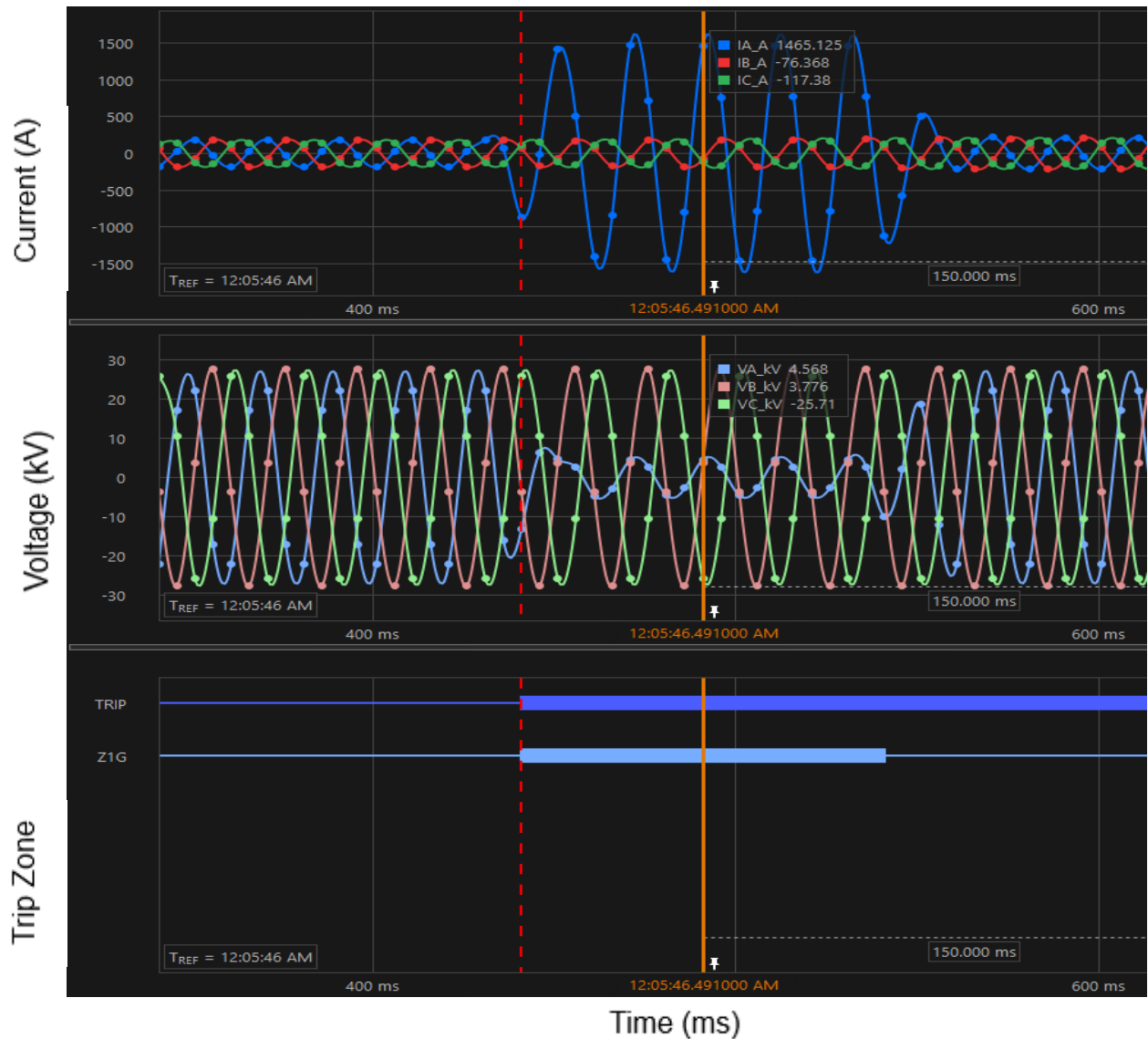


Figure 5.21: SEL 421 event report for a single phase-to-ground fault of relay

Figure 5.21 indicates that the time taken by the relay to clear the fault was very short the relay trip was at the same time as the pick-up time, and these results are well accepted because the fault was in zone 1 and the relay for zone1 is set to trip at 20 ms, in Figure 5.4 above the results shows that the relay clears the fault within defined time and these results are satisfying and accepted.

5.5.3.3 Case Study 2: Voltage and Current Measurements During Double-Phase Fault Conditions

Voltage waveforms during double-phase are presented in Figure 5.22, where voltage waveform disturbance is indicated. From Figure 5.22, two-phase voltages have collapsed due to the high fault current flowing through these phases.

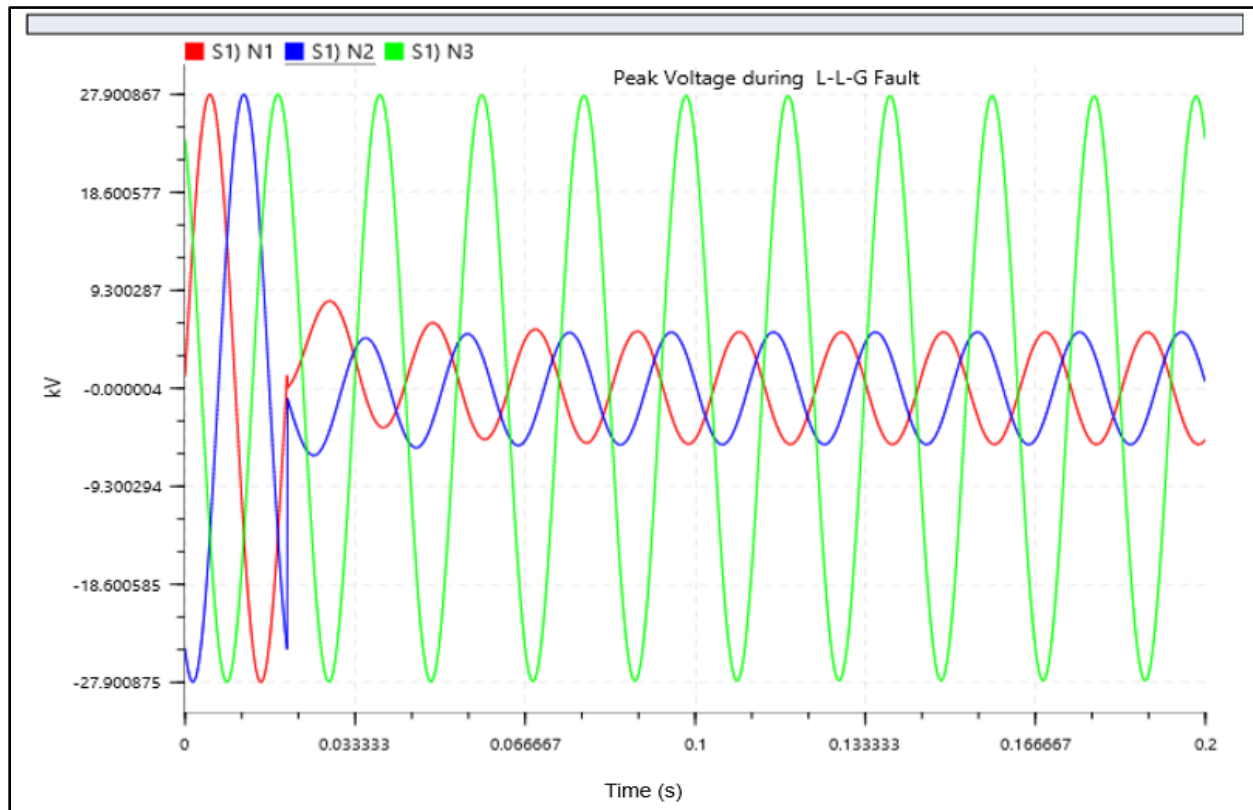


Figure 5.22: Voltage results during a double-phase fault in zone 1 of line 1.

Figure 5.22 indicates that red and blue phase voltage have been affected by the fault current. The waveform for the two-phase fault is provided in Figure 5.23 below.

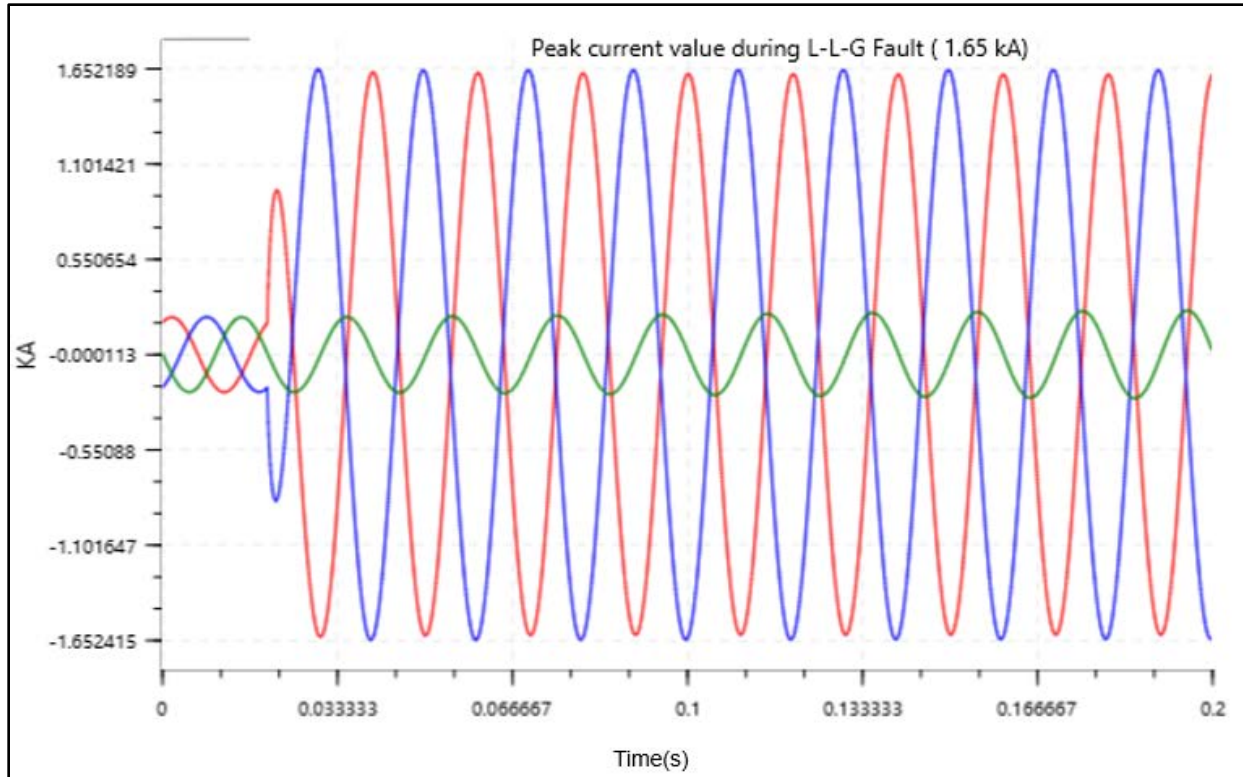


Figure 5.23: Current results during a double-phase fault in zone 1 of line 1.

From Figure 5.23, the peak fault current has been recorded as 1.65 kA where red and blue phases were affected by this fault current. Figure 5.24 below shows the HMI where the RMS fault current is presented and these RSM current values can be obtained as follows:

$$\frac{1.65 \text{ kA}}{\sqrt{2}} = 1166.7 \text{ A}$$

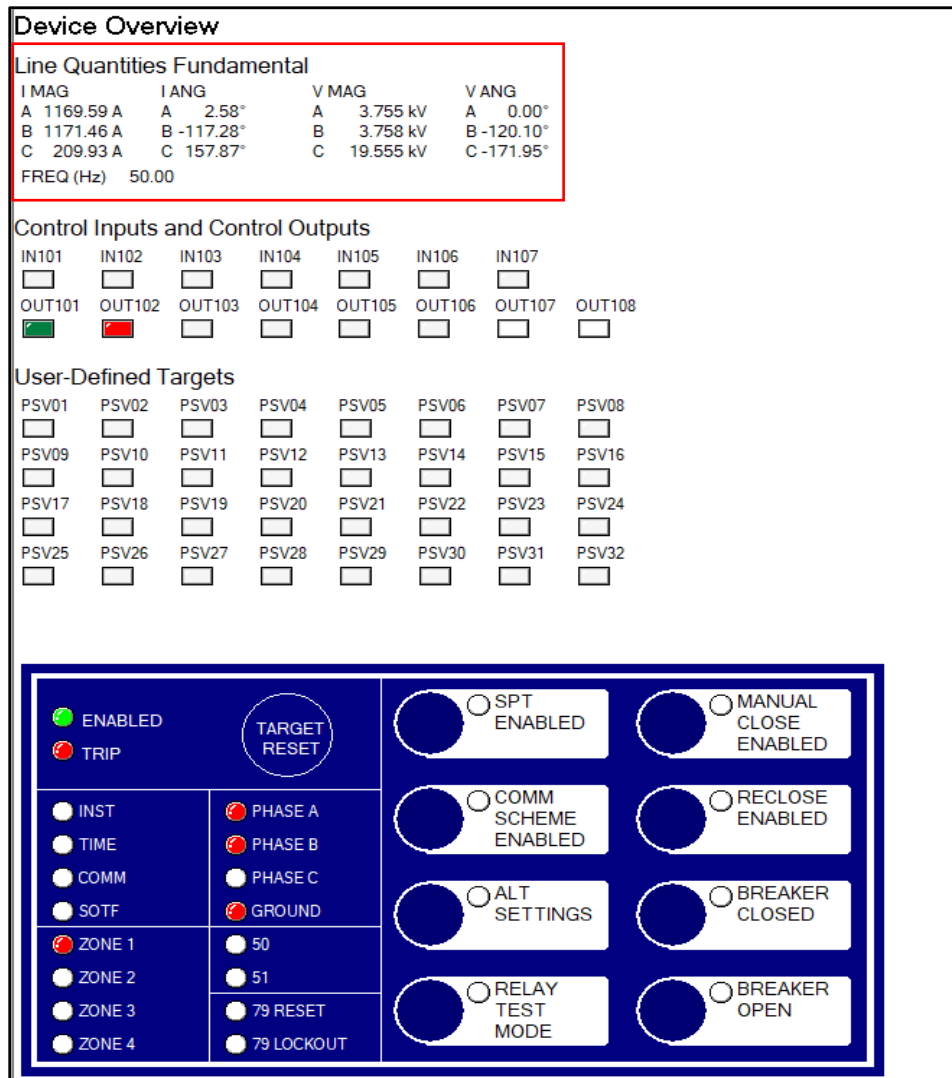


Figure 5.24: SEL 421 HMI view indicating double phase to ground fault trip.

Figure 5.24 provides the line quantities of fundamental data captured by the relay during the double phase to ground fault conditions. The trip zone and the fault type that tripped the relay are indicated. Event reports of the relay have been extracted to see how the relay reacted to this kind of fault and results are presented in Figure 5.25 below.

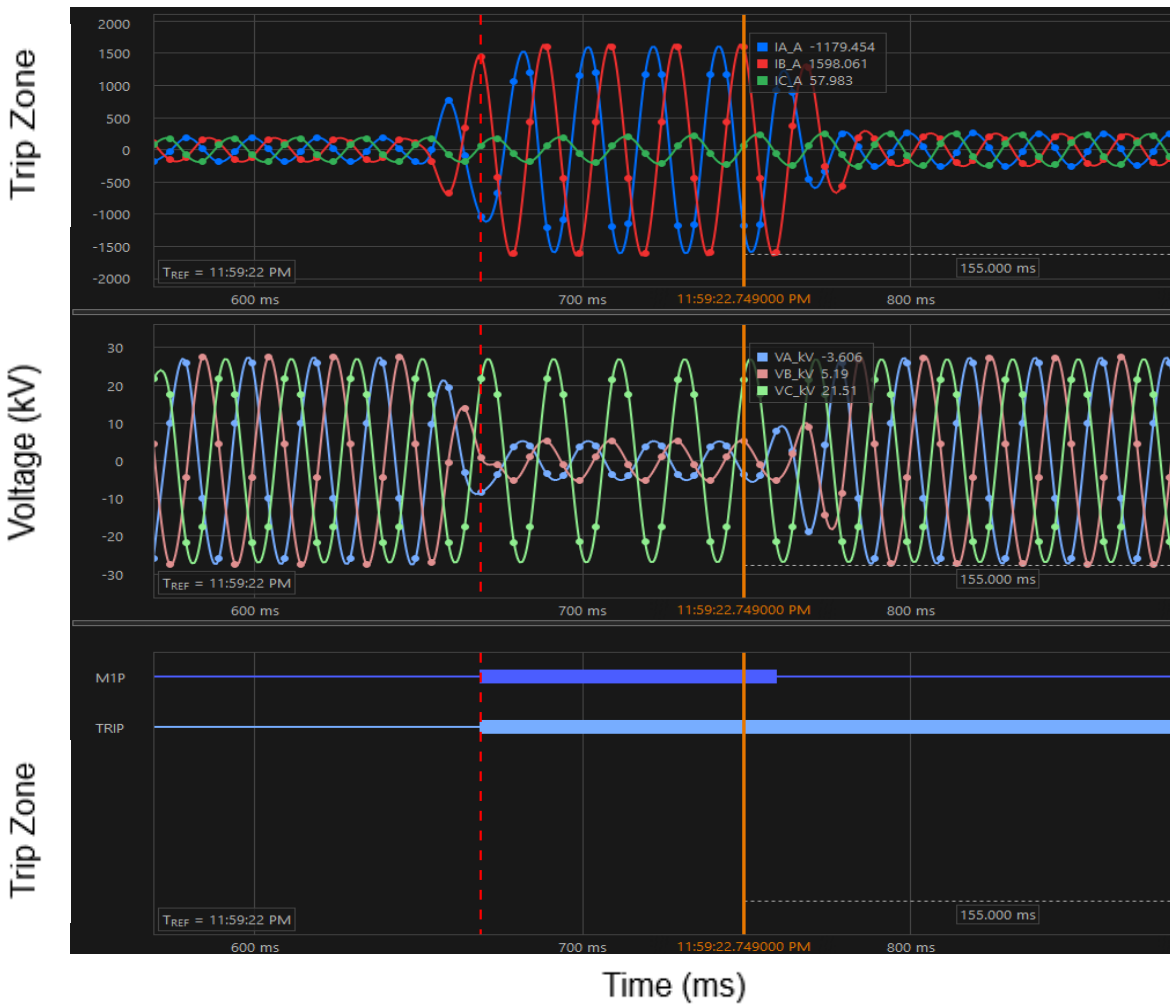


Figure 5.25: Double-phase fault event report from relay 1

From Figure 5.25, relay 1 cleared the fault instantly and the relay is set to trip at 20 ms in this zone of the line. Results obtained prove that the relay can operate as fast as possible.

5.5.3.4 Case Study 4: Voltage and Current Measurements During Three-Phase Fault Conditions

Lastly, even though the three-phase fault is rare to occur on power distribution networks, for results analysis, this type of fault was also simulated, and results from the simulation and relay event report are provided. Figure 5.26 below shows the system voltage during three-phase fault conditions.

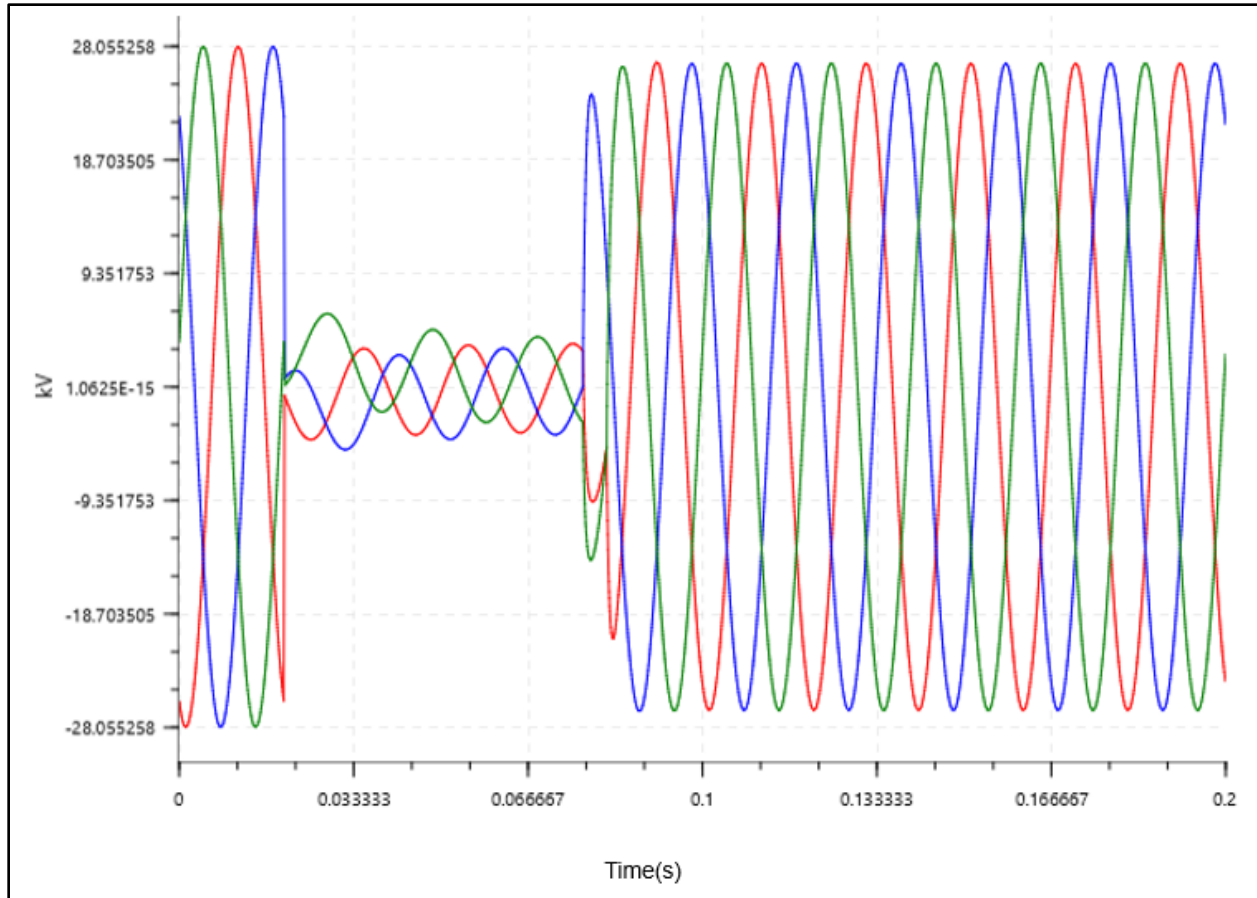


Figure 5.26: Voltage results during a three-phase fault in zone 1 of line 1.

From Figure 5.26, it is indicated that all three phases had experienced the fault, this is proved by voltage collapse in all three phases. The three-phase fault current waveforms are provided in Figure 5.27 below.

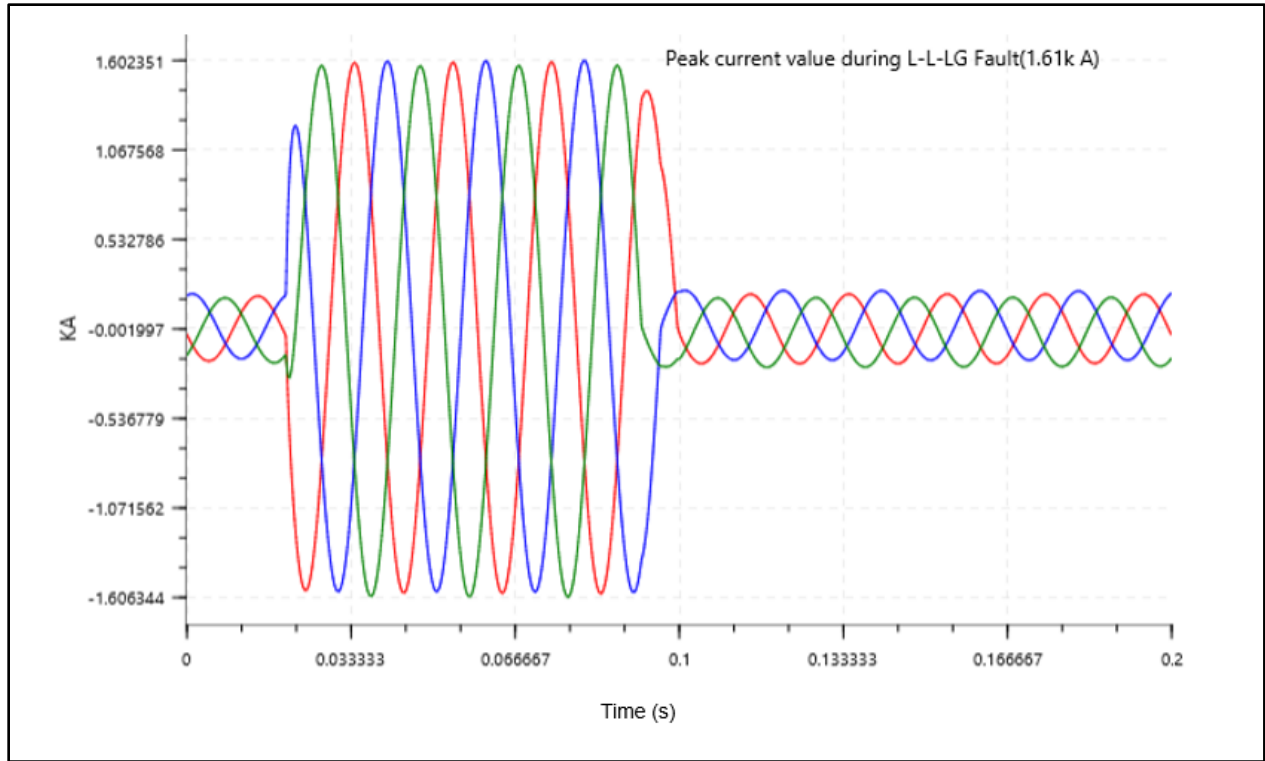


Figure 5.27: Current results during a three-phase fault in zone 1 of line 1.

Figure 5.27 presents a three-phase fault occurring with a peak value of 1.6 kA and the RMS value of the fault current is indicated in Figure 5.28 where the HMI is presented.

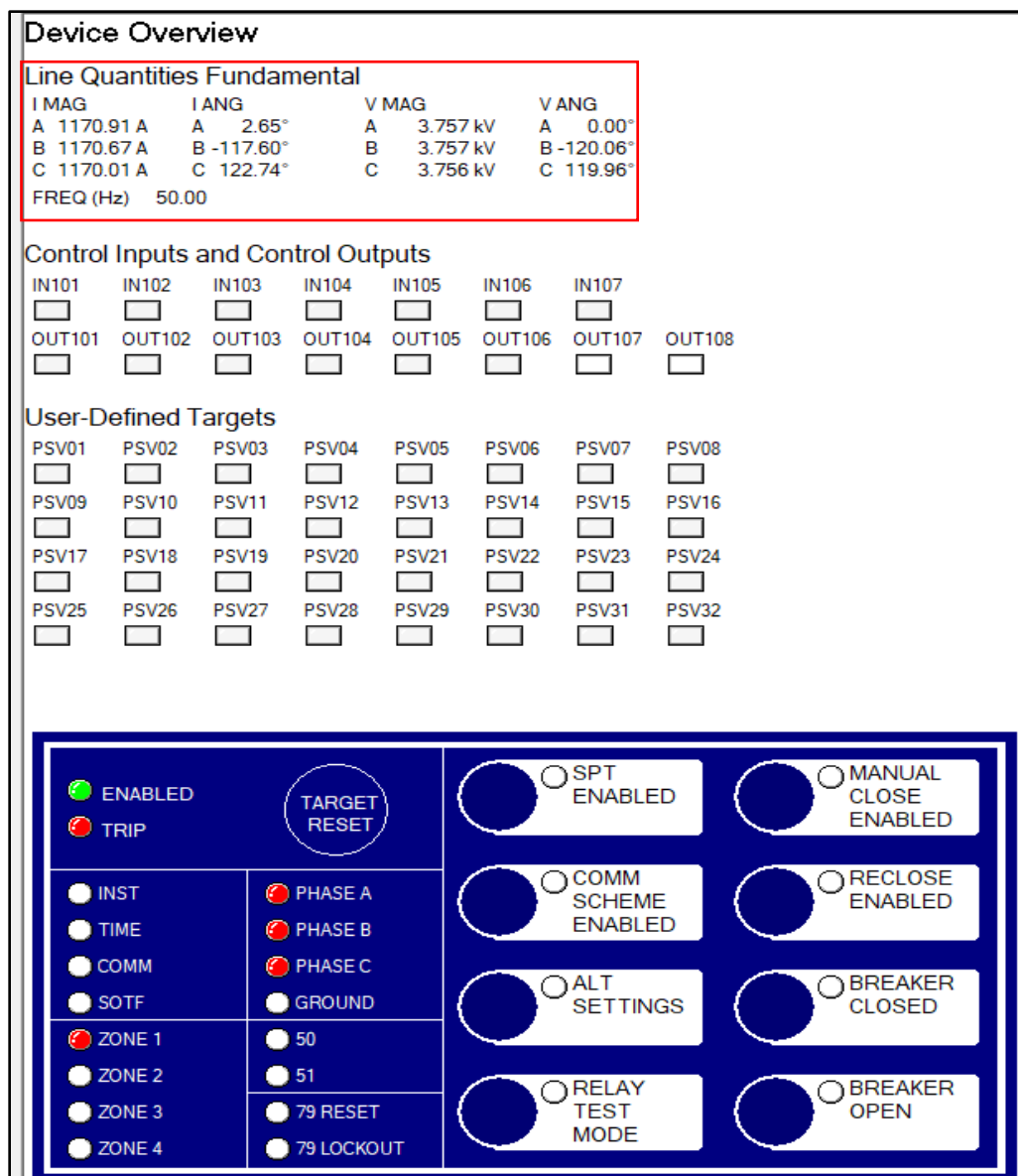


Figure 5.28: SEL 421 HMI view indicating three-phase fault trip.

Figure 5.28 provides the line quantities of fundamental data captured by the relay during the three-phase fault conditions and it further provides the indications for the type of fault that caused the relay to trip.

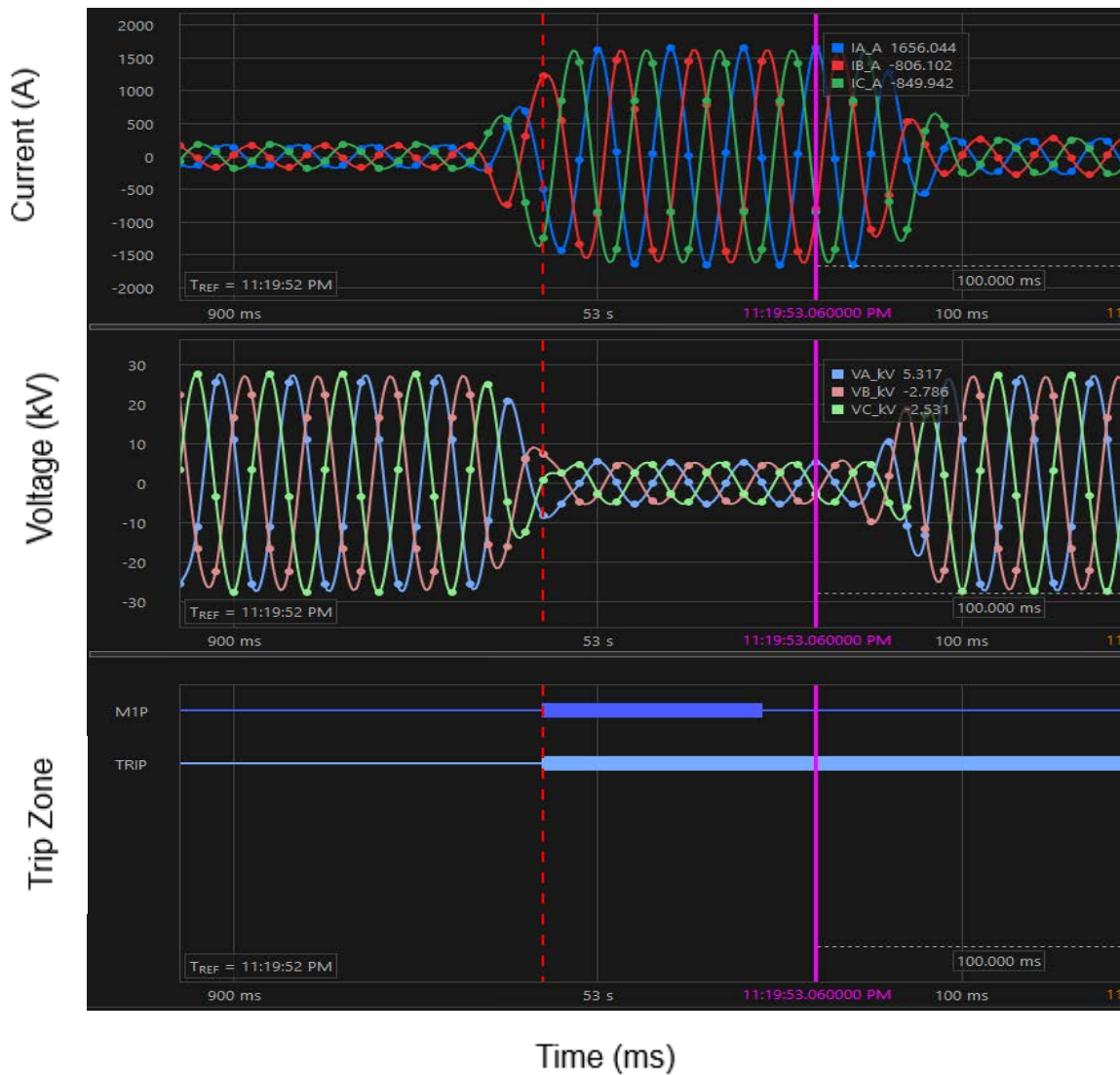


Figure 5.29: Three-phase fault event report from relay 1

Figure 5.29 provides an events report for a three-phase fault. The first part of Figure 5.29 provides the current waveforms, the second part indicates the voltage results, and the last part presents the time graph indicating fault clearing time which is an instant trip since trip time in the relay is set to trip at 20 ms, in Figure 5.29 above the results shows that the relay clears the fault within defined time and these results are satisfying and accepted.

5.6 Discussion on Simulation for all four Case Studies

Table 5.7 below provides the simulation voltage (RMS values) results obtained in HIL simulation during the normal state and fault condition of the system. The results of the HIL simulation are compared with the results of the DigSilent simulation.

Table 5.8 provides comparison of two studies, where the fault was simulated in zone 1 of the protected line.

Table 5.7: RTDS simulation results compared with the DigSilent simulation results.

TYPE OF FAULT AND FAULT AT LINE 1	DIGSILENT	RTDS	DIGSILENT	RTDS	DIGSILENT	RTDS
	VA	VA	VB	VB	VC	VC
Steady-state	19 kV	19 kV	19 kV	19 kV	19 kV	19 kV
L-G @ phase A	19.2 kV	0.321 kV	19.3	22 k V	19 kV	21 kV
L-L-G @ phase A B	3.1kV	3.75 kV	3.1 kV	3.75 kV	19.1 kV	19.55 kV
L-L-L @ Phase A, B, C	3.81 kV	3.75 kV	3.81 kV	3.5 kV	3.81 kV	3.5 kV

Table 5.8: Benchmark literature versus obtained findings of this research

RESEARCH STUDIES	RELAY SET TIME (ms)	RELAY OPERATING TIME (ms)	LOCATION OF THE FAULT IN LINE PERCENTAGE (%)	FAULT TYPE	TRIP ZONE
Reference benchmark. (Penthong et al., 2023b)	0	27	90	L-G	1
		26	90	L-L-G	
		26	90	L-L-L	

Proposed Mho distance protection functional testing results	20	20	85	L-G	1
		10	85	L-L-G	
		20	85	L-L-L	

Table 5.7 provides the system voltages during normal and abnormal conditions. Table 5.7 further presents a steady-state voltage where phase-to-neutral values are indicated (19kV) for a 33kV power system. The results presented in Table 5.7 are obtained from both DigSilent and HIL simulations and compared to each other. Table 5.7 indicates that voltages drop in the event of any type of fault in both simulation tools (DigSilent and HIL simulations).

Table 5.8 presents a comparison of results obtained in chapter five of this study and the results obtained from a different study done by (Penthong et al., 2023b). According to the results obtained from (Penthong et al., 2023b) study, the distance relay was tested on the HIL simulation and the relay was set to trip for a fault in zone 1 with no time delay.

Results of that study show that the relay is not that accurate because it tripped with time delay in all three types of faults that were simulated. Table 5.8 further indicates that the SEL 421 relay used in this research study operated with no time delay as it is configured without time delay, therefore these results were warmly accepted as the protection relay proved to be accurate for all types of faults that were simulated.

5.7 Conclusion

In this chapter hardware-in-the-loop (HIL) implementation was presented and simulation results together with the relay events of different types of electrical faults were provided and analyzed. The HIL testbed setup has been developed using the RTDS simulator. Multivendor devices such as the SEL 421 relay, ethernet switch, and voltage and current amplifiers were used in

implementing the HIL setup for testing distance relay functionality in the hardware in the loop simulation functional testing.

Hardware-in-the-loop (HIL) testing is an important test technique that is used by vendors and utilities to test the hardware devices before implementing them on a real system. The HIL is useful for training and understanding how the system works and operates on real power system networks.

The following chapter (Chapter Six) addresses the recommendations for future works related to this study, provides research deliverables, indicates publications that are associated with this study, and provides a conclusion for the works and outcomes achieved in this research work.

CHAPTER SIX

CONCLUSION

6.1 Introduction

This research has aimed to study, analyze, develop, and implement an appropriate, feasible, and reliable distance protection scheme for a 33kV traction distribution network. A Transnet 4-bus electrical network is considered for the study case of this project. An investigation of relay functional testing has been conducted using Hardware-in-the-loop simulation at the CSAEMS lab at CPUT.

Simulation of symmetrical and unsymmetrical faults have been carried out at different locations of the system to verify the minimum fault levels and two power system simulation tools (DigSILENT and RSCAD) were used as the preferred power system simulation tools for conducting load flow.

Functional Testing of the distance relay elements has been conducted in a lab-scale environment. The lab-scale setup consists of a CMC 256 plus Omicron device, an SEL 421 distance relay, an ethernet switch, and a laptop (configuration tool). AcSELEator and Test Universe software were used to perform engineering configuration for the SEL 421 relay and the CMC 256 plus device respectively.

The communication method used for the test bench setup uses ethernet cables for data exchange between all devices in the setup. Symmetrical and unsymmetrical faults were conducted, and the mho distance protection functional testing was performed. Relay events in response to the faults were also obtained and analyzed. Hardware in the loop test technique was implemented using an RTDS simulator interfaced with RSCAD software.

This chapter aims to summarize the research project's results and outline the research findings and deliverables. The possible future works are outlined and discussed together with the possible industrial applications. Lastly, publications done during this research project are listed.

6.2 Deliverables

This section gives and summarizes the research deliverables.

6.2.1 Literature review

The literature review focused on gathering theoretical and technical information addressing distance protection challenges. The literature review focuses on protection schemes for power distribution and transmission systems.

Distance protection settings design, simulation, and implementation are the focus areas of the study. Basic power system protection requirements such as speed, selectivity, sensitivity, security, and reliability of the protection scheme were reviewed.

Applicable testing techniques used to test protection relays at the laboratory level such as close and open-loop testing methods were reviewed and discussed. The hardware-in-the-loop using RTDS was implemented and closed-loop functional testing of the SEL 421 distance protective relays was performed.

Different scientific and technical publications such as conference papers, and journals, addressing the design, challenges, methods, and implementation of the distance protection schemes for distribution systems were reviewed, and findings were compared in a table form against each other.

6.2.2 DigSILENT simulation and implementation of the distance protection scheme for 33kV traction distribution network

DigSILENT software was used to simulate the 33kV Transnet power system network as part of the simulation investigation to perform load flow analysis, build protection schemes, and test them. Several network conditions were used to mimic faults to verify the protection scheme's functionality.

Since the simulated network produced all expected results, it is clear from the acquired simulation results that the proposed engineering configuration, the designed fault control, and the circuit breaker logic can adequately protect the 33kV network under different fault conditions.

6.2.3 Implementation of the lab scale test bench to test distance protection schemes for the 33kv distribution network.

Designed protection settings were tested on a physical SEL421 distance protection relay. The lab-scale test setup was developed in the CSAEMS research center at CPUT. The SEL 421 distance relay functional testing was conducted using a secondary injection test set called CMC 256-plus to inject the secondary current and voltage signals to emulate the fault conditions in the power system network. Two engineering configuration software (AcSELeator Quickset and Test Universe) were used to configure the distance relay and the secondary test set respectively.

In Chapter Four, single-phase-to-ground, line-line, and three-phase faults were tested in zone 1, zone 2, and zone 3 and the relay passed the test as it has tripped within time for all types of faults in respective zones. Therefore, those results were satisfying and accepted.

6.2.4 Implementation of the hardware-in-the-loop test bench to test the distance protection schemes for a 33kV traction network.

The 33kV traction network was simulated and modeled on RSCAD software. The HIL setup was developed to test the distance protection scheme for a 33kV traction network in a hardware-in-the-loop simulation. The RTDS simulator, SEL421 distance relay, and Omicron amplifiers were used for HIL protection functional testing.

Two CMS 156 Omicron amplifiers were used to boost voltage and current signals in the HIL setup. The modeled network was interfaced with the hardware simulator (RTDS) through the GTWIF card of the RTDS simulator.

The RTDS simulator's digital input channels, to which the physical relay transmits the trip signals, are used to link the SEL 421 relays to the simulator.

The network was used to simulate single-phase, double-phase, and three-phase faults. Protection relays were set up to operate appropriately and clear the faults in the system. The suggested protection plan was highly advised to protect this 33kV traction network after evaluating the data from the HIL test setup.

6.3 Academic and industrial applications

Results from the generated models for RSCAD and DigSILENT may be utilized to help postgraduate and undergraduate students learn more about the distance protection scheme. The findings and substance of the thesis may be applied in both academic and industrial contexts, serving as a standard for initiatives in industry and education.

Thus, it is strongly advised that PRASA test protective relays before putting them on a real network by implementing the protection settings created in this study and using the testing methods covered in this thesis. This will reduce the possibility of the reoccurrence of the faults in the PARSA network due to incorrect engineering configurations on the distance protection relays and improve the protection speed and reliability. As a result, South African passenger rail will improve travel times and won't often be impacted by 33kV line failures at the PARSA network.

6.4 Future work

This research focused on power system simulation, protection setting design, and testing of protection relays using laboratory scale test bench and hardware-in-the-loop testing methods.

The investigated, simulated, tested, and implemented protection scheme is only the Mho distance protection scheme. For future works, it would be great to explore and study the application of other protection schemes on a traction system, the likes of directional overcurrent, and line differential would be great to understand their capabilities on traction network protection.

It would be good to investigate and incorporate additional zones of distance protection schemes in the future so that faults can be simulated in all zones of the protected line and will explore the IEC61850 applications for the HIL simulation of the distance protection scheme.

6.5 Conclusion

Chapter six summarized the research aim, objectives, achievements, and applications where the research outcomes can be applied. The possible future works related to this research study are indicated. This chapter further provides publications achieved during this research work.

6.6 Publications

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APPENDIX

APPENDIX A: DIGSILENT PARSA NETWORK LOAD FLOW SIMULATION RESULTS FOR DIFFERENT LOADING CONDITIONS

- Appendix A.1:** Three-phase system voltage measured in all substation buses when all lines are in service.

Load Flow Calculation					Complete System Report: Voltage Profiles, Grid Interchange				
AC Load Flow, balanced, positive sequence					Automatic Model Adaptation for Convergence				
Automatic tap adjustment of transformers					No	Max. Acceptable Load Flow Error			
Consider reactive power limits					No	Bus Equations(HV)			
						Model Equations			
						1.00 kVA			
						0.10 %			
Grid: Grid		System Stage: Grid			Study Case: Study Case			Annex: / 1	
		nom.V	Bus - voltage				Voltage - Deviation [%]		
		[kV]	[p.u.]	[kV]	[deg]	-10	-5	0	+5
								+10	
Bellville		33.00	0.964	31.80	-1.27				
Goodwood		33.00	0.972	32.06	-0.99				
Main1		33.00	1.000	33.00	0.00				
Main2		33.00	1.000	33.00	0.00				

3. Appendix A.3: Loading percentage of transmission lines when line 3 is out of service.

Load Flow Calculation					Complete System Report: Voltage Profiles, Grid Interchange				
AC Load Flow, balanced, positive sequence					Automatic Model Adaptation for Convergence				
Automatic tap adjustment of transformers					Max. Acceptable Load Flow Error				
Consider reactive power limits					Bus Equations(HV)				
					Model Equations				
Grid: Grid					System Stage: Grid				
					Study Case: Study Case				
					Annex: / 1				
	nom.V [kV]	Bus - voltage [p.u.]	[kV]	[deg]	-10	-5	Voltage - Deviation [%]		
							0	+5	+10
Bellville	33.00	0.947	31.25	-1.84					
Goodwood	33.00	0.973	32.12	-0.89					
Main1	33.00	0.000	0.00	0.00					
Main2	33.00	1.000	33.00	0.00					

4. Appendix A.4: Three-phase system voltage measured in all substations bus when line 1 is out of service.

Grid: Grid					System Stage: Grid				
					Study Case: Study Case				
					Annex: / 1				
	nom.V [kV]	Bus - voltage [p.u.]	[kV]	[deg]	-10	-5	Voltage - Deviation [%]		
							0	+5	+10
Bellville	33.00	0.897	29.59	-3.50					
Goodwood	33.00	0.874	28.83	-4.39					
Main1	33.00	1.000	33.00	0.00					

5. Appendix A.5: Loading percentage of transmission lines when the section between main 2 and Goodwood substation is out of service.

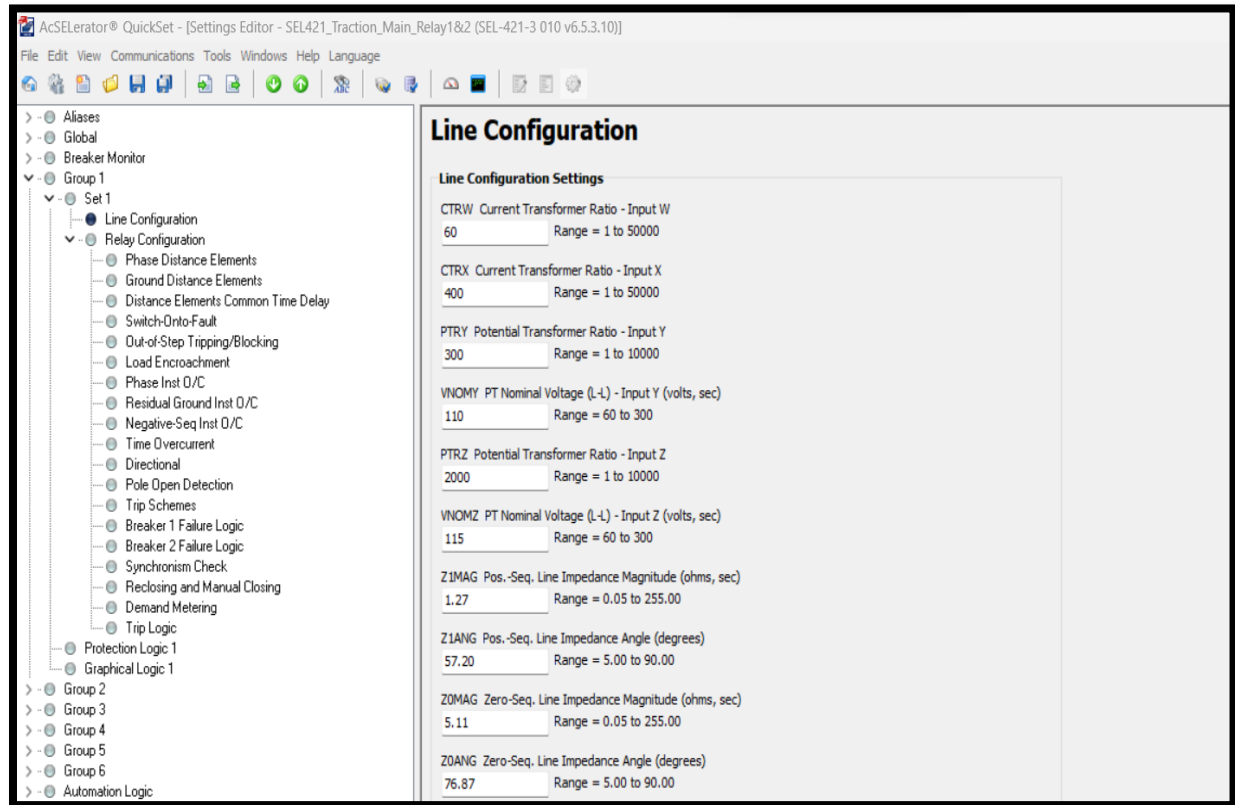
				DIgSILENT PowerFactory 2022 SP3		Project: Date: 6/22/2023		
Grid: Grid		System Stage: Grid		Study Case: Study Case		Annex: / 1		
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power. factor [-]	Current [kA]	Current [p.u.]
General Load1	Lod		Goodwood	7.200	3.487	0.90	0.160	1.145
General Load2	Lod		Bellville	9.000	4.359	0.90	0.195	1.115
External Grid	Xnet		Main1	17.636	10.076	0.87	0.355	0.107
Goodwood-Bellville	Lne	32.04	Goodwood	-7.200	-3.487	-0.90	0.160	0.320
			Bellville	7.332	3.693	0.89	0.160	0.320
Main1-Bellville	Lne	71.07	Main1	17.636	10.076	0.87	0.355	0.711
			Bellville	-16.332	-8.052	-0.90	0.355	0.711

6. Appendix A.6: IEC standard used to calculate load flow on DigSilent software.

Basic Options	Method	IEC 60909	Published	2016	Execute
Advanced Options	Fault Type	3-Phase Short-Circuit			Close
Output	Calculate	Max. Short-Circuit Currents			Cancel
Verification	Max. Voltage Tolerance for LV-Systems	10	%		Contents
Short-Circuit Duration					
	Break Time	0.1	s	Used Break Time	global
	Fault Clearing Time (lth)	1.	s		

APPENDIX B: SEL 421 DISTANCE RELAY ENGINEERING CONFIGURATION SETTINGS

1. Appendix B.1: Line configuration in AcSELEerator quickset software for relay settings configuration



2. Appendix B.2: Mho Phase distance zones, impedance, and time element settings for SEL 421 relay 1&2.

AcSELERator® QuickSet - [Settings Editor - Relay 1 & 2 (SEL-421-3 010 v6.5.3.10)]

File Edit View Communications Tools Windows Help Language

Aliases
Global
Breaker Monitor
Group 1
Set 1
Line Configuration
Relay Configuration
Phase Distance Elements
Ground Distance Elements
Distance Elements Common Tripping
Switch-Onto-Fault
Out-of-Step Tripping/Blocking
Load Encroachment
Phase Inst O/C
Residual Ground Inst O/C
Negative-Seq Inst O/C
Time Overcurrent
Directional
Pole Open Detection
Trip Schemes
Breaker 1 Failure Logic
Breaker 2 Failure Logic
Synchronism Check
Reclosing and Manual Closing
Demand Metering
Trip Logic
Protection Logic 1
Graphical Logic 1
Group 2
Group 3
Group 4
Group 5
Group 6

Phase Distance Elements

E21P Mho Phase Distance Zones
3 Select: N, 1-5

Mho Phase Distance Element Reach

Z1P Zone 1 Reach (ohms, sec)
0.51 Range = 0.05 to 64.00, OFF

Z2P Zone 2 Reach (ohms, sec)
0.95 Range = 0.05 to 64.00, OFF

Z3P Zone 3 Reach (ohms, sec)
1.27 Range = 0.05 to 64.00, OFF

Z4P Zone 4 Reach (ohms, sec)
36.00 Range = 0.05 to 64.00, OFF

Z5P Zone 5 Reach (ohms, sec)
OFF Range = 0.05 to 64.00, OFF

Mho Phase Distance Element Time Delay

Z1PD Zone 1 Time Delay (cycles)
1.000 Range = 0.000 to 16000.000, OFF

Z2PD Zone 2 Time Delay (cycles)
15.000 Range = 0.000 to 16000.000, OFF

Z3PD Zone 3 Time Delay (cycles)
30.000 Range = 0.000 to 16000.000, OFF

3. Appendix B.3: Mho Ground distance zones, impedance, and time element settings for SEL 421 relay 1 & 2

AcSElerator® QuickSet - [Settings Editor - SEL421_Traction_Main_Relay1&2 (SEL-421-3 010 v6.5.3.10)]

File Edit View Communications Tools Windows Help Language

Synchronized Phasor Measurement
Time and Date Management
Breaker Monitor
Group 1
Set 1
Line Configuration
Relay Configuration
Phase Distance Elements
Ground Distance Elements
Distance Elements Common Time Delay
Switch-Onto-Fault
Out-of-Step Tripping/Blocking
Load Encroachment
Phase Inst O/C
Residual Ground Inst O/C
Negative-Seq Inst O/C
Time Overcurrent
Directional
Pole Open Detection
Trip Schemes
Breaker 1 Failure Logic
Breaker 2 Failure Logic
Synchronism Check
Reclosing and Manual Closing
Demand Metering
Trip Logic
Protection Logic 1
Graphical Logic 1
Group 2
Group 3

XGPOL Quad Ground Polarizing Quantity
I2 Select: I2, IG
TANG Non-homogeneous Correction Angle (degrees)
-3.0 Range = -40.0 to 40.0

Ground Distance Element Time Delay

Z1GD Zone 1 Time Delay (cycles)
0.000 Range = 0.000 to 16000.000, OFF

Z2GD Zone 2 Time Delay (cycles)
15.000 Range = 0.000 to 16000.000, OFF

Z3GD Zone 3 Time Delay (cycles)
30.000 Range = 0.000 to 16000.000, OFF

Z4GD Zone 4 Time Delay (cycles)
50.000 Range = 0.000 to 16000.000, OFF

Z5GD Zone 5 Time Delay (cycles)
OFF Range = 0.000 to 16000.000, OFF

Zero-Sequence Compensation Factor

k0M1 Zone 1 ZSC Factor Magnitude
1.033 Range = 0.000 to 10.000, AUTO

k0A1 Zone 1 ZSC Factor Angle (degrees)
25.90 Range = -180.00 to 180.00

AcSElerator® QuickSet - [Settings Editor - SEL421_Traction_Main_Relay1&2 (SEL-421-3 010 v6.5.3.10)]

File Edit View Communications Tools Windows Help Language

Synchronized Phasor Measurement
Time and Date Management
Breaker Monitor
Group 1
Set 1
Line Configuration
Relay Configuration
Phase Distance Elements
Ground Distance Elements
Distance Elements Common Time Delay
Switch-Onto-Fault
Out-of-Step Tripping/Blocking
Load Encroachment
Phase Inst O/C
Residual Ground Inst O/C
Negative-Seq Inst O/C

Ground Distance Elements

E21MG Mho Ground Distance Zones
3 Select: N, 1-5

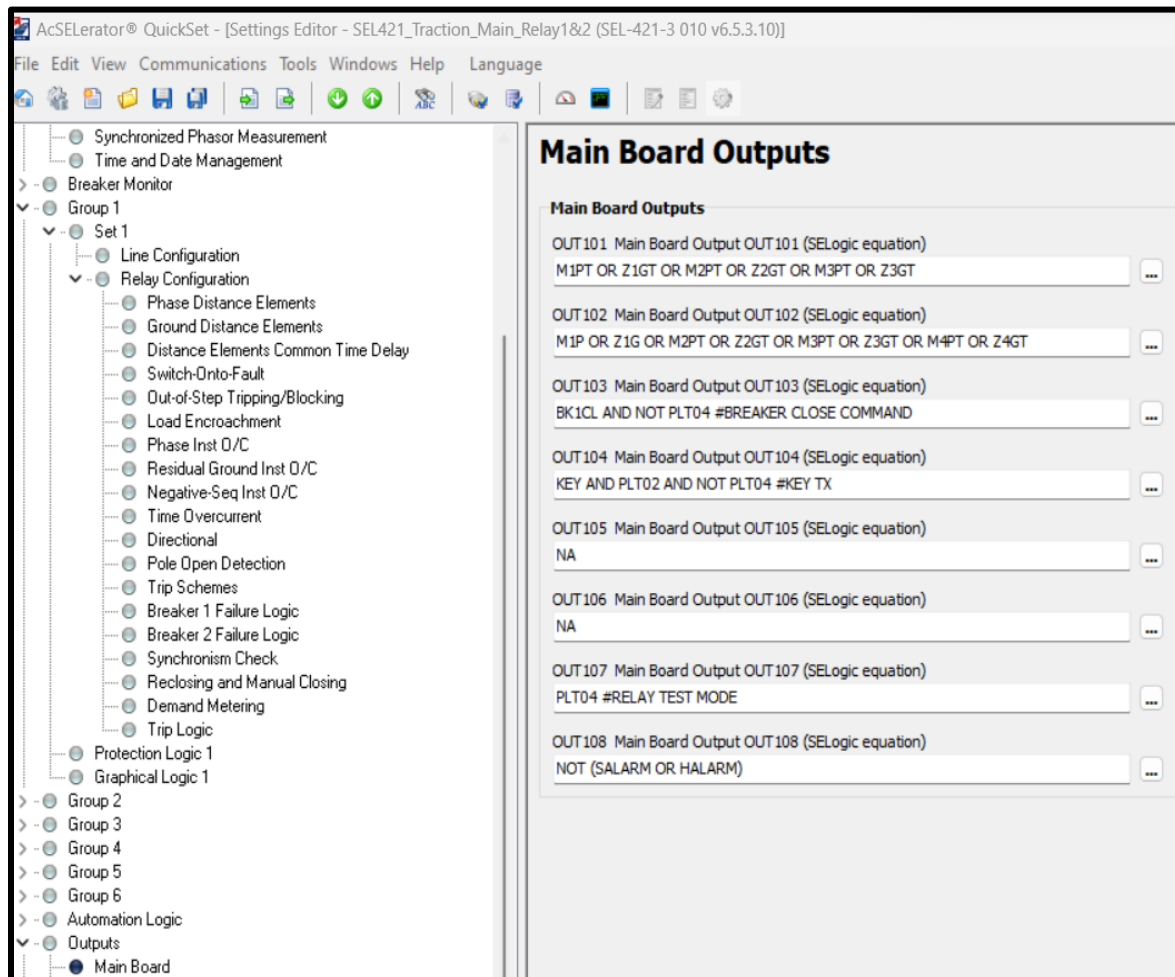
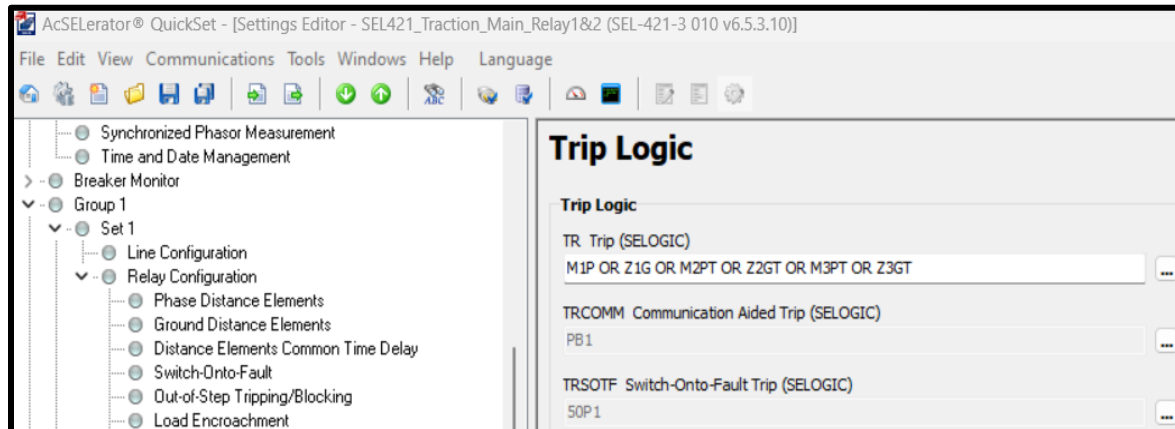
Mho Ground Distance Element Reach

Z1MG Zone 1 (ohms, sec)
0.51 Range = 0.05 to 64.00, OFF

Z2MG Zone 2 (ohms, sec)
0.95 Range = 0.05 to 64.00, OFF

Z3MG Zone 3 (ohms, sec)
1.27 Range = 0.05 to 64.00, OFF

4. Appendix B.4: Trip logic and Main Board configuration



5. **Appendix B.5:** Mho Phase distance zones, impedance, and time element settings for SEL 421 relay 3&4.

AcSElerator® QuickSet - [Settings Editor - Relay 3 & 4 (SEL-421-3 010 v6.5.3.10)]

File Edit View Communications Tools Windows Help Language

Aliases
Global
Breaker Monitor
Group 1
Set 1
Line Configuration
Relay Configuration
Phase Distance
Ground Distance
Distance Element
Switch-On
Out-of-Step
Load Encroachment
Phase Instability
Residual Current
Negative-Sequence
Time Overcurrent
Directional
Pole Operation
Trip Schemes
Breaker 1
Breaker 2
Synchronizing
Reclosing
Demand Load
Trip Logic
Protection Logic 1
Graphical Logic 1
Group 2
Group 3
Group 4
Group 5
Group 6

Phase Distance Elements

E21P Mho Phase Distance Zones
3 Select: N, 1-5

Mho Phase Distance Element Reach

Z1P Zone 1 Reach (ohms, sec)
0.51 Range = 0.05 to 64.00, OFF

Z2P Zone 2 Reach (ohms, sec)
0.95 Range = 0.05 to 64.00, OFF

Z3P Zone 3 Reach (ohms, sec)
1.27 Range = 0.05 to 64.00, OFF

Z4P Zone 4 Reach (ohms, sec)
36.00 Range = 0.05 to 64.00, OFF

Z5P Zone 5 Reach (ohms, sec)
OFF Range = 0.05 to 64.00, OFF

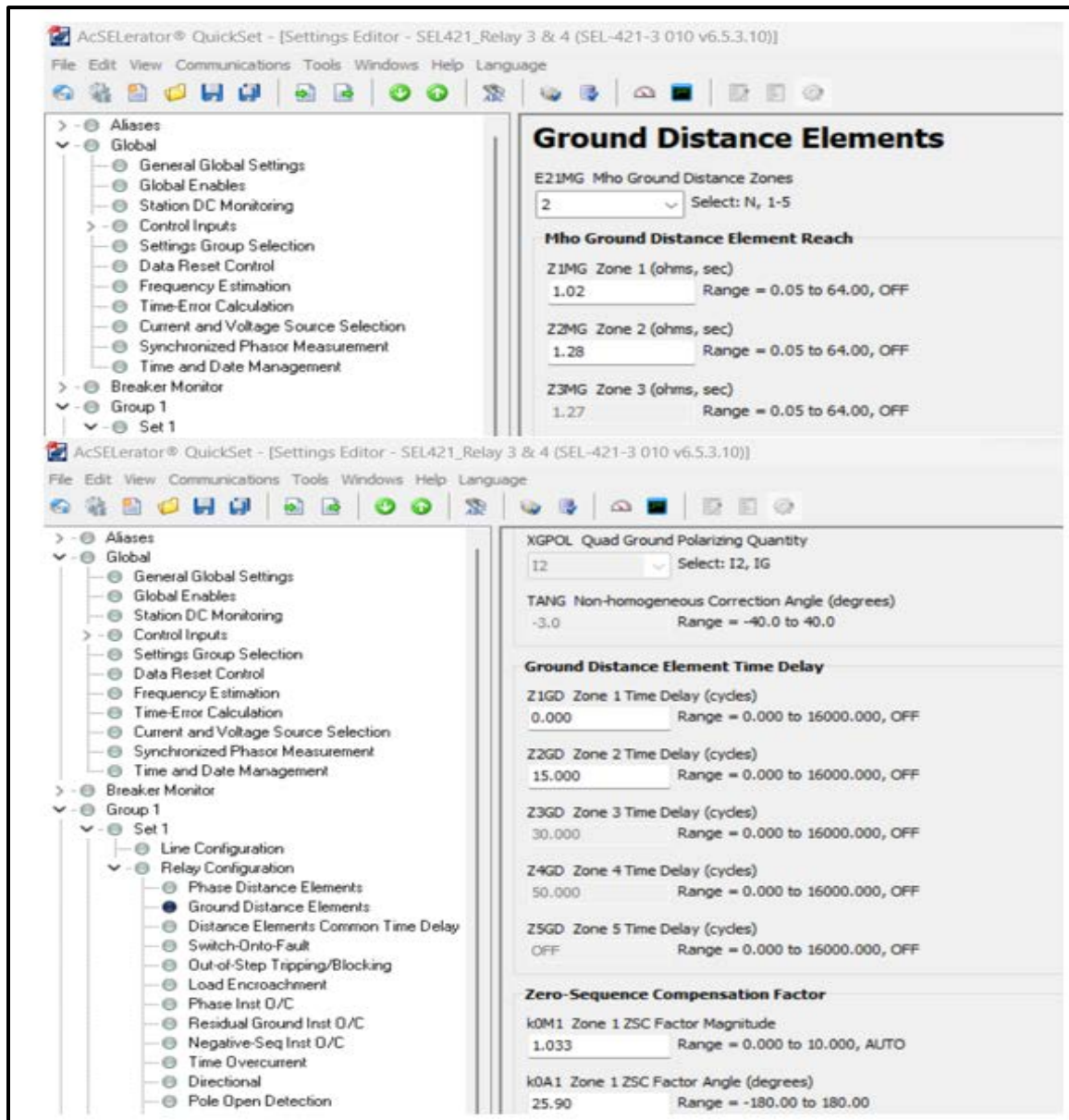
Mho Phase Distance Element Time Delay

Z1PD Zone 1 Time Delay (cycles)
1.000 Range = 0.000 to 16000.000, OFF

Z2PD Zone 2 Time Delay (cycles)
15.000 Range = 0.000 to 16000.000, OFF

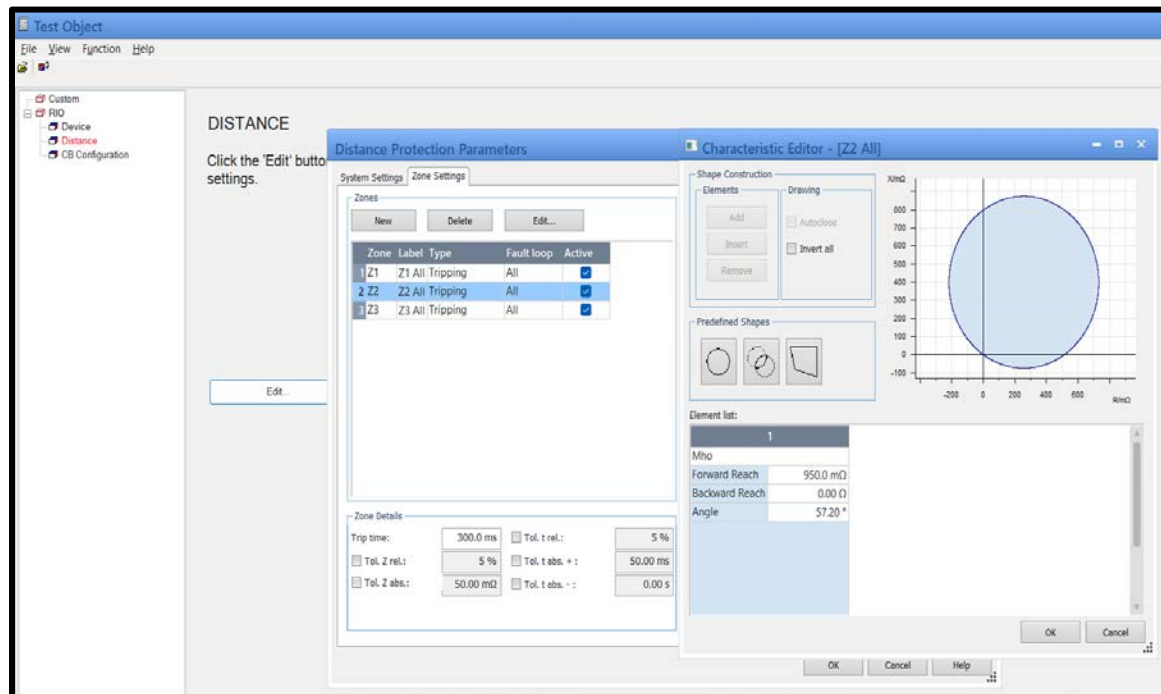
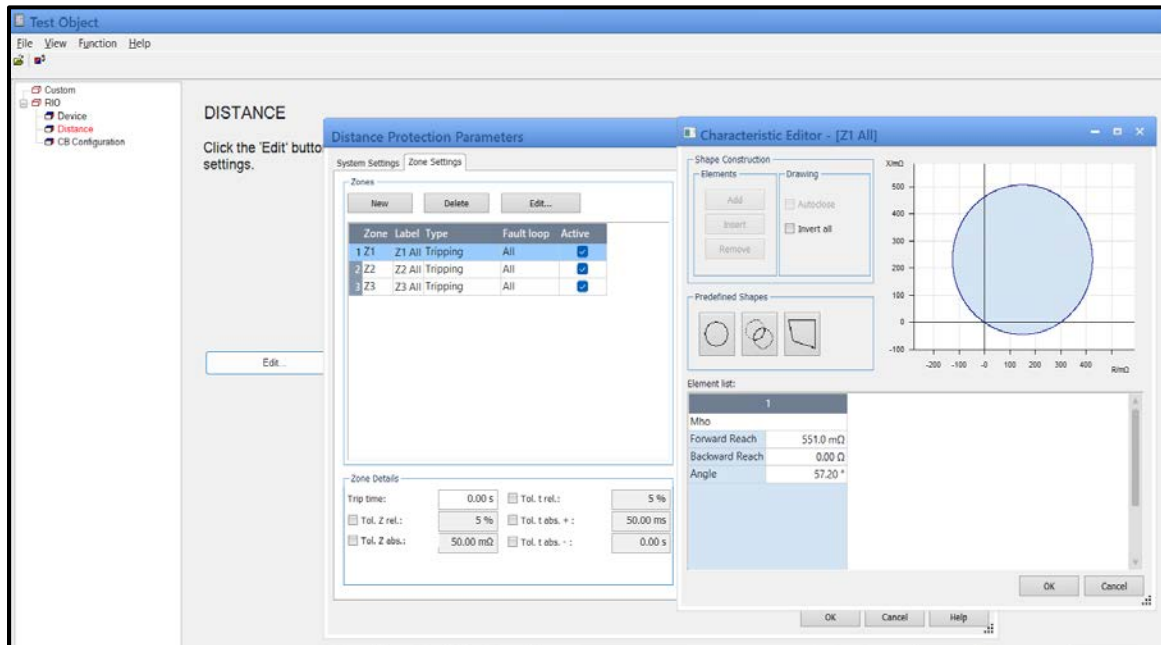
Z3PD Zone 3 Time Delay (cycles)
30.000 Range = 0.000 to 16000.000, OFF

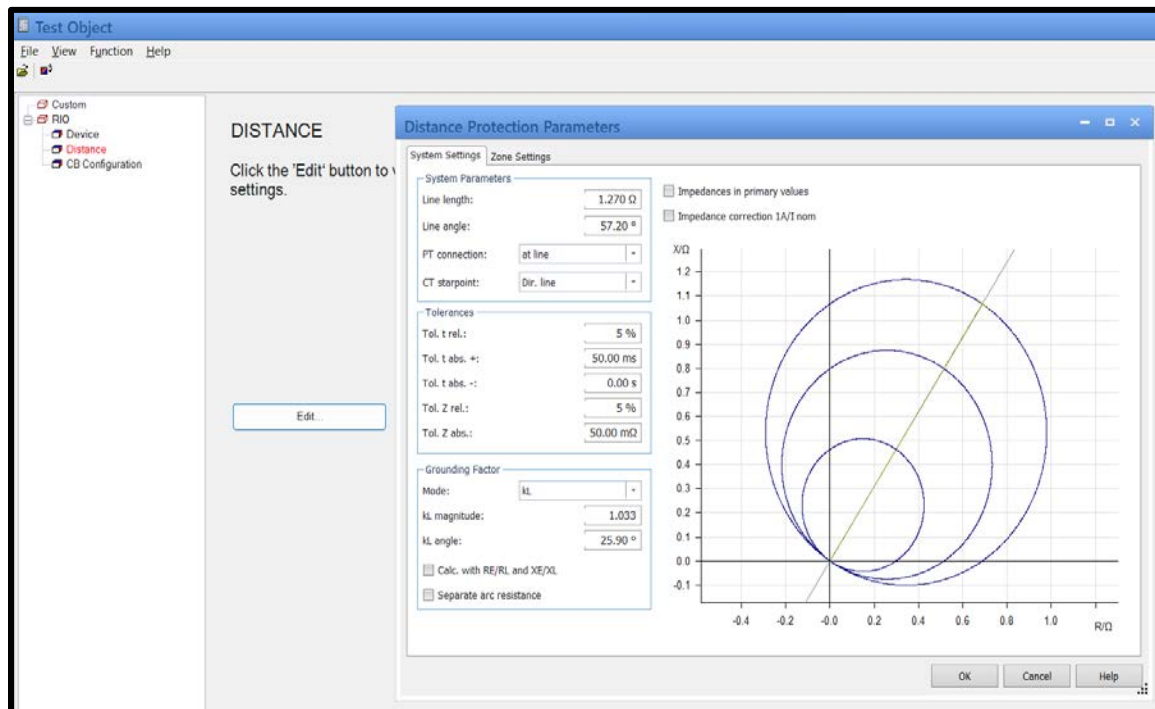
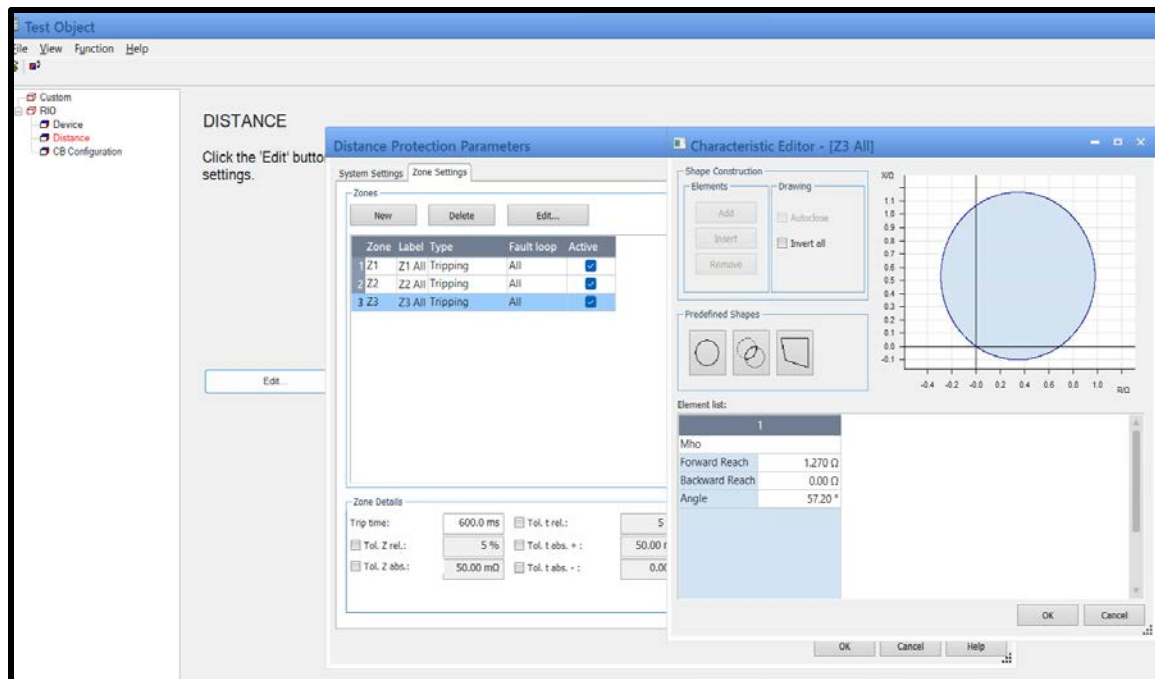
6. **Appendix B.6:** Mho Ground distance zones, impedance, and time element settings for SEL 421 relay 3&4.



APPENDIX C: TEST UNIVERSE DISTANCE RELAY ENGINEERING CONFIGURATION SETTINGS

1. Appendix C.1: Omicron CMC configuration to test protection relays





Global Hardware Configuration

Configure Device

General

Analog Outputs

Binary / Analog Inputs

Binary Outputs

DC Analog Inputs

Time Source

Test set:

CMC256plus

Scan

Test set

Voltage systems

Current systems

Configure...

Analog outputs:

1

1

Configure...

Sampled Values:

0

0

Configure...

Amplifiers / sensor simulation / low level outputs

<none>

Configure...

<none>

Configure...

<none>

Configure...

<none>

Configure...

Virtual binary inputs/outputs:

Configure...

CMC256plus Voltage Outputs

4x100V, 85VA @ 85V, 1Arms

3x300V, 85VA @ 85V, 1Arms

1x300V, 150VA @ 75V, 2Arms

3x300V, 50VA @ 75V, 660mArms, VE automatic

1x600V, 250VA @ 200V, 1.25Arms

2x600V, 125VA @ 150V, 1Arms

Connect VT...

Remove VT

CMC256plus Current Outputs

3x12.5A, 20VA @ 7.5A, 10Vrms

3x12.5A, 20VA @ 7.5A, 10Vrms

3x12.5A, 20VA @ 7.5A, 10Vrms, IE automatic

3x25A, 140VA @ 15A, 10Vrms

2x37.5A, 210VA @ 22.5A, 10Vrms

1x37.5A, 210VA @ 22.5A, 10Vrms

1x37.5A, 210VA @ 22.5A, 10Vrms

1x75A, 420VA @ 45A, 10Vrms

3x12.5A, 140VA @ 7.5A, 20Vrms

1x12.5A, 280VA @ 7.5A, 40Vrms

1x37.5A, 420VA @ 22.5A, 20Vrms

2x12.5A, 140VA @ 7.5A, 20Vrms

1x12.5A, 140VA @ 7.5A, 20Vrms

1x12.5A, 140VA @ 7.5A, 20Vrms

Connect CT...

Remove CT

Voltage Factor

n/a

Fan Mode

Automatic

Max

Compliance Voltage

Burden

Duty Cycle

high

short

low

continuous

100 %

Default

Fan Mode

Automatic

Max

OK

Cancel

Help

Global Hardware Configuration

General

Analog Outputs

Binary / Analog Inputs

Binary Outputs

DC Analog Inputs

Time Source

Display Name	Connection Terminal	CMC256plus V A				CMC256plus I A			
		1	2	3	N	1	2	3	N
V R-E		X							
V Y-E			X						
V B-E				X					
I R						X			
I Y							X		
I B								X	

Global Hardware Configuration

General

Analog Outputs

Binary / Analog Inputs

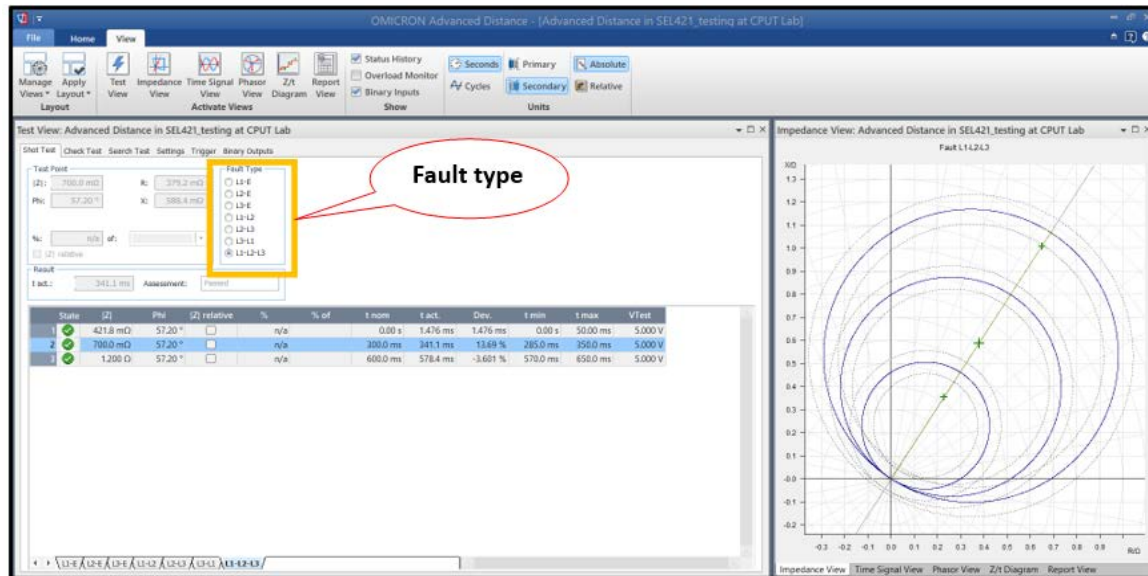
Binary Outputs

DC Analog Inputs

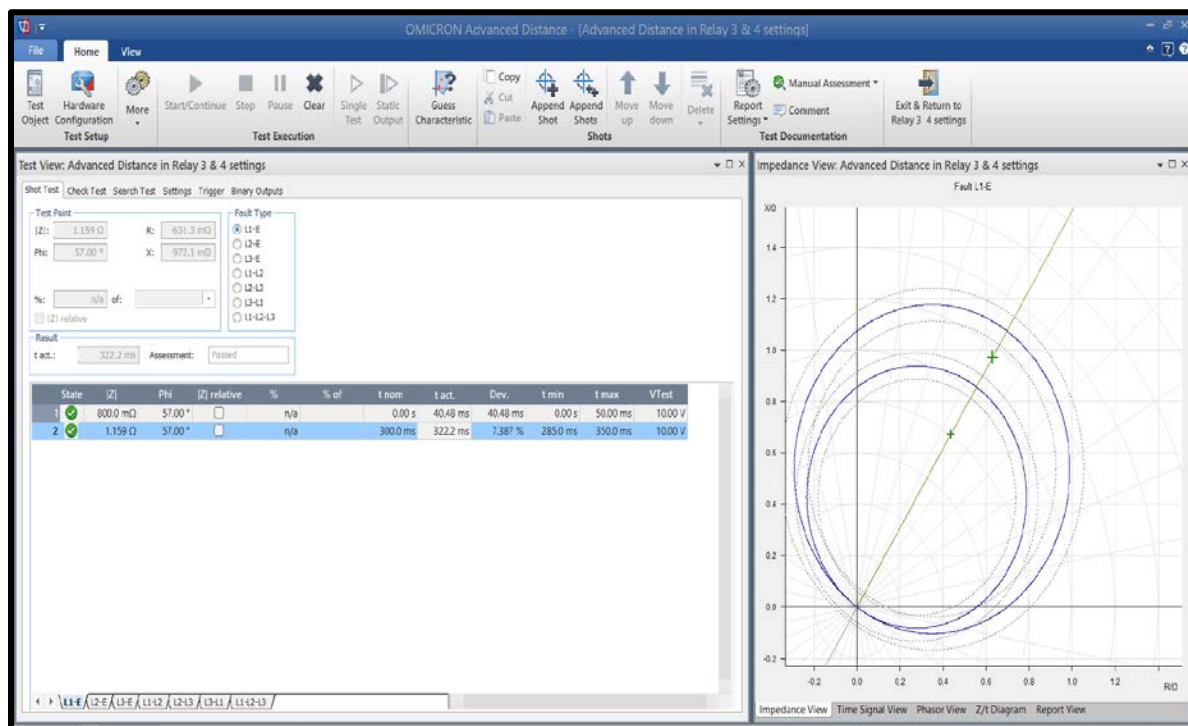
Time Source

		CMC256plus																						
Function		Binary		Binary		Binary		Binary		Binary		Binary		Binary		Binary		Binary		Binary		Counter		
Potential Free		☒		☒		☒		☒		☒		☒		☒		☒		☒		☒				
Nominal Range																								
Clamp Ratio																								
Threshold																								
Display Name	Connection Terminal	1+	1-	2+	2-	3+	3-	4+	4-	5+	5-	6+	6-	7+	7-	8+	8-	9+	9-	10+	10-	1	2	N
Trip		☒																						

2. Appendix C.2: Test univers test results for three-phase fault in line 1 and line 2

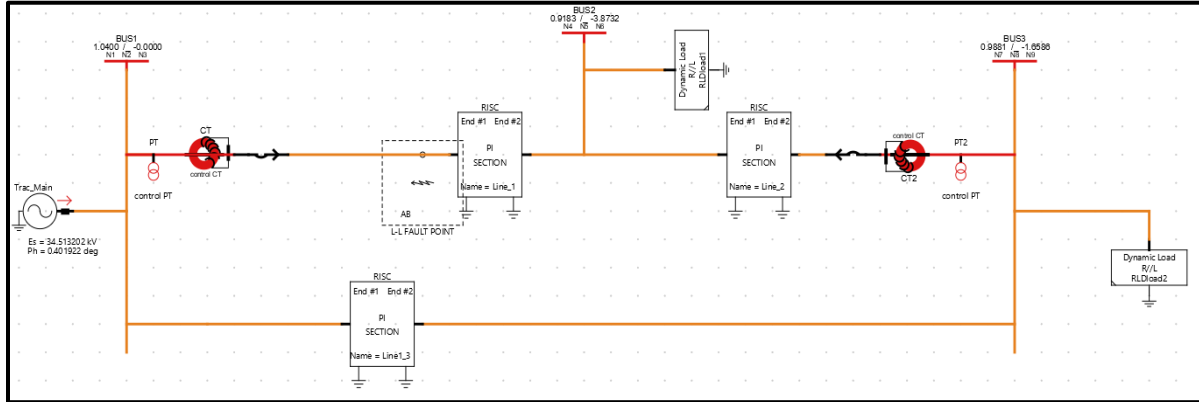


3. Appendix C.3: Test univers test results for three-phase fault in line 3



APPENDIX D: RSCAD PARSA NETWORK MODELLING AND SIMULATION RESULTS

1. Appendix D.1: RSCAD modelled network

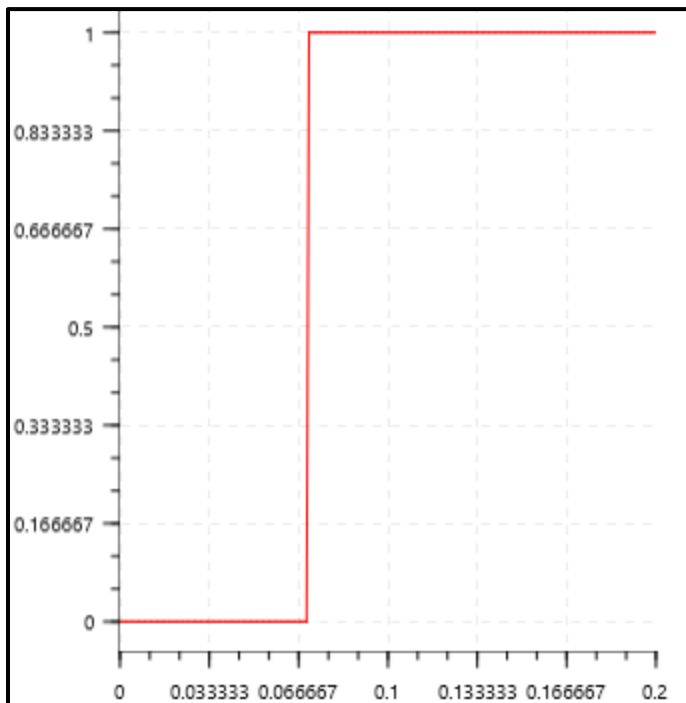


2. Appendix D.2: Circuit breaker status on the RSCAD network

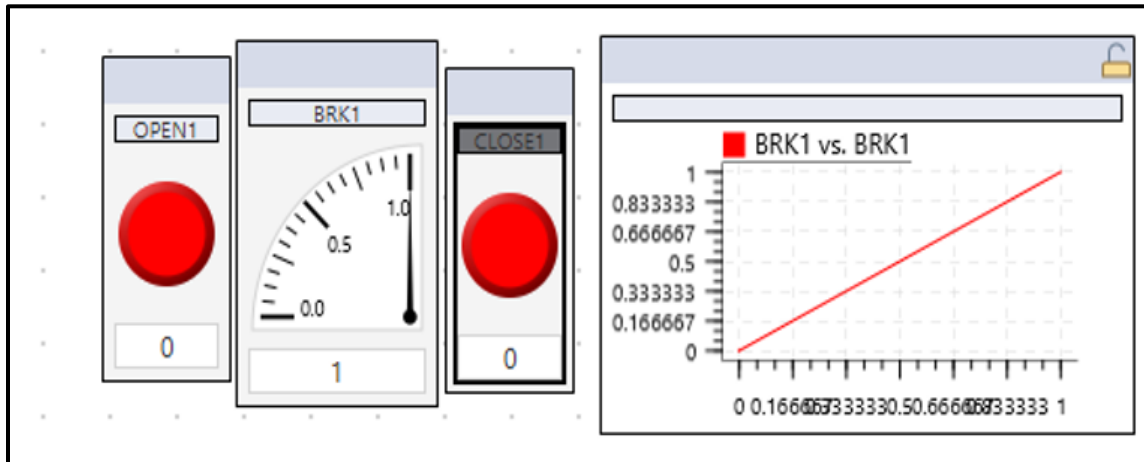
Where:

Open = 0

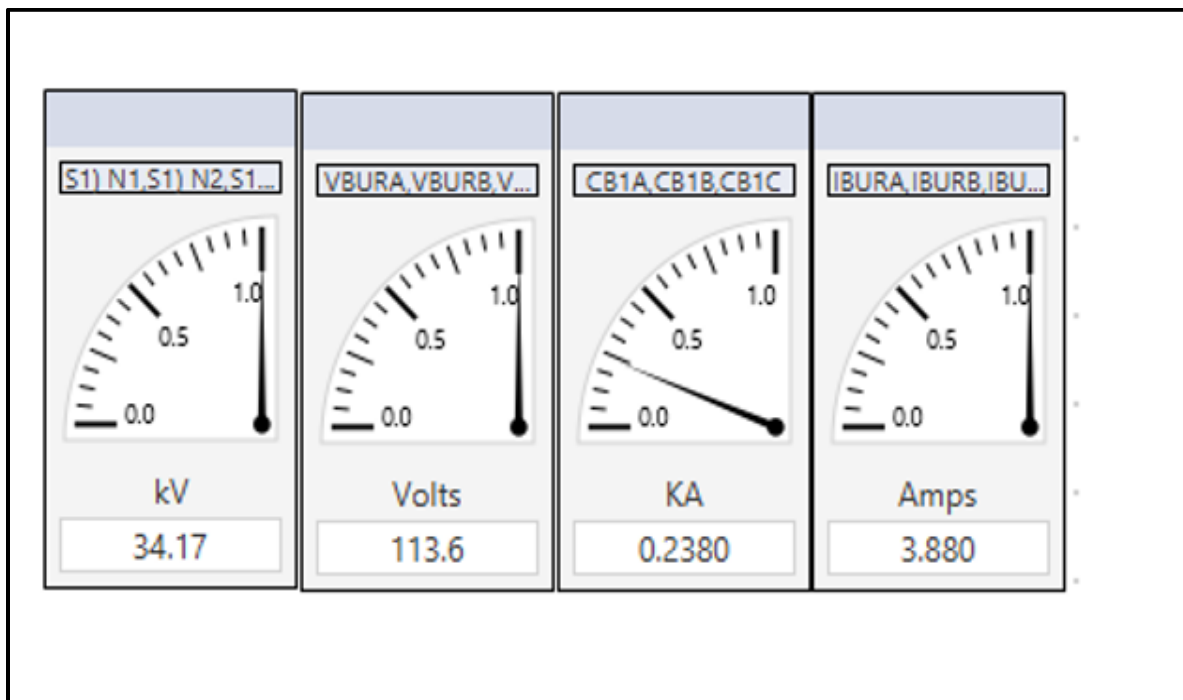
Closed = 1



3. Appendix D.3: RSCAD Breaker control pushbuttons



4. Appendix D.4: RSCAD Measured voltage (L-L), and current by CT1 and VT1



5. Appendix D.5: RSCAD Line configuration settings

Component Parameters for lf_rtds_sharc_sld_PI3

lf_rtds_sharc_sld_PI3

CONFIGURATION	Name	Description	Value	Unit	Min	Max
	f	Line frequency	50	Hz	0.01	
PROCESSOR ASSIGNMENT	Rp	+ve sequence series resistance	1.27	ohms	1.0e-10	
PARAMETERS	Xp	+ve sequence series inductive react.	2.62	ohms	1.0e-10	
MONITORING SELECTIONS	Xcp	+ve sequence shunt cap. reactance of line	0.19	Mohms	1.0e-10	
MONITORING NAMES	Rz	Zero sequence series resistance	2.9	ohms	1.0e-10	
	Xz	Zero sequence series inductive react.	12.45	ohms	1.0e-10	
AUTO-NAMING SETTINGS	Xcz	Zero sequence shunt cap. react. of line	0.37	Mohms	1.0e-10	

OK Cancel Cancel All

6. Appendix D.6: RSCAD current transformer configuration

Component Parameters for _rtds_CT

_rtds_CT

	Name	Description	Value	Unit	Min	Max
MAIN DATA	NAME	CT Unit Name	CT			
TRANSFORMER DATA	SIGA	A Phase Primary Current Signal Name	CB1A			
BURDEN	SIGB	B Phase Primary Current Signal Name	CB1B			
B1,H1 ... B10,H10	SIGC	C Phase Primary Current Signal Name	CB1C			
P-LOSS DATA	F	Frequency	50	Hz	0	
MONITORING	DE	Core characteristics data entry	B,H			
SIGNAL NAMES	csa	Cross-sectional Area	6.5e-3	m^2	0.0	100
	PLen	Path Length	0.5	m	0.0	100
PRE-PROCESSOR VARIABLE (PPV) SELECTION	FLXRS	Enable Flux Reset?	No			
PPV NAMES	ENRMN	Enable The Initial Remanence?	No			
PPV MAXIMUM VALUES	FIT	BH Curve Fitting Algorithm	Least Squire			
CONFIGURATION	ctrlGrp	Assigned Control Group	1		1	54
AUTO-NAMING SETTINGS	Pri	Priority Level	2		1	

OK Cancel Cancel All

7. Appendix D.7: RSCAD voltage transformer configuration

Component Parameters for _rtds_PT

_rtds_PT

	Name	Description	Value	Unit	Min	Max
MAIN DATA	Rp	Primary Side Resistance	11.33	Ohms	0.0	
PT INPUT SIGNAL NAMES	Lp	Primary Side Inductance	6.0	H	0.0	
TRANSFORMER DATA	Np	Primary Side Turns	33000	turns	1	
BURDEN	Rs	Secondary Side Resistance	0.55e-3	Ohms	0.0	
	Ls	Secondary Side Inductance	0.29e-3	H	0.0	
B -VS- H CURVE	Ns	Secondary Side Turns	110	turns	1	
P-LOSS DATA						
MONITORING						
SIGNAL NAME						
CONFIGURATION						
AUTO-NAMING SETTINGS						

APPENDIX E: CMD AND SEL 421 RELAY HMI COMMUNICATION

1. Appendix E.1: Communication establishment between a laptop and RTDS simulator

```
Microsoft Windows [Version 10.0.22621.2428]
(c) Microsoft Corporation. All rights reserved.

C:\Users\Luthando.Nkalitshana>ping 192.168.1.101

Pinging 192.168.1.101 with 32 bytes of data:
Reply from 192.168.1.101: bytes=32 time=1ms TTL=64
Reply from 192.168.1.101: bytes=32 time<1ms TTL=64
Reply from 192.168.1.101: bytes=32 time<1ms TTL=64
Reply from 192.168.1.101: bytes=32 time<1ms TTL=64

Ping statistics for 192.168.1.101:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
    Approximate round trip times in milli-seconds:
        Minimum = 0ms, Maximum = 1ms, Average = 0ms
```

2. Appendix E.2: Communication establishment between a laptop and the SEL 421 relay

```
C:\Users\Luthando.Nkalitshana>ping 192.168.1.155

Pinging 192.168.1.155 with 32 bytes of data:
Reply from 192.168.1.155: bytes=32 time=1ms TTL=255
Reply from 192.168.1.155: bytes=32 time=1ms TTL=255
Reply from 192.168.1.155: bytes=32 time=1ms TTL=255
Reply from 192.168.1.155: bytes=32 time=1ms TTL=255

Ping statistics for 192.168.1.155:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
    Approximate round trip times in milli-seconds:
        Minimum = 1ms, Maximum = 1ms, Average = 1ms
```

3. Appendix E.3: HMI view of an SEL 421 protection settings during conditions when there is no fault in one line.

● Device Overview

○ Phasors

○ Instantaneous

○ Synchrophasor

○ Demand/Peak

○ Maximum/Minimum

○ Energy

○ Targets

○ Status

○ SER

○ Breaker 1 Monitor

○ Breaker 2 Monitor

○ Control Window

Device Overview

Line Quantities Fundamental

I MAG	I ANG	V MAG	V ANG
A 150.28 A	A -28.22°	A 17.734 kV	A 0.00°
B 150.30 A	B -148.29°	B 17.736 kV	B -120.00°
C 150.29 A	C 91.76°	C 17.738 kV	C 120.01°

FREQ (Hz) 50.00

Control Inputs and Control Outputs

IN101	IN102	IN103	IN104	IN105	IN106	IN107
☐	☐	☐	☐	☐	☐	☐

OUT101	OUT102	OUT103	OUT104	OUT105	OUT106	OUT107	OUT108
☐	☐	☐	☐	☐	☐	☐	☐

User-Defined Targets

PSV01	PSV02	PSV03	PSV04	PSV05	PSV06	PSV07	PSV08
☐	☐	☐	☐	☐	☐	☐	☐
PSV09	PSV10	PSV11	PSV12	PSV13	PSV14	PSV15	PSV16
☐	☐	☐	☐	☐	☐	☐	☐
PSV17	PSV18	PSV19	PSV20	PSV21	PSV22	PSV23	PSV24
☐	☐	☐	☐	☐	☐	☐	☐
PSV25	PSV26	PSV27	PSV28	PSV29	PSV30	PSV31	PSV32
☐	☐	☐	☐	☐	☐	☐	☐

☒ ENABLED

☐ TRIP

☐ INST

☐ TIME

☐ COMM

☐ SOTF

☐ ZONE 1

☐ ZONE 2

☐ ZONE 3

☐ ZONE 4

TARGET RESET

☐ PHASE A

☐ PHASE B

☐ PHASE C

☐ GROUND

☐ 50

☐ 51

☐ 79 RESET

☐ 79 LOCKOUT

☐ SPT ENABLED

☐ MANUAL CLOSE ENABLED

☐ COMM SCHEME ENABLED

☐ RECLOSE ENABLED

☐ ALT SETTINGS

☐ BREAKER CLOSED

☐ RELAY TEST MODE

☐ BREAKER OPEN

APPENDIX F: REAL-TIME DIGITAL SIMULATOR (RTDS) GTAO CARD CONFIGURATIONS AND HARDWARE-IN-THE-LOOP SIMULATION SETUP IN CSAEMS LAB AT CPUT

1. **Appendix F.1:** GTAO Card of the RTDS simulator found in CPUT CSAEMS research lab.



2. **Appendix F.2:** Hardware-in-the-loop setup implemented for testing the SEL 421 distance relays.

