Cape Peninsula
University of Technology

INVESTIGATION OF 3 TERMINAL DIFFERENTIAL PROTECTION USING STANDARD-BASED NUMERICAL RELAYS

by

Mkuseli Lwana

Thesis submitted in fulfilment of the requirements for the degree

Master of Engineering: Electrical Engineering

in the Faculty of Engineering

at the Cape Peninsula University of Technology

Supervisor: Prof R Tzoneva
Co-supervisor: C Kriger

Bellville
December 2017

DECLARATION

I, Mkusel Lwana, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed		**Date**	

ABSTRACT

Transmission lines are a vital part of the electrical distribution system, as they provide the path to transfer power between generation and load. Factors like de-regulated market environment, economics, etc. have pushed utilities to operate transmission lines close to their operating limits. Any fault, if not detected and isolated quickly will cascade into a system wide disturbance causing widespread outages for a tightly interconnected system operating close to its limits. Current differential criterion is used with success to protect various elements in power systems, i.e. transmission lines, power transformers, generators and busbars. The alpha plane differential relaying system provides sensitive protection for transmission lines, security and dependability for external faults.

This thesis focuses on three terminal alpha plane differential protection with the aim to develop a complete test method using OMICRON test universe software essentially defining security, dependability and sensitivity of the alpha plane characteristic. The research analyses the three terminal alpha plane characteristic and existing primitive test methods and develops an improved test method using IEC 61850 standard. The primitive methods are time consuming and result in unnecessary prolonged outages.

These methods have been discussed and improved in the thesis by implementing IEC 61850 standard. First the standard IED Capability Description (ICD) file is modified by developing new logical nodes using AcSELerator Architect and XML Maker software. Then the developed logical nodes, three terminal differential protection alpha plane characteristic with its additional infeed/outfeed check logic, and the developed test method are tested simultaneously using Test Universe software.

A laboratory test bench is built using three SEL311L relays, two CMC 356 Omicron injection devices, PC, MOXA switch, CMIRIG-B time synchronising unit, SEL 2407 satellite synchronised clock, and a DC power supplier.

The test method developed in this research vindicates benefits of IEC 61850 standard over hard wired systems. Prolonged outage times due to test set preparation using hard wires are drastically reduced.

The thesis findings and deliverables will be used as a solution to industrial problems, postgraduate studies of other students and research project.

Keywords: Alpha plane, Power system, Transmission, IEC61850; Protection relays, IED, ICD, CID, GOOSE message, Ethernet, Configuration, OMICRON Test Universe, and laboratory test bench

ACKNOWLEDGEMENTS

DEDICATION

This this is dedicated to my family, my wife, my daughter and my son, thank you very much for the support and encouragement throughout the course, this work is for you, particularly, for your inspiration.

I thank God for giving me all the energy and knowledge to finish this thesis on such difficult times.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Terms/Acronyms/Abbreviations	Definition/Explanation
Current Transformer	A device that transforms current from one magnitude to another magnitude
Discrimination	The ability of two or more protection systems to decide which one should react to a certain fault and then take corrective action.
GOOSE	A high performance multi-cast messaging service for inter-IED communications, and is used for fast transmission of substation events.
Numerical Relay	A relay capable of acquiring instantaneous samples of voltage and/or current and process them using a mathematical algorithm
Substation Configuration description Language	Description language for communication in electrical substations related to the IEDs.
Voltage Transformer	A device that transforms voltage from one magnitude to another magnitude
Stable	A protective system/relay is deemed stable when it remains inoperative under all conditions other than those for which it is specifically designed to operate
Protected zone	The portion of a power system protected by a specific protective system or part of that protective system i.e. between defined current transformers.
Pilot wire	A wire used for the interconnecting relay points for the purpose of protection
Power System	Refers to power stations, feeders, station and apparatus whereby electrical energy is made available to the consumers points of supply

BTW	- Backward Travelling Wave
CBTW	- Compensated Backward Travelling Wave
CFTW	- Compensated Forward Travelling Wave
CID	- Configured IED Description
CT	- Current Transformer
EHV	- Extra High Voltage
FTW	- Forward Travelling Wave
GOOSE	- Generic Object Orientated Substation Event
HV	- High Voltage
ICD	- IED Capability Description
IEC	- International Electrotechnical Commission
IEDs	- Intelligent Electronic Devices
LV	- Low Voltage
SCL	- Substation Configuration Language
SONET	- synchronous optical network
SDH	- synchronous digital hierarchy
87LOPA	- Red Phase differential protection operate element
87LOPB	- White Phase differential protection operate element
87LOPC	- Blue Phase differential protection operate element
87LOPG	- Zero sequence differential protection operate element
87LOP2	- Negative sequence differential protection operate element
R87LA	- Red Phase differential protection restraint element
R87LB	- White Phase differential protection restraint element
R87LC	- Blue Phase differential protection restraint element
R87LG	- Zero sequence differential protection restraint element
R87L2	- Negative sequence differential protection restraint element

NOMENCLATURE

R_e is the real part of a complex value

I_m is the imaginary part of a complex value

I_R is the remote current

I_L is the local current

I_A is the red phase current

I_B is the white phase current

I_C is the blue phase current

I_G is the zero sequence current

I_2 is the negative sequence current

I_R is the remote current

I_L is the local current

I_{AR} is the remote red phase current

I_{BR} is the remote white phase current

I_{CR} is the remote blue phase current

CTR is the currents transformer ratio

R_x is the transmit address

T_x is the receive address

α is the alpha value as the ratio of remote to local current

α_A is the red phase alpha value

α_B is the white phase alpha value

α_C is the blue phase alpha value

Z_{app} is the apparent impedance

V_a is the terminal A voltage

I_a is the terminal A current

I_{nom} is the nominal current

$I_{channel\ x}$ is the channel X current

I_{MAG} is the current magnitude

I_{ANG} is the current angle

CHAPTER ONE

INTRODUCTION

1.1   Introduction and background

Any power system is prone to 'faults', (also called short-circuits), which occur mostly as a result of insulation failure and sometimes due to external causes. When a fault occurs, the normal functioning of the system gets disturbed. The high current resulting from a fault can stress the electrical conductors and connected equipment thermally and electro-dynamically. Arcs at the fault point can cause dangerous or even fatal burn injuries to operating and maintenance workers in the vicinity. Faults involving one phase and ground give rise to high 'touch' and 'step' voltages posing danger of electrocution to personnel working nearby. It is therefore necessary to detect and clear any fault quickly. The first device used in early electrical systems was the fuse, which acted both as the sensor and the interrupting device. With larger systems, separate devices became necessary to sense and interrupt fault currents. In the beginning these functions were combined in a single assembly; a circuit breaker with in-built releases. This practice is still prevalent in low voltage (LV) systems. In both high voltage (HV) systems and low voltage systems of higher capacities, the sensing is done by more sophisticated devices called relays. Relays were initially electromechanical devices but static relays and more recently digital relays have become the norm. One of the requirements is to minimize the time for which a fault remains in the circuit; this is necessary to reduce equipment damage and the danger to operating personnel. With more complex systems, it is necessary to detect the point of fault precisely and trip only those sections affected by the fault while the rest of the system can continue to function normally. These requirements necessitate different forms of relaying apart from the simple current sensing relays. Equipment such as generators, transformers, motors and overhead lines also need special forms of protection characterized by their design and operating principles.

As a unit protection having its zone delimited by location of current transformers (CTs), the differential protection principle is considered superior with respect to selectivity, sensitivity, and speed of operation as compared with directional comparison, phase comparison, or stepped distance schemes.
The differential function responds to the sum of all the currents of its zone of protection. Ideally, this sum equals zero under all events except for internal faults. Practically, measurement errors and shunt elements inside the zone may create a spurious differential signal, calling for adequate countermeasures. These countermeasures became more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay,

percentage restraint, and harmonic restraint and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques.

As applied to line protection, the differential principle faced the limitations of line length. Analogue schemes using pilot wires can only be applied to very short lines because of signal attenuation due to series resistance and the shunt capacitance of the pilot. These applications are still beneficial because the very short lines cannot be adequately protected with distance relays.

The development of microprocessor-based line current differential schemes utilizing digital communications channels redefined the field of line protection.

When suitable long-haul digital communications channels became more readily available because of the deployment of digital microwave and direct fibre-optic connections as well as synchronous optical network (SONET) or synchronous digital hierarchy (SDH) systems, applications of line current differential schemes kept expanding.

The key benefits of differential protection as applied to power lines include good performance on multi-terminal and series-compensated lines and lines of any length as compared with distance or directional comparison schemes.

This chapter provides brief description of faults in the power system as well as danger to personnel and equipment as a result of faults. Primitive, conventional and modern sophisticated methods to detect such faults to limit the damages due to faults are also discussed. This chapter also covers the 1.2 Awareness of the problem, 1.3 Statement of the problem, 1.4 Research aims and objectives, 1.5 Hypothesis, 1.6 Delimitation of research, 1.7 Motivation for the research project, 1.8 Assumptions, 1.9 Research design and methodology and 1.10 Thesis Chapters.

1.2 Awareness of the problem

Transmission lines are a vital part of the electrical distribution system, as they provide the path to transfer power between generation and load. Transmission lines operate at voltage levels from 69kV to 765kV, and are ideally tightly interconnected for reliable operation.

Factors like de-regulated market environment, economics, etc. have pushed utilities to operate transmission lines close to their operating limits.

Any fault, if not detected and isolated quickly will cascade into a system wide disturbance causing widespread outages for a tightly interconnected system operating close to its limits.

Transmission lines protection systems are designed to identify the location of faults and isolate only the faulted section. The key challenge to the transmission line protection lies in reliably detecting and isolating faults compromising the security of the system.

The high level factors influencing line protection include the criticality of the line (in terms of load transfer and system stability), fault clearing time requirements for system stability, line length, the system feeding the line, the configuration of the line (the number of terminals, the physical construction of the line, the presence of parallel lines), the line loading, the types of communications available, and failure modes of various protection equipment.

The more detailed factors for transmission line protection directly address dependability and security for a specific application.

Current differential criterion is used with success to protect various elements in power systems, i.e. power transformers, generators, busbars and transmission lines. The basic operating principle of this criterion is to compare currents flowing into the object with the currents flowing out of the object at the other end.

Countermeasures of measuring differential current became more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay, percentage restraint, and harmonic restraint and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques.

The alpha plane differential relaying system provides sensitive protection for transmission lines, security and dependability for external faults. The relaying system is tolerant of unequal communication channel delays.

Test procedures have been developed for testing alpha plane characteristic on two terminal differential applications only. 3 terminal differential application needs to be developed, thus testing between two terminals at a time i.e. terminals A-B; B-C and A-C has been the test method for 3 terminal application. This poses a need for research on Intelligent Electronic Devices (IED) algorithm and or test methods which is mainly the subject of this thesis or considered in this thesis.

1.3 Statement of the problem:

Protective relays are important parts of the power system. The protection guards valuable equipment, and protective relays play a vital role in performing the task. The relay detects fault conditions within an assigned area and opens or closes output contacts to cause the operation of other devices under its control. The relay acts to operate the appropriate circuit breakers to prevent damage to personnel and property. To ensure consistent reliability and proper operation, protective relay equipment must be evaluated and tested.

The importance of the relay evaluation issue is linked to capability to test the relays and relaying systems using very accurate waveform representation of a fault event. The purpose of testing protective relays is to ensure correct operation of the relay for all possible power system conditions and disturbances. To fulfil this purpose, relay testing in varying network configurations and with different fault types is required.

Test methods have been developed for alpha plane characteristic on 2 terminal differential applications. Recent presentation on testing the Alpha Plane Characteristic for two terminal differential protection at OMICRON User Conference 2010 clearly outlined a need for research on three terminal differential application.

Problem Statement: To develop a complete test method for three terminal differential alpha plane characteristic using OMICRON test universe software on evaluation and analysis of methods and algorithms of existing IEDs implementing alpha plane characteristic or algorithm.

1.3.1 Sub Problems

Operating characteristics of protective relays are important because protective relays respond and operate according to defined operating characteristic and applied settings. Each type of protective relays has distinctive operating characteristic to achieve implementation objective: sensitivity, selectivity, reliability and adequate speed of operation in protecting elements of the power system. Relays are available in many implementations, serving different purposes and having distinctive design characteristics. Evaluation and analysis of the existing test methods developed for 2 terminal differential alpha plane characteristic is performed.

1.4 Research Aim and Objectives

1.4.1 Aim:

On evaluation and analysis of the methods and algorithms of existing IEDs implementing alpha plane characteristic, the aim is to develop a complete test method for three terminal differential alpha plane characteristic using OMICRON test

universe software essentially defining security, dependability and sensitivity of the alpha plane characteristic. This is achieved by simulating and analysing the behaviour of three terminal differential protection implemented into alpha plane characteristic using OMICRON test universe software.

1.4.2 Objectives:

The amount of tolerance a unit-type protection system has for current transformer saturation, channels delay asymmetry, and current outfeeds depends largely on the operating characteristic. The unit protection scheme performance is often limited by these tolerances. These limitations are reduced by alpha plane differential characteristic, posing a need for evaluation, examination and development of proper test procedures for the characteristic.

- Conduct literature review on methods and algorithms of existing IEDs implementing alpha plane characteristic for 3 terminal differential protection.
- Evaluate three terminal differential protection algorithm of IEDs implementing alpha plane characteristic.
- Conduct literature review on OMICRON test universe software looking at modules available to test complete alpha plane region for three terminal differential protection.
- Evaluate capabilities of the OMICRON test universe software for simulation of 3 terminal networks, simulating internal and external faults throughout the restraint and operate region of alpha plane characteristic.
- Analyse simulation results from the OMICRON test universe software.
- Evaluate test procedures used on testing alpha plane characteristic for 2 terminal differential protection relays.
- Develop a complete test method for alpha plane characteristic on three terminal differential applications using OMICRON test universe software.
- Develop test bed for implementation of the developed method
- Performing testing of the IEDs based on various case studies
- Analysis of the test results and recommendations

1.5 Hypothesis

Test methods for 2 terminal differential alpha plane characteristic have been developed. 3 terminal differential application need to be developed, thus testing between two terminals at a time i.e. terminals A-B; B-C and A-C has been the test method for 3 terminal application. Review of 3 terminal alpha plane differential characteristic show possible test methods for such application.

1.6 Delimitation of research

The current differential principle is considered to be suited to protect three-terminal lines and it does not need to contend with problems associated with voltage, loading, and swings. The research project concentrates on alpha plane differential characteristic.

First, differential characteristics implemented in the current-ratio plane and their relation to the conventional percentage differential principle are reviewed. Then, evaluation and analysis of alpha plane differential characteristic and test methods on two terminal applications are carried out. Since alpha plane differential characteristic is unique to Schweitzer Engineering Laboratories (SEL), the Schweitzer Engineering Laboratories series of IED's are used in this regard. Next, alpha plane differential characteristic and relay algorithm on three terminal applications are tested and evaluated. Finally, complete test methods for alpha plane differential characteristic on three terminal applications are developed.

To achieve these aims and objectives, the following steps are carried out:

Literature review and analysis are carried out on alpha plane for three terminal applications.

Interviews and information acquisition from specialists and engineers directly involved in development of α- plane characteristic are done.

Analogue values required to test α- plane characteristic to its extents are calculated. Evaluation of test procedure used on testing alpha plane characteristic for 2 terminal differential applications is carried out.

Then complete test methods for alpha plane characteristic on three terminal differential applications are developed using OMICRON test universe software.

1.7 Motivation for the research project

Modern power transmission and distribution systems need high-performance protection devices. Relays must have high speed of operation for internal system fault conditions and high level of discrimination between internal and external power system faults. Relays, together with the circuit breakers, shall disconnect faulty parts of the power system. Their main role is to protect the primary equipment against unnecessary damages, save people in vicinity of the electrical plant from injuries, and enable continued service in the undamaged parts of the network. To accomplish its main tasks, requirements on protection system are: speed, sensitivity, selectivity and reliability. Evaluation and testing protective devices must be conducted to check and predict how capable the relays are to fulfil the main requirements for system protection.

Multi-terminal lines are more often used in modern power systems than before. They are becoming particularly popular in sub-transmission networks. Multi-terminal line protection has evolved, over the years, from relatively primitive devices with limited capability, to complex systems that involve extensive use of modern hardware components and software solutions. These modern protective systems are more sensitive and selective in their detection and operation. They require greater analytical effort in the analysis and application as well as advanced methods for evaluation and testing.

1.8 Assumptions

It is assumed that OMICRON test universe software is the suitable tool to simulate three terminal network and evaluation of three terminal alpha plane differential characteristic as well as to develop test methods for three terminal alpha plane differential characteristic.

1.9 Research design and Methodology

To achieve the aims and objectives the scope of work in this thesis and the plan implemented is depicted in the form of comprehensive flow chart as shown on Figure 1.1 and in point form as follows;

- Literature Review through IEEE Journals was conducted, as well as related books and other information sources
- Interviews were conducted and information acquisition from specialists and engineers directly involved in development of α- plane characteristic as well as IEC 61850 standard
- New logical nodes required to test the α- plane were developed
- Analogue values required to test α- plane characteristic extents were calculated
- Obtained analogues values were injected to the IEDs
- Once 3 terminal α- plane characteristic was functioning as required, the new test method was developed using new logical nodes
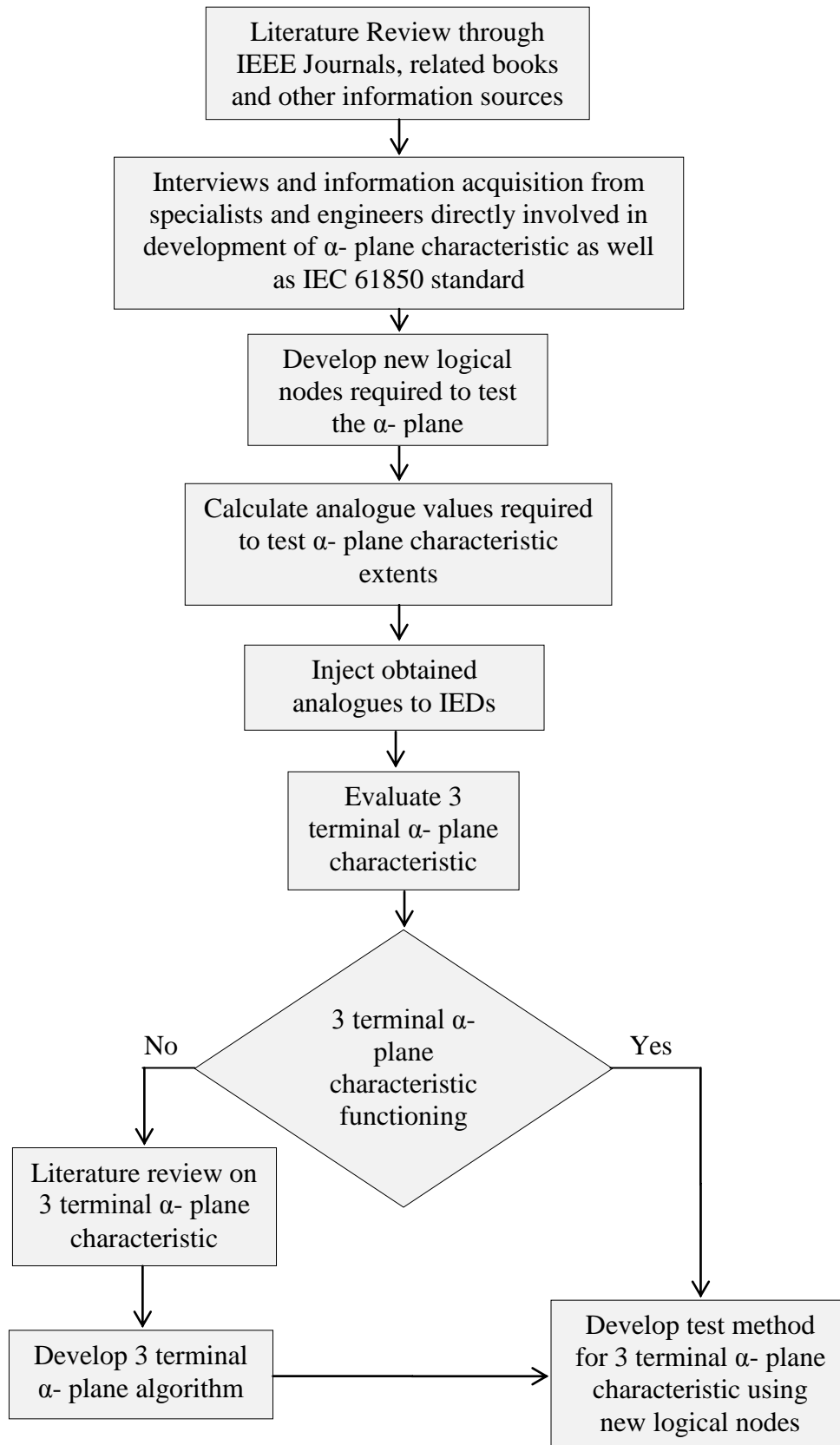
Figure 1.1: Research design and Methodology flow chart

1.10 Thesis Chapters

This Thesis or research document is divided into the seven chapters followed by the appendix as follows;

1.10.1 Chapter 1

This chapter provides brief description of faults in the power system as well as danger to personnel and equipment as a result of faults. Primitive, conventional and modern sophisticated methods to detect such faults to limit the damages due to faults are also discussed. This chapter also covers the awareness of the problem, statement of the problem, research aims and objectives, hypothesis, delimitation of research, motivation for the research project, assumptions and research design and methodology.

1.10.2 Chapter 2

This chapter covers literature review on multi-terminal line protection particularly unit protection with more emphasis on differential protection. A number of papers on unit protection are discussed, compared and analysed.

1.10.3 Chapter 3

Theoretical aspects of multi terminal line protection are discussed in this chapter three particularly the effects of infeed and outfeed.

1.10.4 Chapter 4

This chapter provides a brief description of applicable parts of IEC-61850 standard in developing new logical nodes. Step by step process engineering in developing new logical nodes is also discussed which is important aspect in evaluation of existing test methods for 3 terminal differential protection and development of new test method.

1.10.5 Chapter 5

This chapter discusses relay parameter settings applied to all 3 relays in this research. Settings adjustments when using relays with different nominal currents for two terminal line protection is discussed. Different communication channel settings applicable to 3 terminal line protection as well as Ethernet interface settings for test purposes using IEC6180 are also discussed.

1.10.6 Chapter 6

This chapter first describes the alpha plane algorithm applicable to 2 terminal line protection as well new discovery of additional check logic when applied on 3 terminal lines. This chapter also demonstrates test simultaneous results of the newly developed logical nodes and new test method for 3 terminal line protection.

1.10.7 Chapter 7

This chapter summarises and discusses the results and key findings of the research as well as recommendation of possible future work in line with this project.

1.10.8 Appendix

Appendix A details application description of the protection software tools. The software tool packages used for the IED configuration and development of new logical nodes for the project are described. These software tools can be used on products or relays from different vendors.

1.11 Conclusion

Different faults in the power system as well as danger to personnel and equipment as a result of faults are described. Primitive, conventional and modern sophisticated methods to detect such faults to limit the damages due to faults are also discussed. Research layout and methodology is also explained.

The next chapter discusses literature review on multi-terminal line unit protection.

CHAPTER TWO

LITERATURE REVIEW

2.1   Introduction

Literature review on multi-terminal line protection is presented in this chapter. Various forms of multi-terminal line protection are presented in 2.2 but emphasise is on differential protection in 2.5 for the purpose of this research as it is considered superior with respect to selectivity, sensitivity, stability and speed of operation as compared with other forms of protection. Short description of the project and required knowledge to achieve the objective is discussed in 2.2.

A wide range of papers on multi-terminal transmission line protection have been reviewed and analysed. Main papers in line with the research project are analysed and general remarks are given in the interest of this research and conclusion thereof.

2.2   Literature review on multi-terminal transmission line protection

The protection of multi-terminal transmission lines is a challenging task due to possible infeed or outfeed currents contributed from the taped lines. The key challenge with multi-terminal transmission line protection lies in reliably detecting and isolating faults compromising the security of the system. The project is focused on investigation of 3 terminal differential protection of transmission lines using standard-based numerical relays. This requires expert knowledge of power system and related primary and secondary plant, protection systems testing methods and procedures, protection software protocols applicable to High Voltage and Medium Voltage protection relays (IEC 61850, etc).

Different methods of multi-terminal line protection are explored. The graded overcurrent system though attractively simple in principle, does not meet all the protection requirements of a power system. Application difficulties are encountered for two reasons; firstly satisfactory grading cannot always be arranged for a complex network, and secondly the settings may lead to maximum tripping times at some points in the system that are too long to prevent excessive disturbances occurring (NPAG, 2002).

These problems led to the concept of 'Unit Protection', whereby sections of the power system are protected individually as a complete unit without reference to other sections. One form of 'Unit Protection' is 'Differential Protection', as the principle is to sense the difference in currents between the incoming and outgoing terminals of the unit being protected. Other forms can be based on directional comparison, Impedance/distance teleprotection schemes, and phase comparison (NPAG, 2002).

2.3 Phase and Directional Comparison Protection

With phase comparison principle, the carrier channel transfers a logic or 'on/off' signal that switches at the zero crossing points of the power frequency waveform. Comparison of a local logic signal with the corresponding signal from the remote end provides the basis for the measurement of phase shift between power system currents at the remote ends and hence discrimination between internal and external faults. Phase comparison schemes respond to any phase shift from the reference conditions, but tripping is usually permitted only when the phase shift exceeds an angle of typically 30 to 90 degrees, determined by the time delay setting of the measurement circuit, and this angle is usually referred to as the 'Stability Angle' (NPAG, 2002).

One of the schemes implemented into this principle is presented by Bostwick and Harder, (1943). Each of the many taps is tripped by power reversal to the line. The system is being so arranged that this can occur only during a fault on the supply line. This requires that all lines feeding a given network emanate from the same bus so that for normal load conditions the supply-line voltages are nearly equal and little or no reverse power flows through any transformer bank. Many modifications of this basic scheme have been used in which some power reversal can take place when tripping is not required (Bostwick and Harder, 1943). Usually such systems are arranged for only one or two sources of ground current, the taps being tripped by residual voltage. On long taps with overcurrent protection considerable improvement in selectivity can be secured through the use of angle discrimination. On such lines fault current occurs at a phase angle which could not occur for large load currents or swings (Bostwick and Harder, 1943).

2.4 Impedance/Distance Protection

Distance protection is the method of measuring the impedance of the protected object in order to determine the presence and location of the fault. One of the disadvantages of conventional time-stepped distance protection is that the instantaneous Zone 1 protection at each end of the protected line cannot be set to cover the whole of the feeder length and is usually set to about 80% (NPAG, 2002). This leaves 'end zones' each being about 20% of the protected feeder length. Faults in these zones are cleared in Zone 1 time by the protection at one end of the feeder and in Zone 2 time (typically 0.25 to 0.4 seconds) by the protection at the other end of the feeder. Communication channels are used to solve this problem. The purpose of the communication channel is to transmit information about the system conditions from one end of the protected line to the other, including requests to initiate or prevent tripping of the remote circuit breaker. The former arrangement is generally known as

'transfer tripping scheme' while the latter is generally known as 'blocking scheme'. One of the schemes implementing into this principle is presented by Abdelaziz et al, (2011). This proposed scheme is an extension of the distance scheme with the security of using the local distance relay's Zone 2, where Zone 1 of the relay covers 80% of the protected line, while Zone 2 is equal to 120% of the line (Abdelaziz et al, 2011). This scheme is presented on 3-terminal line with no parallel lines.

Another scheme implemented in this principle is presented by Redfern et al, (2005). Several schemes can be considered, but the one offering the most effective solution is based on distance relaying and an ON/OFF keyed carrier communications system. This Enhanced Blocking Scheme offers the advantages of offering 'instantaneous' protection for faults anywhere on the protected line together with 'instantaneous' carrier independent protection for faults on the spur and part of the line close to the tap point. An acknowledged limitation of the scheme is its ability to accommodate circuits in parallel with the line circuit (Redfern et al, 2005).

2.5 Differential Protection

As a unit protection having its zone delimited by location of current transformers, the differential protection principle is considered superior with respect to selectivity, sensitivity and speed of operation as compared with directional comparison, phase comparison, or stepped distance schemes. Conventional differential function responds to the sum of all the currents of its zone of protection. Ideally, this sum equals zero under all events except for internal faults. Practically, measurements errors and shunt elements inside the zone may create a spurious differential signal, calling for adequate countermeasures. These counter measures became more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay, percentage restraint, harmonic restraints to sophisticated fault detection algorithms and adaptive restraining techniques.

2.5.1 Percentage Restraint Differential Protection

Percentage restraint differential protection works on Kirchoff's current law, stating that the currents flowing into a node of the power system must sum to zero. To improve the selectivity and security of this basic scheme, percentage of operate to restraint current was introduced. Operating current is typically the vector sum of all terminal currents of the protected object. This operating current must be greater than some percentage of the restraint quantity which is typically derived from the magnitude of all terminal currents of the protected object. Percentage differential protection scheme

is one of the oldest protection schemes. One of the schemes implementing into this principle is present by Aggarwal and John, (1986) on three terminal application.

The basic relay operating principle hinges upon deriving a differential quantity and a Bias quantity using the instantaneous values of the modal currents at the three terminals. In its simplest form, the relay would operate for faults when the magnitude of the differential quantity exceeds the Bias by a certain pre-defined threshold value. Other important findings in relation to the relay described are: (a) the differential relay is immune to the so called 'feed –around' problem. (b) the relay performance is satisfactory in double-circuit line applications (Aggarwal and John, 1986).

Al-Fakhri and Elagtal, (2001) describe a differential relay showing the possibility of using the vector difference as a restraint quantity, while keeping the vector sum as a differential quantity. The vector difference is between the largest incremental current and the vector sum of the incremental currents of the other terminals. This is as compared with the existing algorithms that used scalar sum of current terminals as a restraining quantity, which is somewhat arbitrary. This is as well as reducing the need to provide some form of synchronization to the relays at either end of the line, or to provide additional restraint when Current Transformer saturation occurred during external fault since the algorithm considers these conditions inherently as an external fault.

Current differential protection based on transmission line equation is described by Sachdev et al, (1993), as follows. The currents at each terminal of the line are used to calculate the currents expected during normal operating conditions at the tee junction. The information concerning the current phasors at the tee junction, as calculated from the data acquired at the three terminals, is exchanged between the relays at the line terminals. Current differential principle is then used to decide if there is a fault in the protected zone. The algorithm also provides, without using extra hardware and software, a practical method for data synchronization that is not affected by the length of the transmission line. Double circuit lines can be treated as transposed six phase lines or two parallel three phase lines which are fully transposed.

Gao et al, (2006) describes other method of current differential protection scheme for Teed transmission lines using superimposed components. When a fault occurs, the corresponding superimposed networks can be represented using superposition theory. The applied equations indicate that the phase angles of the three superimposed terminal currents are nearly the same for an internal fault, because the

14

system impedances and line impedance have similar phase angles on an Extra High Voltage network. A unique differential criterion is then used to make trip decision. The theoretical analysis and simulation results confirmed that the scheme has significant advantage over traditional differential schemes. Firstly, it has inherent immunity to the effect of load condition on differential protection, which builds a base to be able to detect high resistance faults. Secondly, the unique design for the criteria assures the maximum sensitivity for internal faults, for the unusual internal fault with out-feeder at one of the three terminals.

Yang et al, (2003) present a differential protection based on sampled values. In comparison with the phasor method, the sampled value differential protection uses instantaneous sampling values to calculate the differential and through currents, and checks whether samples meet operating criterion or not. So the differential and through currents are time-varying even during the steady state. Consequently the restraint effectiveness of some samples is strong while the restraint effectiveness of others is weak. To avoid the sample with the weak restraint effectiveness during external fault and enable protection to operate reliably during internal faults, measures have been taken that the protection send tripping command in case that there are certain amount of samples (S) satisfying percentage restraint criteria during continuous number of sample's judgement (R) (Yang et al, 2003).

2.5.2 Other forms of Differential Protection

Apart from percentage restraint current differential protection, Ha et al, (2008) present a novel transient differential protection based on distributed parameters for Extra High Voltage (EHV) transmission lines, which the fault transients and the distributed capacitive current are all taken into account completely. Firstly, two quantities are defined as the compensated forward travelling wave (CFTW) and the compensated backward travelling wave (CBTW) that are calculated with the data of voltage and current of the other terminal based on the distributed parameter line model, under the assumption that the whole line is healthy. Based on the fault analysis, for the external faults, the forward traveling wave (FTW) equals CFTW at the receiving end terminal, and the backward traveling wave (BTW) equal the CBTW at the sending end terminal. However, for internal faults, the difference between FTW and CFTW at the receiving end should be the product of the surge impedance and fault current, at the same time, the difference between BTW and CBTW at the sending end should be the product of the surge impedance and fault current. This criterion defines the restraint voltage operating quantity (Ha et al, 2008).

Dambhare et al, 2009 present a methodology for adaptive control of the restraining region in a current differential plane. In this methodology, the positive sequence representation of an uncompensated transmission line is considered. The line can be represented by an equivalent π–model. The equivalent π circuit models the effect of distributed line parameter at the line terminals at the fundamental frequency. Then, current in the series branch of the π-equivalent line model at one node can be computed as the difference between the positive sequence component of line current measured at one bus and the current in shunt path at this bus. If there is no internal fault on the line, then the differential current which is the sum of the currents in the series branches of the π-equivalent line model is equal to zero. The restraint current is calculated as the difference of these currents. However, it has been shown that numerical differential relay can be set more accurately in a current differential plane. Using the phase and magnitude information of series branch currents, the ratio of the remote end currents is calculated in the absence of an internal fault equal to 1 and angle 180°. However, even in the absence of an internal fault, in real life the operating point may deviate from (1, 180°) due some reasons like synchronization error, delay equalizer error, etc. Further, explicit modelling of the shunt capacitance of the line reduces the modelling errors. Therefore, the width of the restraint region in the current differential plane can be reduced to corresponding value in conventional relay setting approach approximately 0.43 (Dambhare et al, 2009).

2.5.3 Alpha-Plane Differential Protection

The Alpha-Plane is a complex ratio of two currents. In the case of two-terminal current differential protection, it is the complex ratio of remote to local currents (I_R/I_L). The ratio has real and imaginary parts, or in polar coordinates consists of a magnitude or radius r and an angle. There is a separate Alpha-Plane for every possible current (phase, sequence, etc.). Distance and directional element characteristics are often depicted on either the complex admittance or impedance plane. Warrington, (1969) introduces a complex plane called Alpha Plane (α-plane) that depicts the complex ratio I_R/I_L of the remote I_R to the local current I_L neglecting line-charging current, for through load conditions the magnitude of I_L and I_R are equal, and their phases are 180° out of phase. Therefore I_R/I_L =1 at angle 180° (Altuve et al 2004). For internal faults, the angles of the phase currents I_L and I_R depend on the angles of the corresponding source voltages and on the angles of the impedances from the corresponding source to the fault point. In general, the currents at both line ends are not exactly in phase for an internal fault. Altuve et al, (2004) define α-plane characteristic and its advantages over traditional percentage slope characteristic and

conclude that among other advantages; (a) percentage differential relays schemes using a slope setting cannot achieve the same sensitivity and security as the new α-plane relay element when the cumulative errors of CT saturation and channel asymmetry are considered , and (b) the slope setting of a traditional percentage differential element defines its restrain region security, dependability and sensitivity. It is difficult to increase one without decreasing another.

Miller et al, (2010) outline general design directions for a next generation line current differential protection scheme. A reliable α-plane restraining technique is presented for multi-terminal applications with any number of local current inputs to the relays. The size and structure of the communication payload are independent from the number of terminals or the number of local currents in the system, making the implementation simple and thus the solution more robust. The presented solution applies the α-plane differential trip equation, carrying forward all tried-and-true advantages of this approach, but enhances the original concept to multi-terminal applications and allows for harmonic restraining of the α-plane to facilitate in-line transformer protection.

2.5.4 Literature review of existing papers on unit protection

Literature review has been done focusing on methods of protection, differential characteristic, application of different methods of protection and components required to fulfil these methods of protection.

Figure 2.1 is a graphical representation of the number of papers reviewed from 1943 to 2016. These papers discuss evolution of unit protection.
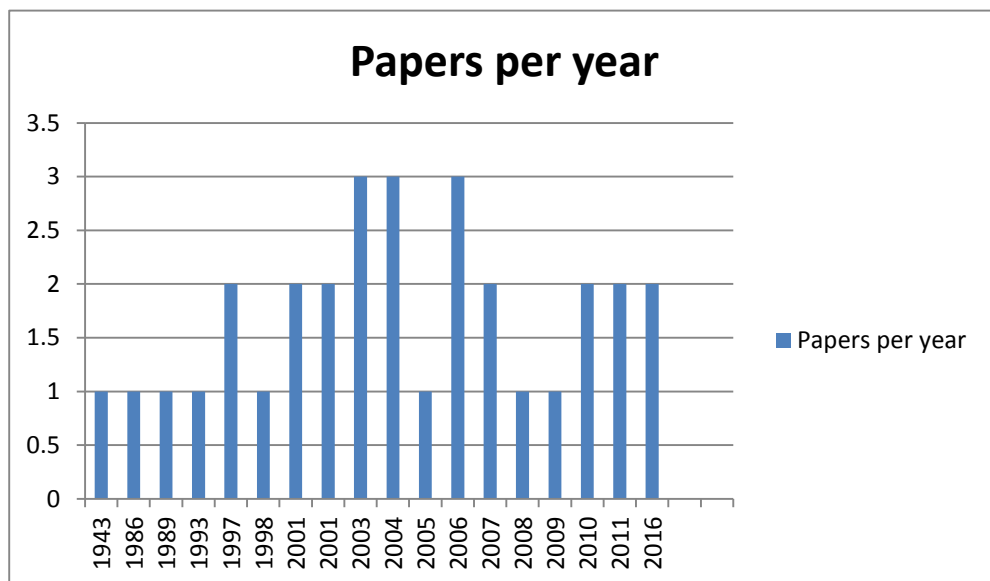
Figure 2.1: Number of publications per year

2.5.5   Analysis of different methods of unit protection

Different types of unit protection are discussed in detail in Table 2.1. Excerpts of different author's statements and conclusions are tabulated accordingly in light of a particular method of protection. Component required to fulfil a particular method of protection are specially selected as it is an important criterion that defines reliability of method of protection.

Table 2.1: **Comparison of existing papers on multi-terminal transmission line protection**

Paper	Statement	Method of protection or differential characteristic	Application and components required to archive objective	Author's conclusion
(Bostwick and Harder, 1943) "Relay protection of tapped transmission lines".	The presented paper deals with the methods of protection for lines under the headings of Directional overcurrent protection, impedance or distance protection, Pilot-wire and carrier protection. It is hoped that by summarizing the existing schemes and presenting data on certain new schemes, particularly on pilot-wire protection, that some help can be given in the solution of this currently important problem.	Directional overcurrent protection, Impedance protection, pilot-wire and carrier pilot protection	Applicable on Multi-terminal lines, Voltage and Current measurements required.	The co-ordination of directional and distance-type relays is more difficult in three-terminal lines because of two principal problems. 1. Unequal impedances to remote terminals. 2. Mutual impedance effects from fault and load current entering or leaving at the tap. Blocking-type pilot schemes assist in solving these problems, but on three-terminal lines with paralleling ties undesired blocking may be produced by: power flow out at one terminal to a fault within the protected zone near another terminal.
(Aggarwal and Johns, 1986) "The development of a new high speed 3-terminal line protection scheme".	A new high speed (HS) current differential protection scheme for application to three-terminal transmission lines is described. The scheme utilises a wide-band Fibre Optic Link (FOL) and the results show that the special filtering and signal processing techniques developed provide a performance which satisfies the requirements for reliable and secure protection of Teed feeders.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required.	A new HS current differential Teed feeder protection scheme for use in conjunction with a HS FOL has been developed. The special filtering and signal processing techniques developed, in particular the decision process, ensure maximum relay stability for through faults.
(Arbes, 1989) "Differential line protection application to multi-terminal lines".	This article describes the principles chosen for the construction of the various protection elements and gives their results and performance	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required.	Prototype of the differential protection has been tested on a T.N.A. Simulator and in the E.d.F St Denis Laboratory.

	levels in terms of operating features: detection sensitivity for resistive faults, stability in the presence of faults external to the system being protected.			The results obtained are in conformity with the projections of the study and with all the requirements of the E.d.F. specifications.
(Sachdev et al, 1993) "A differential algorithm for protecting parallel-teed transmission lines".	An algorithm based on the transmission line equations is presented in this paper. The proposed algorithm uses a segregated scheme, facilitates the coordination of multi-phase tripping and reclosing on HV and EHV parallel-teed transmission lines.	Operate-Restraint characteristic (Dual bias slope), based on transmission line equations.	Applicable on 3 terminal lines, Voltage and Current measurements required.	The information concerning the current phasors at the tee junction, as calculated from the data acquired at the three terminals, is exchanged between the relays at the line terminals. Current differential principle is then used to decide if there is a fault in the protected zone. The proposed algorithm also provides, without using extra hardware and software, a practical method for data synchronization that is not affected by the length of the transmission line.
(Southern et al, 1997) "A new type of differential feeder protection relay using the global positioning system for data synchronization".	This paper describes a new technique for sampling synchronisation in a numerical differential feeder protection relay. The protection uses a Global positioning System satellite receiver for sampling synchronization at each end of the protected feeder.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required	The problem of sampling synchronization can be overcome if a timing signal is available from an external source. The global positioning system provides time synchronization to an accuracy of 1µs anywhere in the world. All the results described in this paper support the conclusion that synchronized differential feeder protection can provide high levels of sensitivity and dependability on internal faults and high levels of stability on external faults.
(Southern et al, 1997) "GPS synchronizes current differential protection".	A new technique for current differential feeder protection employing measurement synchronisation is described in this paper. The application of current differential protection to feeders can present several difficulties. These problems are briefly described together with how their effects can be reduced by the use of synchronised measurements.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required	This paper described the benefits of using phasor measurements synchronised by GPS for differential feeder protection. Two methods of implementing phasor synchronisation are possible – synchronised sampling and phasor phase angle compensation. The phase angle compensation method has been shown to give excellent synchronisation accuracy, to better than

				4µs.
(Houlei et al, 1998) "Development of GPS synchronized digital current differential protection".	The proposed protection is different from existing ones in two aspects: one is using GPS time information to implement synchronized sampling at all terminals of the protected line. Another is the application of new differential algorithm based on fault component instantaneous value.	Differential algorithm based on fault component instantaneous value.	Applicable on Multi-terminal lines, only current measurements required.	In GPS based digital current differential protection, the problem of synchronized sampling is perfectly solved by using GPS time information. The proposed differential algorithm based on fault component has the features of high sensitivity, strong ability to withstand fault resistance and fast operating speed, and hence can be used to substitute for conventional phasor differential algorithm.
(Al-Fakhri and Elagtal, 2001) "A unique current differential based algorithm for protection of multi-terminal lines".	The paper describes a new differential relay showing the possibility of using the vector difference as a restraint quantity, while keeping the vector sum as a differential quantity. The purpose of the paper is to establish the principle and the applicability if the algorithm in Multi-terminal lines.	Vector sum as an operating quantity and vector difference between the largest incremental current and the vector sum of incremental currents of other terminal as restraint quantity.	Applicable on Multi-terminal lines, only current measurements required.	The authors have presented a new method of achieving differential protection of multi-terminal lines alongside a well-established method. The Idea of choosing the terminal with the largest current change and the designation of this as the key terminal is the innovative step in this work. The particular algorithm chosen by the authors seem to achieve both sensitivity and performance. This is due to the well-established theory behind and without imposing any arbitrary assumptions or additional complicated technique and arbitrary restraint for more than two terminals.
(Koglin et al, 2001) "Differential protection of multi-terminal lines without synchronization".	The positive-sequence components of currents and voltages is calculated from the sampled values. Then, using line parameters, currents and voltages as well the admittances or apparent powers at the tap pinot, are calculated for each line section. The sum of the admittances, and also the sum of apparent powers are equal to zero for the sound line. Phase shifts between currents at all terminals in the prefault stage, caused by the not synchronized sampling can also be calculated. An appropriate sum of	Sum of admittance, apparent power and currents.	Applicable on Multi-terminal lines, Voltage and Current measurements required.	In the paper, three methods for differential protection of multi-terminal lines are proposed. The methods don't require sampled values and therefore no synchronization. Four different criteria have been developed and investigated: admittance, active and reactive power as well as current criteria. Most suitable for usage in differential protection is the method based on the current criterion. The method can also be applied for detection of single-phase faults with considerable

	currents at the tap point is also equal to zero under sound line conditions.			resistance. The method based on admittance cannot be applied for the detection of three phase faults without fault resistance. The fast algorithms for the estimation of symmetrical components are very sensitive to waveform distortion.
(Yufeng et al, 2002) "The theory and application of differential protection based on instantaneous values".	This paper introduces the new current differential protection based on instantaneous values. Firstly, some theory problems about the novel method are discussed, the operation equation of the protection is presented and its reliability effected by data window is analysed. The main result is got that the width of the data window should be greater than $\pi/2$.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required.	Different from the conventional differential method, the novel scheme doesn't compare the amplitude of differential current with the set value, but calculates the number of sampled points whose values fulfil the operation criterion and decide whether the protection operates. So its operation character is different and has many special problems needed to be discussed in the theory and application. Aiming to these problems, the paper gives detailed analysis.
(Chen, et al, 2002) "Three terminal transmission line protection using synchronized voltage and current phasor measurements".	This paper presents a new relaying algorithm for EHV three-terminal transmission line protection using synchronized voltage and current phasors. The development of the scheme is based on distributed transmission line model and the mutual coupling effect of lines is decoupled using Clarke transformation. Then, a robust fault detection index composed of voltages, currents and modal line parameters is derived.	Clarke Transformation and fault detection index.	Applicable on 3-Terminal lines, Voltage and Current measurements required.	A new PMU-based protection scheme for EHV three-terminal transmission lines is presented in this paper. Simulation results show that the scheme gives correctly response under various system and fault conditions. The tripping decision time including fault detection, faulted-zone discrimination, and fault classification is mostly within half a cycle. The algorithm considers the effect of shunt charging capacitance such that the scheme is very suitable for long distance transmission line protection.
(Yang et al, 2003) "The study of sampled value differential protection".	The sampled value differential protection is described in this paper. The basic selective rule of S, R values is to ensure the restraint effectiveness of the sampled value differential protection equal or superior to the corresponding phasor differential protection during external faults.	Sampled value differential protection based on instantaneous values	Applicable on Multi-terminal lines, only current measurements required.	To ensure the restraint effectiveness of sampled value differential protection equal or super to the corresponding phasor method, the selection of S value should satisfy S>0.25N for restraint mode 1 and mode 3, S>0.27N for restraining mode 2. The operating

	The operating characteristic phasor analysing method is proposed to analyse the operating characteristic of the sampled value differential protection, which uses the phasor relationships of input currents of the protected system to represent the operating zone, fuzzy operating zone and restraint zone.			characteristic phasor analysing method enables us to analyse the characteristic of sampled value differential protection clearly and directly.
(Jingchao et al, 2003) "Study on the operating characteristic of sampled value differential protection".	The sampled value differential protection is described in this paper. The selections of S, R values are investigated and the basic selective rule is to ensure that the restraint effectiveness of the sampled value differential protection be equal or superior to the corresponding phasor differential protection during external faults.	Sampled value differential protection based on instantaneous values	Applicable on Multi-terminal lines, only current measurements required.	For restraint mode 1, to ensure that the restraint effectiveness of sampled value differential protection be equal or super to the corresponding phasor differential protection, the selection of S should satisfy S>0.25N. Two protection systems, which are based on the sampled value differential technique, have been put into operation.
(Villamagna et al, 2003) "Design of a symmetrical component based current differential protection scheme".	To ensure stability, the operating threshold is raised at the through fault current is increased. This has a detrimental effect on sensitivity and may prevent the detection of internal resistive faults. This paper discusses how symmetrical components allow the biased operating threshold to be reduced when CT saturation occurs.	Operate-Restraint characteristic (Dual bias slope), using symmetrical components.	Applicable on Multi-terminal lines, only current measurements required.	The results indicate that enhanced sensitivity can be achieved with a symmetrical component based current differential protection system, while maintaining a high level of protection stability. The early detection of significant rate-of-change allowing for improved protection stability. Where a positive polarity of di_{diff}/di_{bias} detects an external fault and a negative polarity of di_{diff}/di_{bias} detects an internal fault. By adaptive biasing technique, the biased threshold setting can be set (or reshaped, i.e. provide an additional bias threshold parameter according to the symmetrical component fault level.
(Forford et al, 2004) "An analogue multi-terminal line differential protection"	In this paper it is shown how a multi-terminal current differential protection scheme can be applied using standard components and necessary considerations for the application are discussed.	Basic pilot wire current differential protection.	Applicable on Multi-terminal lines, only current measurements required.	The well proven analogue current differential protection RADHL-principle has been developed to handle also multi-terminal lines. This will enable a low-cost fast and selective short-circuit protection of

	The RADHL pilot wire relay has traditionally been used for protection of short to medium length two terminal cables or overhead lines. The relay application requires a dedicated metallic pilot wire between the line ends.			meshed distribution and sub-transmission networks. This concept permits re-use of existing installations of two-terminal RDAHL installations by adding just what is needed for the extension in case of adding taps on the line.
(Al-Fakhri, 2004) "The theory and application of differential protection of multi-terminal lines without synchronization using vector difference as restraint quantity - simulation study".	This paper presents an application of a new differential relay algorithm for EHV three terminal as well as multi-terminal transmission line, using phase measurement unit in a form of incremental current.	Vector sum as an operating quantity and vector difference between the largest incremental current and the vector sum of incremental currents of other terminal as restraint quantity.	Applicable on Multi-terminal lines, only current measurements required.	The author have presented a laboratory testing of the new well-established method of achieving differential protection of teed feeders and multi-terminal lines alongside with the idea of choosing the terminal with largest current change and the designation of this as the key terminal is the innovation step in this work. Simulation results show that the scheme gives correct response under difficult cases and it supported the conclusion that the algorithm has high dependability against out feed, and it is not necessary to calculate any settings.
(Altuve et al, 2004) "Transmission line differential protection with an enhanced characteristic".	The new relaying system design, presented in this paper, provides sensitive protection for transmission lines and cable faults, and high security and stability for external faults. The relay system is tolerant of the unequal communication channel delays that are typical of modern networked digital communications channels.	Alpha Plane characteristic	Applicable on two-terminal lines, only current measurements required.	Percentage differential relays using a slope setting cannot achieve the same sensitivity and security as the new α-plane relay element when we consider the cumulative errors of CT saturation and channel asymmetry. The slope setting of a traditional percentage differential element defines its restrain region security, dependability, and sensitivity. It is difficult to increase one without decreasing another.
(Redfern et al, 2005) " A flexible protection scheme for multi-terminal transmission lines".	This paper introduces a novel protection scheme designed for protecting multi-terminal transmission lines. The scheme is based on a conventional carrier assisted, distance relay protection scheme and is designed to accommodate variations in tap position.	Distance/Impedance measurement.	Applicable on Multi-terminal lines, voltage and current measurements required.	Several schemes can be considered, but the one offering the most effective solution is based on distance relaying and an ON/OFF keyed carrier communications system. This Enhanced Blocking scheme offers the advantages of offering 'instantaneous' protection for faults anywhere on the

				protected line together with 'instantaneous' carrier independent protection for faults on the spur and part of the line close to the tap point. An acknowledgement limitation of the scheme is its ability to accommodate circuits in parallel with the line circuit.
(North American Electric Reliability Council, 2006) "The complexity of protecting three terminal transmission lines".	The intent of this paper is to describe the most common types of three-terminal protection complexities found in the industry.	Distance/Impedance measurement.	Applicable on multi-terminal lines, Voltage and Current measurements required.	The current differential principle is considered to be suited to protect three-terminal lines and it does not need to contend with problems associated with voltage, loading and swings. However, a three-terminal line may affect line current differential protection schemes if outfeed conditions occur during internal lines faults.
(Gao et al, 2006) "A new current differential protection scheme for teed transmission lines".	This paper presents a current differential protection for Teed transmission lines using superimposed components. Basing on the characteristics of the superimposed current in Teed feeders, a unique differential criteria was proposed and analysed under different operating conditions.	Current differential protection using superimposed current.	Applicable on 3-Terminal lines, only Current measurements required.	Aiming at the two stubborn problems encountered by the traditional line differential protections, the paper provided an effective solution without increasing any other quantities, such as voltage, zero-sequence current or impedance. Theoretical analysis and simulation results confirmed that the proposed scheme has significant advantages over traditional differential schemes.
(Zhang et al, 2006) "A novel criterion for neutral current differential protection".	Sensitivity of phase segregated current protection is decreased for it introduces load current into restraint quantity. Superimposed current differential protection is only available within a short period after occurrence of a fault, inapplicable to evolving faults. As a result, neutral current differential protection by which both terminal neutral currents are introduced to form the criterion is presented as a backup for the foregoing ones in case of high resistance grounded faults for heavy load lines.	Operate-Restraint characteristic (Dual bias slope), using neutral currents.	Applicable on tow-terminal lines, only current measurements required.	By the comparison between the new operation criterion and existing ones, new criterion makes up the shortage of existing one, the sensitivity under single-pole open condition is greatly increased and the reliability for external faults is improved also. The new criterion is not suitable for weak-feeder lines and some cases when zero sequence current of one end is too small to be noticed.

(Zhang et al, 2007) "Performance comparison of current differential protection scheme based on symmetrical components".	It has been proved that the sequence currents also obey the Kirchhoff's current law, which is the theoretical basis of current differential protection. Accordingly, it is possible for symmetrical components to be applied in current differential scheme.	Operate-Restraint characteristic (Dual bias slope), using sequence components.	Applicable on Multi-terminal lines, only current measurements required.	Comprehensive comparison based on theoretic analysis and extensive simulation shows that positive-sequence differential scheme is not reliable, because it is affected by system conditions seriously. Negative-sequence and zero-sequence schemes produce excellent performance for internal high resistance faults under heavy load conditions, while they are very stable for external faults. The two schemes show similar results for unbalance ground faults, but the negative-sequence one provides additional coverage to phase-to-phase faults.
(Wu et al, 2007) "Research on transmission lines multi current differential relay scheme".	Multi-differential protection which combines phasor value differential protection with sampled values based differential protection is proposed. In such scheme, the shortcoming of each differential theory is overcome and the merits are compensatory to each other.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required.	In brief, multi current differential relay scheme is perfect combination of phasor value based differential relay with sampled value based differential relay. It can improve the protection performances such as reliability, sensitivity, trip speed and immunity to CT saturation to great extent. Especially, multi current differential relay scheme can be implemented easily on existing microcomputer based relay protection hardware, which is suit for project application very well.
(Ha et al , 2008) "Novel Transient differential protection based on distributed parameter for EHV transmission lines".	A novel scheme and algorithm of differential protection, which employs not only the power frequency components but the transient components based on distributed parameter line model, is proposed, as well as the distributed capacitive current is taken into accordingly.	Transient differential protection based on distributed parameter line model.	Applicable on two-terminal lines, Voltage and Current measurements required.	The Electromagnetic Transients Programme (EMTP) simulation tests associated with the typical double extra High Voltage power network shows that the new differential principle is capable of instantaneous identifying internal and external faults. At the same time the criterion has higher reliability and security. Additionally, the trip order can be sent within 10ms. The new criterion is not sensitive to transient

				components, fault resistance, fault inception angle, fault types and system swing.
(Dambhare et al, 2009) "Adaptive current differential protection schemes for transmission-line protection".	The paper proposes a methodology for adaptive control of the restraining region in a current differential plane. An error analysis of conventional phasor approach for current differential protection is provided using the concept of dynamic phasor. Subsequently, the methodology for protection of series compensated transmission lines is extended.	Current differential scheme based on *equivalent-π* line model.	Applicable on two-terminal lines, Voltage and Current measurements required.	We conclude that the proposed adaptive control of restraint region together with phasorlet algorithm for phasor estimation provide the best solution for current differential protection of (series compensated) transmission lines.
(Miller et al , 2010) "Modern Line Current Differential Solutions".	This paper reviews technical solutions to the line current differential design and application, addressing the common design constraints and utility-driven application needs. The paper is a tutorial in this challenging area where protection principles and applications mix with communications and signal processing.	Alpha Plane characteristic	Applicable on Multi-terminal lines, only current measurements required.	A reliable Alpha Plane restraining technique was proposed for multi-terminal applications with any number of local current inputs to the relays. The size and structure of the communications payload are independent from the number of terminals or the number of local currents in the system, making the implementation simple and thus the solution more robust.
(Gajic et al, 2010) "Multi-terminal Line differential protection with innovative charging current compensation algorithm"	Here a new approach is Proposed. Simply the line differential protection learns the amount of symmetrical false differential current value over the time and subtracts it from the presently measured fundamental frequency, RMS differential currents. An additional fault position discriminator distinguishes between internal and external faults and is based on an analysis of the negative sequence current component at all ends of the protected circuit.	Operate-Restraint characteristic (Dual biased slope) and Distance/Impedance measurement for reserve protection	Applicable on multi-terminal lines, only Current measurements required.	In this paper it has been shown that the multi-terminal line differential protection is a good solution for protection of long, series-compensated, high-voltage lines with more than two ends. The innovating charging current compensation method, independent from voltage measurements, seems to work very well for such long overhead line configurations. Combination of differential protection and distance protection provides good protection solution for such applications.
(Abdelaziz et al, 2011) "Distance protection for multi-terminal transmission	This paper presents a protection scheme designed for protecting multi-terminal lines using distance relays. The advantage of the	Distance/Impedance measurement.	Applicable on Multi-terminal lines, Voltage and Current measurements required.	This paper presented overview of the several schemes for the protection of multi-terminal transmission line and proposed

lines".	proposed scheme is that it nearly eliminates the need for communication channels among the differential protection system components.			distance based protection technique. The simulation results showed the effectiveness of the proposed distance relaying scheme. This distance based relay scheme provides a cost effective method as there is no need for separate communication link for each phase. As well it does not need for matched current transformers like the differential and directional schemes.
(Bejmert et al, 2011) "Enhanced differential protection algorithm for tapped transmission lines".	In order to find an optional solution various disturbances that may be the sources of unbalance of differential signals are discussed. The newly developed protection except differential current itself employs also negative-sequence and zero-sequence signals calculated for differential currents.	Operate-Restraint characteristic (Dual bias slope).	Applicable on Multi-terminal lines, only current measurements required.	It has to be stressed that proposed solution does not demand: supporting distance function, increase of pick-up (which decreases sensitivity) and second harmonic restraint (which may deteriorate operation speed for internal fault with CT saturation.
(Kasztenny, et al) "Application of current differential protection to tapped transmission lines".	This paper discusses application problems and solutions permitting the application of current differential protection to tapped transmission lines without measurements at the tap point (-s).	Operate-Restraint characteristic (Dual biased slope) and Distance/Impedance measurement for supervision.	Applicable on Multi-terminal lines, only current measurements required.	The approach taken does not require measurements at the taps, and therefore, is economically attractive. The presented application uses distance supervision to prevent misoperation for faults on the low voltage sides of the tapped transformers and zero-sequence removal to cope with external ground faults on the high voltage system.
(Y. Manju Sree, et al, 2016), Multi-Terminal-Transmission Line Protection using Wavelet Based Digital Relay in the Presence of Wind Energy Source".	The scheme is tested for different types of faults with varying fault incidence angles and fault resistances using typical transmission line model. The Discrete Fourier Transform have some disadvantages that can be overcome by using Discrete Wavelet transform. The system is modeled in MATLAB SimPower systems environment. Results indicate that the proposed scheme is reliable, fast and highly accurate.	Discrete Fourier Transform	Applicable on Multi-terminal lines, only current measurements required.	This paper adopts an innovative technique based on wavelet transform to determine the fault location in the presence of wind plant. The verification of wavelet fault analysis method is implemented on multi-terminal transmission line connecting wind energy source irrespective of fault impedance, fault inception angle and location of the fault. The suggested protection scheme is found to be fast,

				reliable and accurate for all types of faults on transmission lines.
(Amir Ghorbani, et al, 2016) "Synchrophasors-Based Transmission Line Protection in the Presence of STATCOM".	The proposed method is a combination of differential and distance protection. The data of buses containing voltages and current signals are sent to the relay location or system protection centre. Then using obtained synchrophasors, the effect of fault resistance and Static Synchronous Compensator STATCOM is removed from the measured impedance.	Combination of Distance/Impedance protection base on active power calculations of the buses	Applicable on Multi-terminal lines, Voltage and Current measurements required.	Analytical and modelling results indicate that fault resistance and the presence of STATCOM both increase the calculated impedance by the distance relay and the relay could not detect the fault location currently. Differential protection has no effects of fault resistance, and the effect of shunt compensation can be eliminated. With calculating the active power in buses, the fault resistance is obtained and its effects is deducted from calculated impedance in the algorithm.

2.6 Comparative analysis of the developments in the existing literature

With reference to the research papers as tabulated in Table 2.1, there is a number of multi-terminal transmission line protection methods. Bostwick and Harder, (1943) present one form protection based on directional overcurrent method. Other form of multi-terminal transmission line protection based on impedance/distance protection is presented by Abdelaziz et al, (2011). Multi-terminal transmission line protection based on current differential method is one of the oldest methods of protection and continues to be used or dominates other forms of protection as it is considered superior with respect to selectivity, sensitivity, stability and speed of operation as compared with other forms of protection. Apart from percentage current differential protection method, (Ha et al, 2008) present a novel transient differential protection based on distributed parameter and Dambhare et al, (2009) present a methodology for adaptive control of the restraining region in a current differential plane based on equivalent π–model. These methods inherit a common disadvantage of Voltage Transformer fuse failures.

Traditional percentage current differential protection as one form of differential protection is mostly used in one form or the other. Yang et al, (2003) presents one form of protection based on sampled values implementing percentage differential protection. Gao et al, (2006) describe other method of current differential protection scheme for Teed transmission lines using superimposed components, also implementing percentage differential protection.

Interestingly, Altuve et al, (2004) present Alpha Plane differential characteristic on two terminal application in comparison with percentage current differential characteristic and outline the advantages of Alpha Plane differential characteristic over percentage current differential characteristic. Miller et al, (2010) also present Alpha Plane differential protection for multi-terminal transmission line and outline general design directions for a next generation line current differential protection scheme.

The alpha plane method has been a tool available to protective engineers to study line current differential characteristics and faults, but now is been deployed as algorithm within relays for protection purpose. Apart to multi-terminal application, alpha plane has been implemented for 3-terminal application with different algorithm. The research is aimed at investigating, evaluating and analysing methods and algorithms of existing IEDs implementing alpha plane characteristic. The aim is to develop a complete test method for three terminal differential alpha plane characteristic using OMICRON test universe software essentially defining security, dependability and sensitivity of alpha plane characteristic

2.7   Review of the test methods for 3 terminal alpha plane different protection

SEL is the solitary vendor that uses alpha plane characteristic for differential protection. One test method was developed by SEL which formed basis of this project. The preliminary method is discussed in chapter 1 in 1.2 of this thesis. The method required hard wiring of test outputs of protection relays to the inputs of the test equipment. New test method has now been developed in the thesis which required creation of new logical nodes to replace hard wiring of test inputs and outputs. Development of new logical nodes is discussed in detail in chapter 4 of this thesis.

2.8   Conclusion

Literature review in multi-terminal transmission line protection has been presented in this chapter. Different methods applicable on multi-terminal transmission line protection as well as their advantages and disadvantages have been discussed. Main papers in line with the research project have been highlighted as the direction to the research objectives.

Theoretical aspects of multi terminal line protection is presented in chapter 3.

CHAPTER THREE

THEORETICAL ASPECTS OF MULTI TERMINAL LINE PROTECTION

3.1 Introduction

The protection of teed HV and EHV transmission lines is much more complex than the protection of two terminal lines. The conventional relaying techniques do not perform the task of protecting teed lines satisfactorily. For a line that runs partially or totally in parallel with another line, mutual coupling between them and cross-circuit faults affect the performance of the relays. The usual problems the relays have include:

- an inability to adjust fully to wide variations of current distribution and infeed/outfeed ratios.
- substantial difficulty in identifying faulted phases during cross-circuit faults requiring that both circuits be interrupted instead of using single phase tripping on the circuits .
- the possibility that the directional and phase comparison relays will incorrectly identify internal faults due to current flow out of one of the line terminals under some operating conditions (Sachdev et al, 1993).

Throughout the history of power system protection, researchers have strived to increase sensitivity and speed of apparatus protection systems without compromising security. With the significant technological advances in wide-area measurement systems, for transmission system protection, current differential protection scheme outscores alternatives like overcurrent and distance protection schemes (Dambhare et al, 2009).

Effects of infeed and out feed are analysed in 3.2 and 3.3 respectively. Then application of unit protection, particularly different forms of distance protection is presented in 3.4 including differential protection in 3.5.

Differential protection is one form of unit protection as the principle is to sense the difference in currents between the incoming and outgoing terminals of the unit being protected. This chapter presents theoretical aspects of multi-terminal lines. Chapter 4 discusses IED modelling and configuration.

3.2 Effect of Infeed at the Tee Point – Apparent Impedance

For a fault on a transmission line, a distance relay will measure impedance equal to the line positive sequence impedance, provided there are no sources of fault current between the line terminal at which the relay is located and the fault. The distance

relay measures impedance by comparing the voltage drop between its location and the fault with the current at the relay.

Referring to Figure 3.1, the actual line impedance from the relay terminal (Terminal A) to the fault is not always the impedance measured by the relay. This is because the third line terminal (Terminal C) tapped (Tee point) to a line is an additional source of current for a line fault. Current will be supplied to a fault that occurs on the line section beyond the tap of Terminal C through both Terminal A and Terminal C. The voltage drop resulting from the input of fault current from each of these sources into the common section of the line will be measured by the distance relay at the Terminal A. Since the current input from Terminal C is not applied to the relay at Terminal A, the impedance measured by this relay is higher than the actual impedance from the Terminal A to the fault. The relay will underreach; that is, for a given relay setting the relay does not cover the same length of line it would if the additional current source were not present (System Protection and Control Task Force of the NERC Planning Committee September 13 2006).
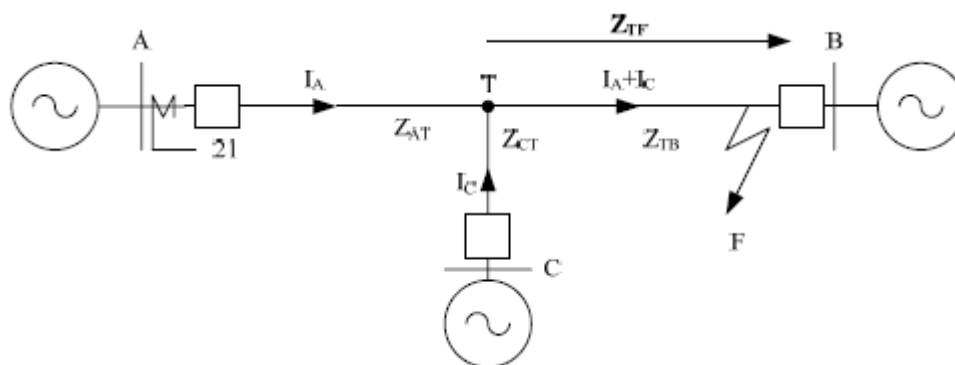
Figure 3.1: **Infeed effects**

Refering to Figure 3.2,the apparent impedance from Station A to the same fault, with the line terminal at Station C closed is;

$$Z_{app\ A\text{-}B} = \frac{V_a}{I_a} = \frac{(1 \times 1) + (1 \times 2)}{1} = 3\Omega$$

(3.1)
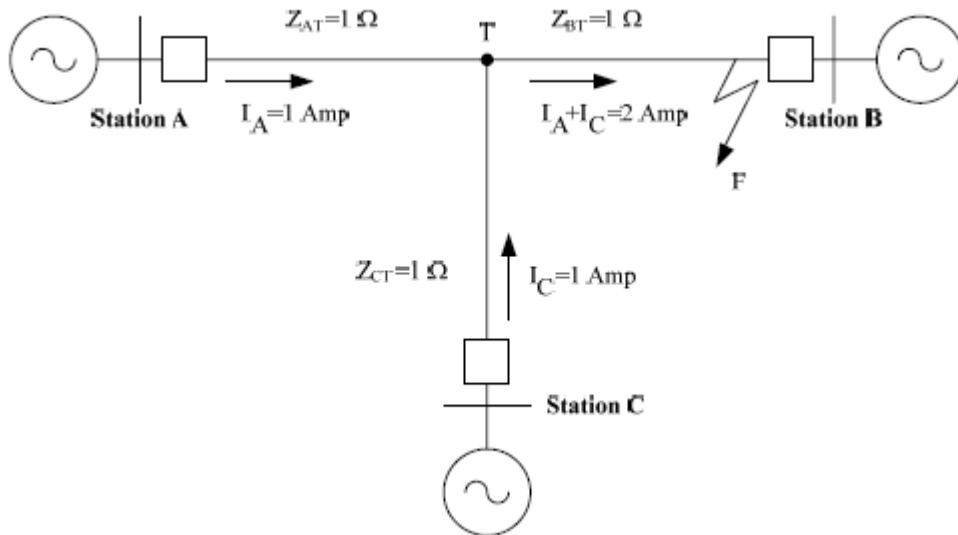
Figure 3.2: Infeed example

3.3 Effect of outfeed at the Tee Point

It is also possible, based on system configuration, to experience an outfeed at the "Tee" location for a fault internal to the protection section. For these cases, the same equations apply, but instead of an underreaching effect, the tendency is to overreach.
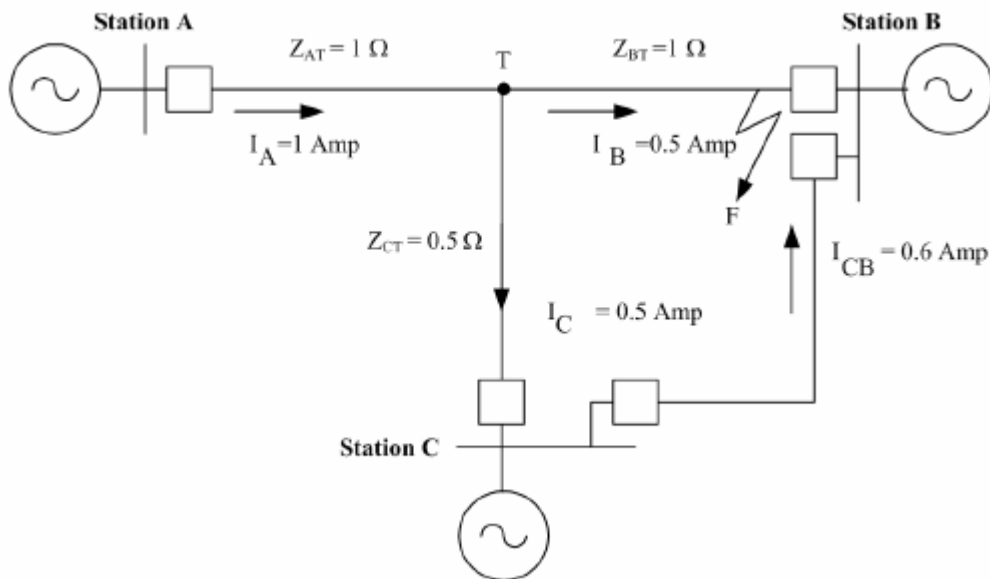
Figure 3.3: Outfeed example

For Terminal A relaying, the actual line impedance to the fault is 2.0 Ohms, however, the apparent impedance measured is:

$$Z_{app\,A\text{-}B} = \frac{V_a}{I_a} = \frac{(1\text{x}1) + (0.5\text{x}1)}{1} = 1.5\Omega$$

(3.2)

The relay overreaches.

The protection of multi-terminal transmission lines is a challenging task due to possible infeed or outfeed currents contributed from the taped lines. The key challenge with multi-terminal transmission line protection lies in reliably detecting and isolating faults compromising the security of the system.

3.4 Multi-ended feeders - application of distance protection schemes

Different type of distance protection schemes used for the protection of plain feeders may also be used for teed feeder protection. However, the applications of some of these schemes are much more limited in the case of multi terminal feeders. Distance schemes can be subdivided into two main groups namely; transfer trip schemes and blocking schemes. The usual consideration when comparing these schemes is security, that is, no operation for external faults, and dependability, that is, assured operation for internal faults (Alstom NPAG, 2011).

In addition, transfer trip schemes require fault current infeed at all the terminals to achieve high-speed protection for any fault in the feeder. This is not the case with blocking schemes. While it is rare to find a plain feeder in high voltage systems where there is current infeed at one end only, it is not difficult to envisage a teed feeder with no current infeed at one end, for example when the teed feeder is operating as a plain feeder with the circuit breaker at one of the terminals open. Nevertheless, transfer trip schemes are also used for teed feeder protection, as they offer some advantages under certain conditions. A summary of the main problems met in the application of distance protection to teed feeders is given in Table 3.1 (Alstom NPAG, 2011).

Table 3.1: Main problems met in the application of distance protection to teed feeders.

Case	Description
1	Under-reaching effect for internal faults due to current infeed at the T point
2	Effect of pre-fault load on the impedance 'seen' by the relay
3	Over-reaching effect for external faults, due to current flowing outwards at one terminal
4	Failure to operate for an internal fault, due to current flowing out at one terminal
5	Incorrect operation for an external fault, due to high current fed from nearest terminal

3.4.1 Transfer Trip Under-Reach Schemes

The main requirement for transfer trip under-reach schemes is that the Zone 1 of the protection, at one end at least, shall see a fault in the feeder. To meet this requirement, the Zone 1 characteristics of the relays at different ends must overlap, either the three of them or in pairs. If the conditions mentioned in case 4 in Table 3.1 are found, direct transfer tripping may be used to clear the fault; the alternative is to trip sequentially at end C when the fault current I_C reverses after the circuit breaker at terminal B has opened; see Figure 3.4 (Alstom NPAG, 2011).
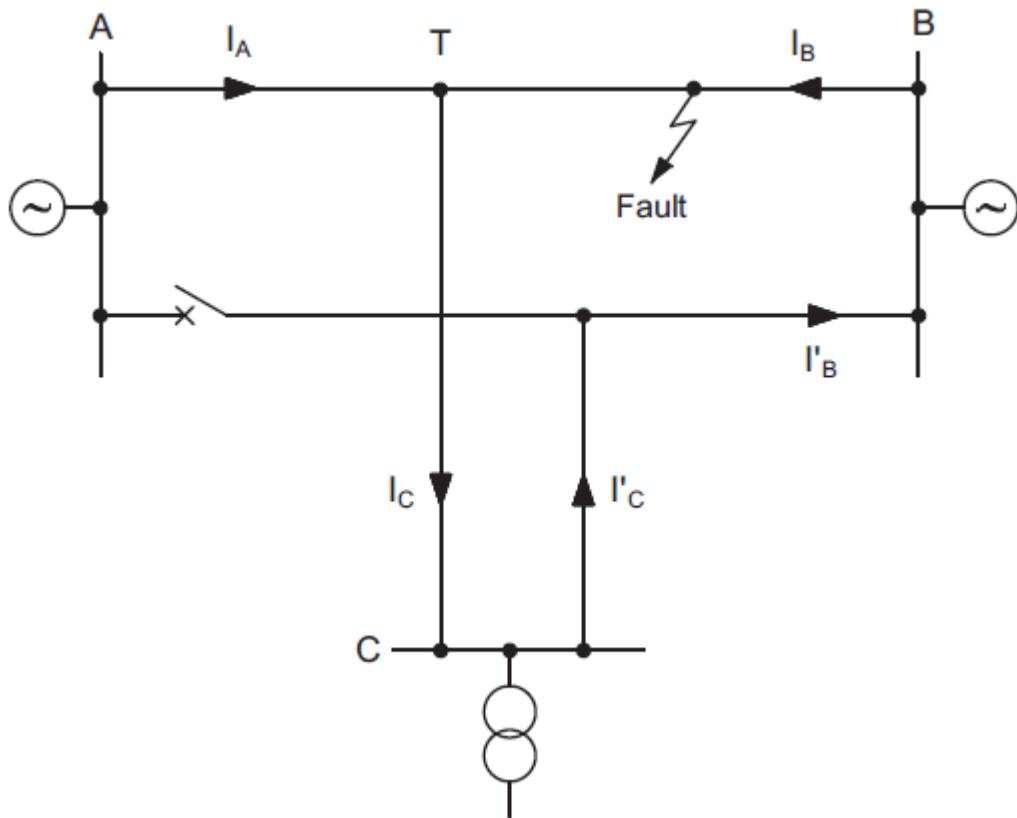
Figure 3.4: Internal fault near busbar B with current flowing out at terminal C

Transfer trip schemes may be applied to feeders that have branches of similar length. If one or two of the branches are very short, and this is often the case in teed feeders, it may be difficult or impossible to make the Zone 1 characteristics overlap. Alternative schemes are then required. Another case for which under-reach schemes may be advantageous is the protection of tapped feeders, mainly when the tap is short and is not near one of the main terminals. Overlap of the Zone 1 characteristics is then easily achieved, and the tap does not require protection applied to the terminal (Alstom NPAG, 2011).

3.4.2 Transfer Trip Over-Reach Schemes

For correct operation when internal faults occur, the relays at the three ends should see a fault at any point in the feeder. This condition is often difficult to meet, since the impedance seen by the relays for faults at one of the remote ends of the feeder may be too large, as in case 1 in Table 3.1, increasing the possibility of maloperation for reverse faults, case 5 in Table 3.1. In addition, the relay characteristic might encroach on the load impedance. These considerations, in addition to the signalling channel requirements mentioned later on, make transfer trip overreach schemes unattractive for multi-ended feeder protection (Alstom NPAG, 2011).

3.4.3 Blocking Schemes

Blocking schemes are particularly suited to the protection of multi-ended feeders, since high-speed operation can be obtained with no fault current infeed at one or more terminals. The only disadvantage is when there is fault current outfeed from a terminal, as shown in Figure 3.4. This is case 4 in Table 3.1. The protection units at that terminal may see the fault as an external fault and send a blocking signal to the remote terminals. Depending on the scheme logic either relay operation is blocked or clearance is in Zone 2 time. The directional unit should be set so that no maloperation can occur for faults in the reverse direction; case 5 in Table 3.1 (Alstom NPAG, 2011).

3.4.4 Signalling Channel Considerations

The minimum number of signalling channels required depends on the type of scheme used. With under-reach and blocking schemes, only one channel is required, whereas a permissive over-reach scheme requires as many channels as there are feeder ends. The signalling channel equipment at each terminal should include one transmitter and (N-1) receivers, where N is the total number of feeder ends. This may not be a problem if fibre-optic cables are used, but could lead to problems otherwise.

If frequency shift channels are used to improve the reliability of the protection schemes, mainly with transfer trip schemes, N additional frequencies are required for the purpose. Problems of signal attenuation and impedance matching should also be carefully considered when power line carrier frequency channels are used (Alstom NPAG, 2011).

3.4.5 Directional Comparison Blocking Schemes

The principle of operation of these schemes is the same as that of the distance blocking schemes described in the previous section. The main advantage of directional comparison schemes over distance schemes is their greater capability to

detect high-resistance earth faults. The reliability of these schemes, in terms of stability for through faults, is lower than that of distance blocking schemes. However, with the increasing reliability of modern signalling channels, directional comparison blocking schemes offer good solutions to the many difficult problems encountered in requirements mentioned later on, make transfer trip overreach schemes unattractive for multi-ended feeder protection (Alstom NPAG, 2011).

3.5   Differential protection

Differential protection is ideally suited to teed feeders because of its absolute selectivity and wide adaptability. Moreover, micro-computer technology, digital communications and time synchronization has significantly enhanced the capabilities of differential protection and now it is the best form of protection for feeders on transmission networks, particularly those that are teed (Houlei Gao and Peter A. Crossley, 2006).

A phasor differential criteria based on the fundamental frequency component of the phase currents is widely used in differential protection. The operating quantity is the vector sum of the currents measured at all the terminals on a per phase basis, whilst the restraining quantity is the scalar sum. Under normal conditions, the terminal currents are the load currents, but when a fault occurs, the currents change to their post-fault steady state values including load. Generally, this type of criteria provides adequate sensitivity for solid (or low resistance) internal faults and complete stability for external faults. However two problems can occur:

- Inability to detect high resistance faults on a heavily loaded feeder. This is because the operating behaviour must be biased in proportion to the through current to ensure the protection remains stable during an external fault. However, the load current is now seen as the "through" current and the biased characteristic results in a reduction in the protection sensitivity.

- The out-feed or 'feed around' phenomenon that is seen when a particular location of internal fault occurs on some networks (Houlei Gao and Peter A. Crossley,2006)

Different methods of differential protection are discussed in chapter 2 of this thesis.

3.6   Conclusion

Parallel transmission circuits are often installed, either as duplicate circuits on a common structure, or as separate lines connecting the same two terminal points via different routes. Also, circuits may be multi-ended, a three-ended circuit being the most common. For economic reasons, transmission and distribution lines can be much more complicated, maybe having three or more terminals (multi-ended feeder), or with more than one circuit carried on a common structure (parallel feeders). Other possibilities are the use of series capacitors or direct-connected shunt reactors. The protection of such lines is more complicated and requires the basic schemes to be modified. This chapter discusses different protection methods applicable to multi ended transmission lines.

Chapter 4 discusses IED modelling and configuration to develop test method of multi-terminal line differential protection.

CHAPTER FOUR

IED MODELLING AND CONFIGURATION

4.1   Introduction

SEL 311L relay with restraint elements in Differential Protection logical Node (PDIF) is modelled in this chapter. XML Marker software in conjunction with SEL AcSELerator Architect engineering tool for SEL relays is the program used for modelling. XML stands for EXtensible Markup Language and is a text based markup language. XML files can be created and edited using a simple text editor like Notepad. With XML, data can be exchanged between incompatible systems. In the real world, computer systems and databases contain data in incompatible formats. One of the most time consuming challenges for developers has been to exchange data between such systems over the Internet. Converting the data to XML can greatly reduce this complexity and create data that can be read by many different types of applications.

The purpose of new logical node development is explained in 4.2. Overview of IEC 61850-7-4 standard as guidelines applicable to the development of PDIF logical Node is presented in 4.3. Brief description of XML Marker program functions used in modelling the SEL 311L Intelligent Electronic Device (IED) is done in 4.6.1.

First the standard SEL 311L relay model is presented and analysed. Using the standard model of IED Capability Description file (ICD), restraint elements for Phase A, Phase B, Phase C, Zero Sequence and Negative sequent are developed.

Testing of the newly developed Logical Node is done in chapter 6 in conjunction with evaluation of newly developed test method for 3 terminal alpha plane differential protection characteristic.

4.2   Purpose of new logical nodes development

Primitive test methods have been developed for testing alpha plane characteristic on two terminal differential applications only. 3 terminal differential application needed to be developed, thus testing between two terminals at a time i.e. terminals A-B; B-C and A-C has been the test method for 3 terminal application. This primitive test method required that all differential elements to be hardwired from the relay to the OMICRON device at each substation as shown on Figure 4.1. Differential elements include 5 operate elements and 5 restraint elements. Prior to wiring, the elements had to be programmed or mapped to 10 relay outputs which created a big room for human error either in programing or wiring. The entire process is time consuming, resulting to prolonged outages.

To avoid the shortcomings of the primitive test method, a new method is developed using IEC61850 standard which allowed differential elements to be published by the relay in a form of Generic Object Orientated Substation Event (GOOSE) message and subscribed by the OMICRON devise as opposed to had wiring. However, the standard IED Capability Description (ICD) file for SEL311L relay only has operate elements logical nodes and does not have restraint elements logical nodes which explains the need for new logical nodes to be developed. The process of new logical nodes development is presented in this chapter. The new logical nodes a developed in XML Marker software and saved as an XML file which is later used during the design of the test method.
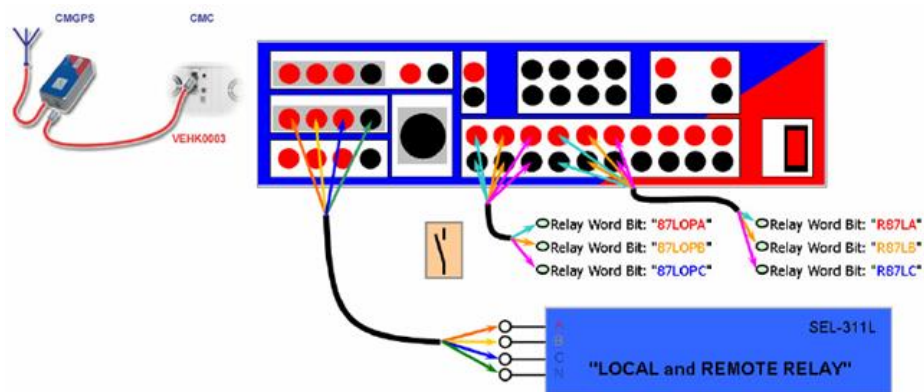
Figure 4.1: **Hardwiring of differential elements**

4.3   Overview of IEC61850-7-4 Standard

IEC 61850 is the global communications standard that facilitates the development of a new range of protection and control solutions, allowing significant benefits over conventional hard-wired solutions. The goals of IEC 61850 are interoperability, free configuration and long term stability between protective relays and control devices from different vendors (www.selinc.com).

In the early 1990s, the Electric Power Research Institute (EPRI) and the Institute of Electrical and Electronics Engineers, Inc. (IEEE) began to define a Utility Communications Architecture (UCA). The two organizations focused initially on inter-control centre and substation-to-control centre communications and produced the Inter-Control Centre Communications Protocol (ICCP) specification. This specification, which IEC later adopted as 60870-6 TASE.2, became the standard protocol for real-time exchange of data among databases.

In 1994, EPRI and IEEE began work on UCA 2.0 for Field Devices (simply referred to as UCA2). In 1997, EPRI and IEEE combined efforts with Technical Committee 57 of

the IEC to create a common international standard. The joint efforts of these three organizations resulted in the present IEC 61850 standard.

The IEC 61850 standard, a superset of UCA2, contains most of the UCA2 specification, plus additional functionality. The standard describes client/server and peer-to-peer communications, substation design and configuration, testing, and project standards (www.selinc.com).

The IEC 61850 standard consists of the following parts (www.selinc.com), Table 4.1

Table 4.1: IEC 61850 Document Set

IEC 61850 Sections	Definitions
IEC 61850-1	Introduction and overview
IEC 61850-2	Glossary
IEC 61850-3	General requirements
IEC 61850-4	System and project management
IEC 61850-5	Communication requirements
IEC 61850-6	Configuration description language for substation IEDs
IEC 61850-7-1	Basic communication structure for substations and feeder equipment –Principles and models
IEC 61850-7-2	Basic communication structure for substations and feeder equipment –Abstract communication service interface (ACSI)
IEC 61850-7-3	Basic communication structure for substations and feeder equipment –Common dada classes
IEC 61850-7-4	Basic communication structure for substations and feeder equipment –Compatible logical node (LN) classes and data classes
IEC 61850-8-1	SCSM-Mapping to Manufacturing Messaging Specification (MMS) (ISO/IEC 9506-1 and ISO/IEC8802-3)
IEC 61850-9-1	SCSM-Sampled values over serial multidrop point-to-point link
IEC 61850-9-2	SCSM-Sampled values over ISO/IEC 8802-3
IEC 61850-10	Conformance testing

IEC 61850 Part 7-4: Basic communication structure for substation and feeder equipment – Compatible logical node classes and data classes is part of IEC61850 standard.

This part of IEC 61850 specifies the information model of devices and functions related to substation applications. In particular, it specifies the compatible logical node names and data names for communication between Intelligent Electronic Devices (IED). This includes the relationship between Logical Nodes and Data.

To avoid private and incompatible extension rules this part specifies normative naming rules for multiple instances and private extensions of Logical Node (LN)

Classes and Data Names. In Annex A of IEC 61850 Part 7-4, all rules are given (making use of examples) for:

- multiple instances of logical node classes by use of a LN instance identification (ID);
- multiple instances of data by use of a data instance ID;
- selecting data not included in LN out of the complete data name set; creating new logical node classes and data names

Figure 4.2 provides a general overview of IEC61850-7-4 standard
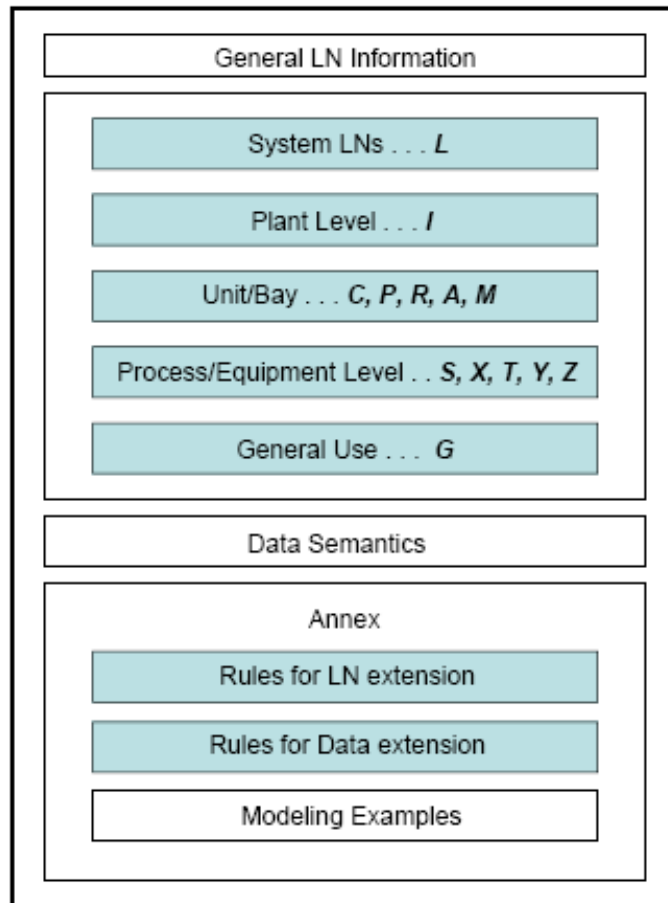
Figure 4.2: General overview of IEC61850-7-4 standard

These rules have been applied in developing the new logical nodes for testing 3 terminal alpha plane differential protection characteristic as discussed in 4.6 of this thesis.

4.4 Measuring Logical Node (MDIF) and Protection Logical Node (PDIF)

MDIF is a Measuring Logical Node for IEDs with differential protection functions. In the case of a three terminal line differential protection, each IED at each terminal of the line will measure the local phase and sequence components and prepare the phasors (MDIF). This information is then sent to the IEDs at the other ends of the line (not part of this standard). Based on the local measurement and the received

measurements, each IED (PDIF) calculates the differential current (the sum of the three vectors for each phase current) and the restrained (bias) current (for example the sum of the three scalars divided by some constant). These are available as measurements from each IED through the MDIF. The example in Figure 4.3 illustrates a line protection scheme consisting of functions for differential protection PDIF (three instances for three zones) with remote provision of data by MDIF (differential measurements). MDIF comprises all three phases for a real time view including all phase relations of the other side. In Figure 4.3 TCTR represents the current transformer, PTRC is the protection trip and XCBR represents the circuit breaker.
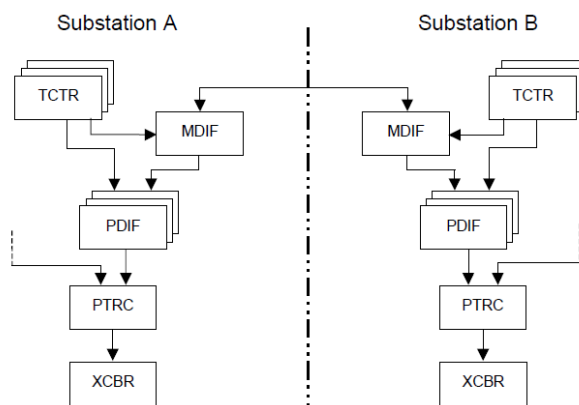
Figure 4.3: Use of MDIF and PDIF - example

4.5 Referencing an instance of a class

Rules of referencing an instance of a class are discussed as applied to the newly developed logical nodes for testing of 3 terminal alpha plane differential protection characteristic. Step by step procedure on developing the new logical node is discussed in 4.6 of this thesis.

According to IEC61850-7-2 in line with IEC 61850-7-4, the following length definitions shall apply.

LDName/LNName.

DataName[.DataName[. ...]].DataAttributeName[.DAComponentName[. ...]]

The inner square bracket "[. ...]" shall indicate further recursive definitions of nested data attribute components.

LDName   = up to 32 characters, application specific
LNName   = [LN-Prefix] LN class name [LN-Instance-ID]
LN-Prefix   = m characters (application specific)
LN class name   = 4 characters (for example, compatible logical node name as defined

	in IEC 61850-7-4)
LN-Instance-ID	= n numeric characters (application specific)
m+n	≤ 7 characters
DataName	= up to 10 characters (as, for example, used in IEC 61850-7-4
FCD	≤ 29 characters including all separators "." (without the value of the FC)

4.6 Common Logical Node

The compatible logical nodes classes defined in IEC 61850 document are specialisations of the common logical node class as shown on Table 4.2. Mandatory Logical node information was applied in developing the new logical nodes for testing of 3 terminal alpha plane differential protection.

Table 4.2: Common Logical Node Class

Common Logical Node class				
Attribute Name	Attr. Type	Explanation	T	M/O
LNName		Shall be inherited from Logical-Node Class (see IEC 61850-7-2)		
Data				
Mandatory Logical Node Information (Shall be inherited by ALL LN but LPHD)				
Mod	INC	Mode		M
Beh	INS	Behaviour		M
Health	INS	Health		M
NamPlt	LPL	Name plate		M
Optional Logical Node Information				
Loc	SPS	Local operation		O
EEHealth	INS	External equipment health		O
EEName	DPL	External equipment name plate		O
OpCntRs	INC	Operation counter resetable		O
OpCnt	INS	Operation counter		O
OpTmh	INS	Operation time		O
Data Sets (see IEC 61850-7-2)				
Inherited and specialised from Logical Node class (see IEC 61850-7-2)				
Control Blocks (see IEC 61850-7-2)				
Inherited and specialised from Logical Node class (see IEC 61850-7-2)				
Services (see IEC 61850-7-2)				
Inherited and specialised from Logical Node class (see IEC 61850-7-2)				

4.7 Development of new logical node

The new logical nodes were developed using XML Marker software and AcSELerator Architect software. First, the SEL standard IED Capability Description (ICD) file is extracted, exported and saved in a general directory or folder using the AcSELerator Architect software. The SEL standard ICD file is edited using the XML Marker software. New logical node are added to the SEL standard ICD file in line with the IEC 61850-7 standard as discussed in 4.3, 4.3 and 4.6 of this thesis. The edited file with new logical nodes is then saved in the same folder with a different name and

imported back to AcSELerator Architect software as a new ICD. 4.7.1 to 4.7.3 discuss the development of new logical nodes also shown in the form of flowchart in Figure 4.4

Export SEL standard IED Capability Description (ICD) file using AcSELerator Architect software and save in a general folder.

Edit the SEL standard IED Capability Description (ICD) file using XML Marker Software by adding new logical nodes and save with a different name in the same folder

Import the edited IED Capability Description (ICD) file using AcSELerator Architect software and save with a different name.

The new ICD file is now ready to be configured to produce the Configured IED Description (CID) file which is used for testing 3 terminal alpha plane differential protection characteristic

Figure 4.4: Flowchart of new logical nodes development

4.7.1 SEL standard Logical devices

The vendor, SEL has its standard Logical Devices in AcESLerator Architect palette as shown in Figure 4.5. The IED Palette provides a source of IED files to add to a project, to export and import ICD files. To configure GOOSE messages through the use of Architect software, an engineer copies and pastes graphical objects representing IEDs from the IED Palette into a project and then accesses the properties of the selected IED for either outgoing or incoming GOOSE messages.

IED Palette

SEL_2411	SEL_2414	SEL_2440	SEL_311C
SEL_311L	SEL_351	SEL_351A	SEL_351RS
SEL_351S	SEL_3530	SEL_387E	SEL_411L
SEL_421	SEL_451	SEL_487B	SEL_487E
SEL_487V	SEL_700G	SEL_710	SEL_751
SEL_751A	SEL_787		

Select IED to add to the project
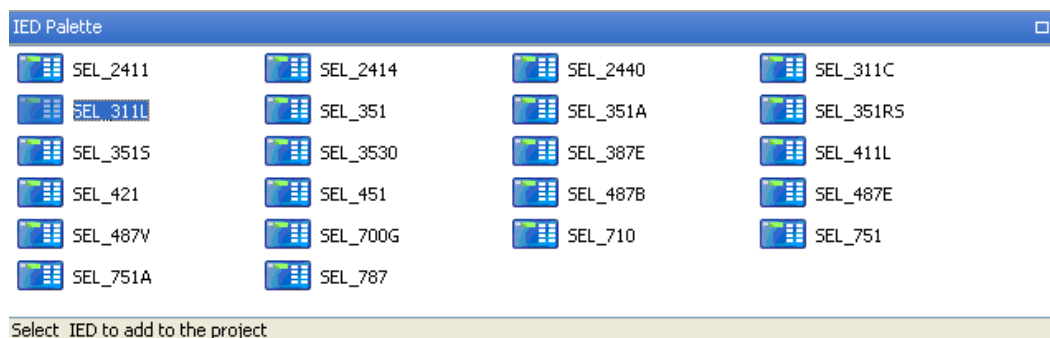
Figure 4.5: SEL standard Logical Devices in AcESLerator Architect software

SEL-311L Standard Logical Device does not have PDIF Differential Logical Node with Restraint elements as shown on Figure 4.6, only the operate Elements are available.

These operate elements are PRO.D87LPDIF1.Op.phsA, PRO.D87LPDIF1.Op.phsB, PRO.D87LPDIF1.Op.phsC, PRO.D87LPDIF1.Op.neut, PRO.D87LPDIF1.Op.neg as shown on Figure 4.6.
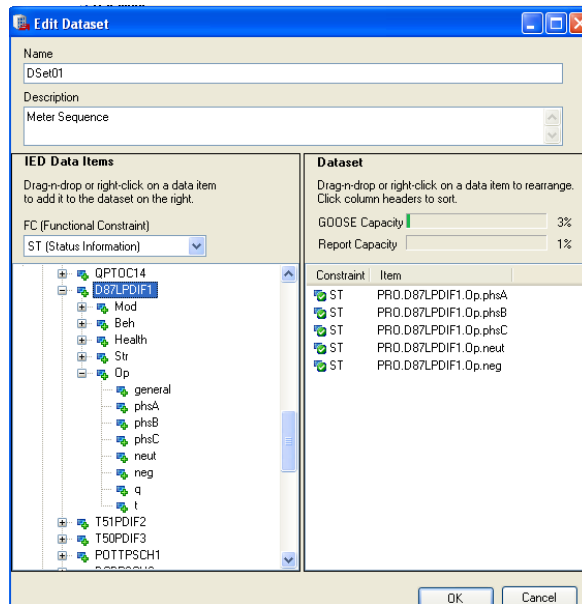
Figure 4.6: SEL standard Logical Devices in AcESLerator Architect software

4.7.2 Development of PDIF Logical Node with Restraint Elements

To model a SEL 311L IED PDIF Logical Node with restraint elements, first the standard SEL 311L ICD file is exported from the palette using AcSELerator Architect software and renamed as 'SEL-311L with restraint elements - R411 and Higher' in this case as shown on Figure 4.7
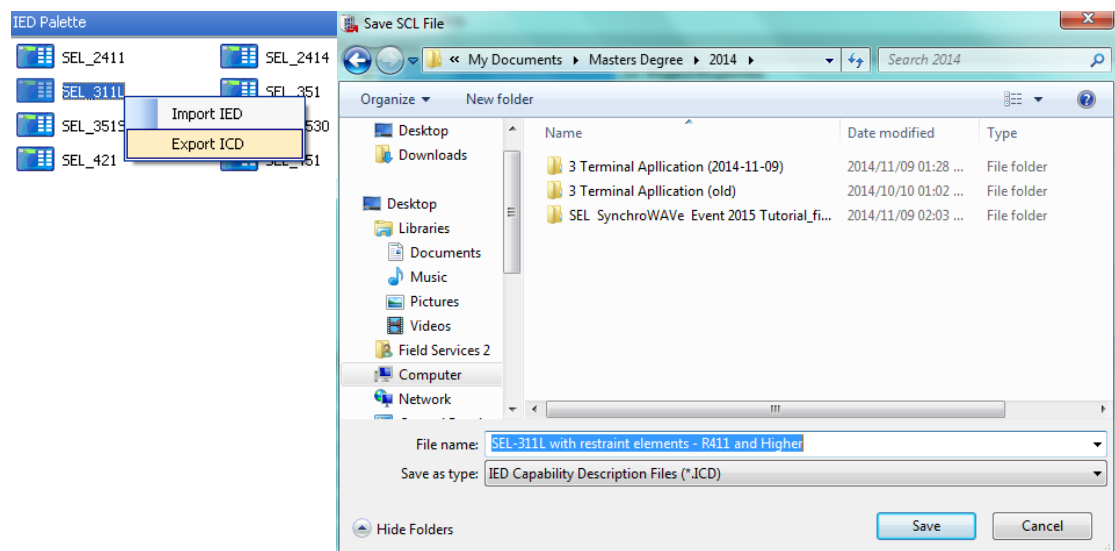
Figure 4.7: Exporting of standard ICD file

This SEL 311L ICD file is then edited using XML Marker. In XML marker language, SEL Configuration Language (SCL) is the root element, IED is the child element and AccessPoint, Server, Ldevice, LN, DOI and DAI are the subchild elements as shown in Figures 4.8 and 4.9. The SEL standard structure consisting of root, child and subchild elements was maintained.

Figure 4.8: XML Marker Language
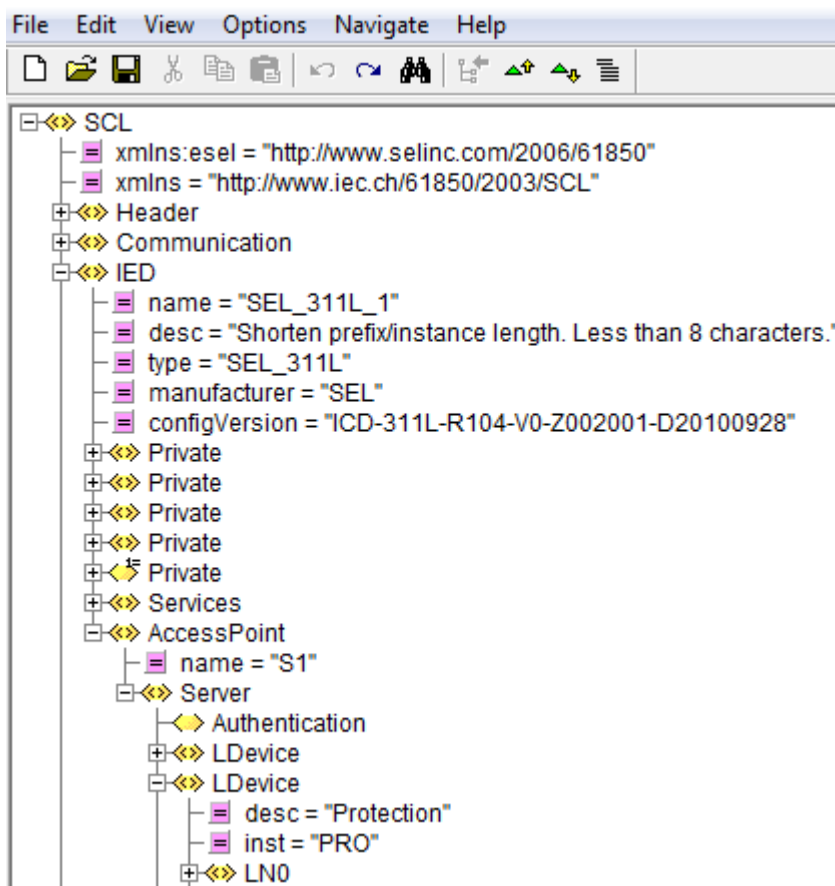
Figure 4.9: SEL standard structure consisting of root, child and subchild elements

Based on the IEC61850-7-4 guidelines outlined in this chapter, using XML Marker, the Logical Node Type, Class Instance and Prefix was defined as shown from Figure 4.10 to Figure 4.19.

```
<LN lnType="PDIF1" lnClass="PDIF" inst="4" prefix="R87L">
```

Figure 4.10: Logical Node Type, Class Instance and Prefix description

Further, the mandatory and optional Logical Node information is defined as shown on Figure 4.11 to Figure 4.16 in line with common logical node class in Table 4.2.

```
<DOI name="Mod">
   <DAI esel:datasrc="db:E3_001?5:1" name="stVal"/>
   <DAI esel:datasrc="db:E3_001" name="q"/>
   <DAI esel:datasrc="imm" name="ctlModel">
      <Val>0</Val>
   </DAI>
</DOI>
```

Figure 4.11: Mode: consisting of Status Value, Quality and Control Model data attributes.

```
<DOI name="Health">
   <DAI esel:datasrc="db:E3_001?3:1" name="stVal"/>
   <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 4.12: Health: consisting of Status Value and Quality data attributes.

```
<DOI name="Beh">
   <DAI esel:datasrc="db:E3_001?5:1" name="stVal"/>
   <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 4.13: Behaviour: consisting of Status Value and Quality data attributes.

```
<DOI name="NamPlt">
   <DAI esel:datasrc="imm" name="vendor">
      <Val>SEL</Val>
   </DAI>
   <DAI esel:datasrc="dbi:FID" name="swRev"/>
   <DAI esel:datasrc="imm" name="configRev">
      <Val>0</Val>
   </DAI>
   <DAI esel:datasrc="imm" name="d">
      <Val>Protection</Val>
   </DAI>
</DOI>
```

Figure 4.14: Nameplate: consisting of Vendor swRev and configRev and description data attributes.

```xml
<DOI name="Str">
    <DAI esel:datasrc="db:E3_008" name="general"/>
    <DAI esel:datasrc="imm" name="dirGeneral">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:R87LA" name="phsA"/>
    <DAI esel:datasrc="imm" name="dirPhsA">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:R87LB" name="phsB"/>
    <DAI esel:datasrc="imm" name="dirPhsB">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:R87LC" name="phsC"/>
    <DAI esel:datasrc="imm" name="dirPhsC">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:R87LG" name="neut"/>
    <DAI esel:datasrc="imm" name="dirNeut">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:87L2" name="neg"/>
    <DAI esel:datasrc="imm" name="dirNeg">
        <Val>1</Val>
    </DAI>
    <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 4.15: Start: consisting of restraint elements General, Directional General, Phase A, Directional Phase A, Phase B, Directional Phase B, Phase C, Directional Phase C, Neutral, Directional Neutral, Negative Sequence, Directional Negative and Quality data attributes.

```xml
<DOI name="Op">
    <DAI esel:datasrc="db:E3_008" name="general"/>
    <DAI esel:datasrc="db:R87LA" name="phsA"/>
    <DAI esel:datasrc="db:R87LB" name="phsB"/>
    <DAI esel:datasrc="db:R87LC" name="phsC"/>
    <DAI esel:datasrc="db:R87LG" name="neut"/>
    <DAI esel:datasrc="db:R87L2" name="neg"/>
    <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 4.16: Operate: consisting of restraint elements General, Phase A, Phase B, Phase C, Neutral, Negative Sequence, and Quality data attributes.

Figure 4.17 and Figure 4.18 show the information of enabling logics including the newly developed restraint elements in E3_008 logic and complete logical nodes for restraint elements.
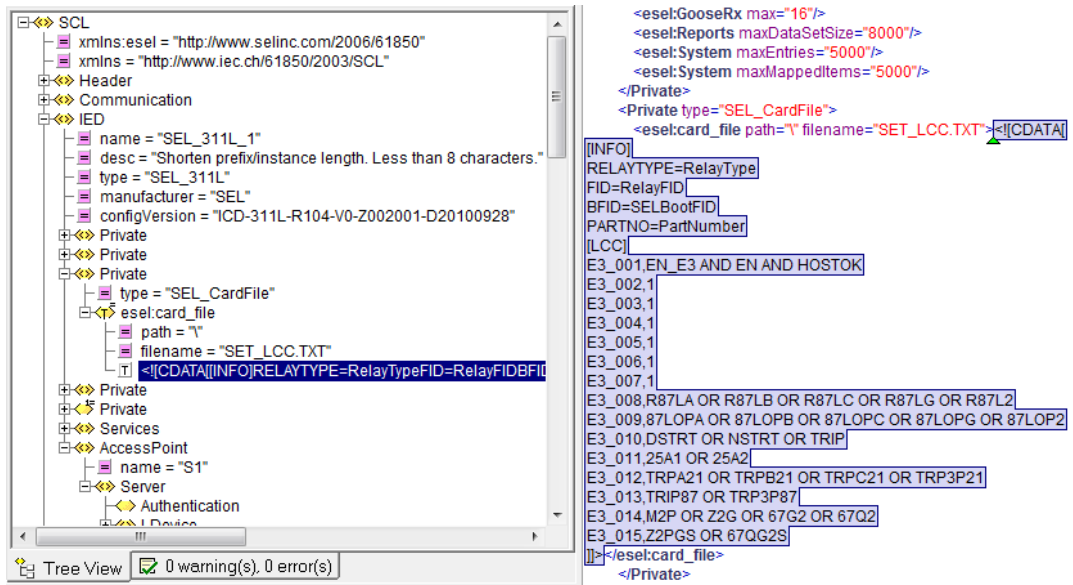
Figure 4.17: Information tab for additional enabling logic E3_008
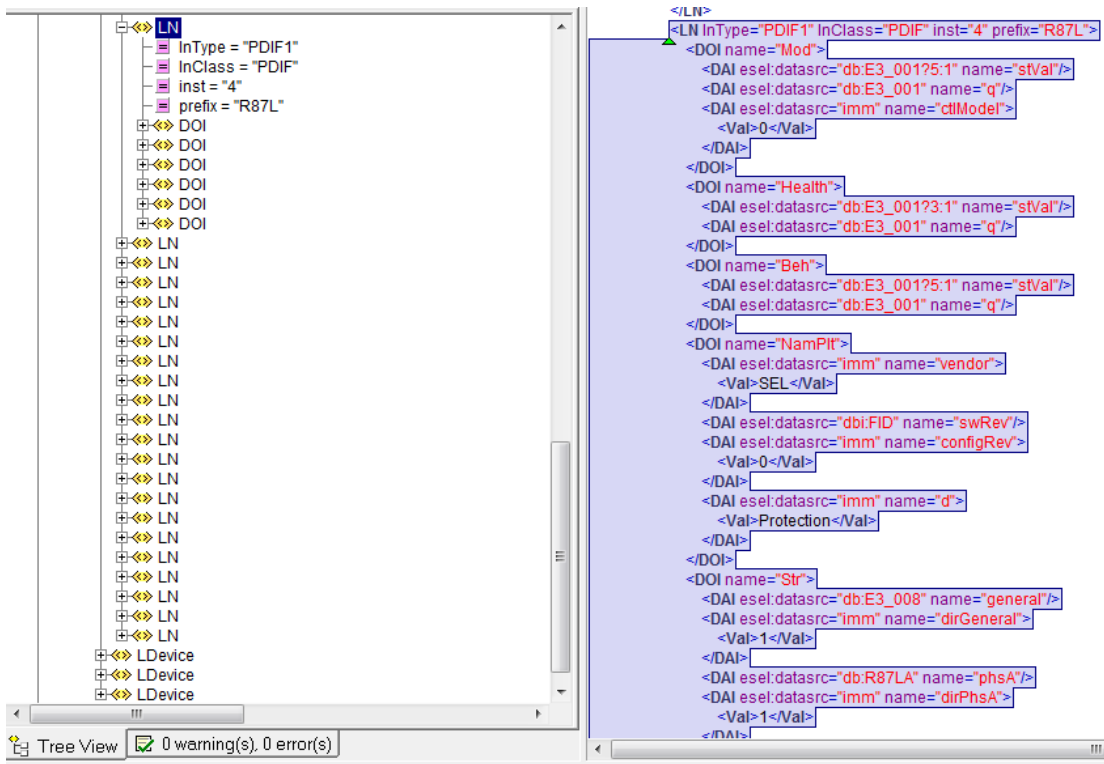
Figure 4.18: Edited ICD file with new logical nodes

4.7.3   Importing and configuration of newly developed ICD file

The new model of SEL 311L relay ICD file has now been developed. This model is now imported as a new SEL 311L relay ICD file into the AcSELerator Architect palette as a new SEL311L with restraint elements as its name implies as shown on Figure 4.19. The CID file is then configured using AcSELerator Architect software to develop the CID file with newly developed logical nodes for restraint elements. Once

developed, the CID file is then tested in conjunction with the 3 terminal alpha plane characteristic as discussed in 4.8 and chapter 6.
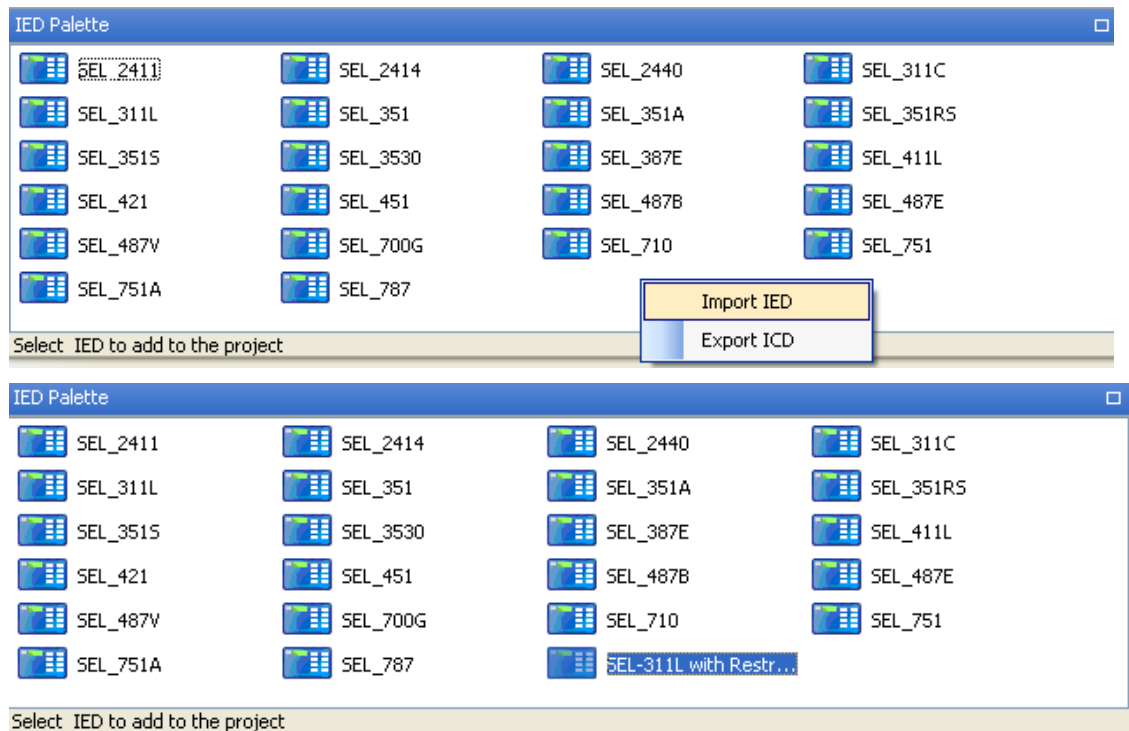
Figure 4.19: New SEL 311L IED into the AcSELerator Architect palette

Figure 4.20 shows the newly developed restrain elements in PDIF logical node. These restraint elements are;

- Red Phase restraint element (PRO.R87LPDIF4.Op.phsA)
- White Phase restraint element (PRO.R87LPDIF4.Op.phsB)
- Blue Phase restraint element (PRO.R87LPDIF4.Op.phsC)
- Zero sequence restraint element (PRO.R87LPDIF4.Op.neut)
- Negative sequence restraint element (PRO.R87LPDIF4.Op.neg)
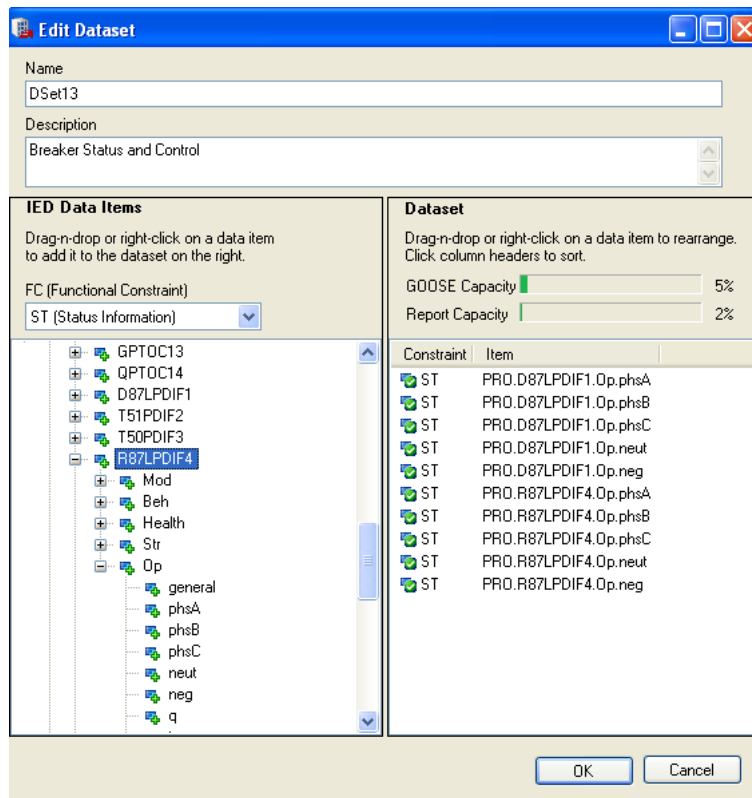
Figure 4.20: Newly developed logical nodes with restraint elements

4.8 Configuration of the IEDs and OMICRON devices

Once the CID file is developed, it is necessary to test it to prove its functionality. First the CID file is exported from AcSELerator Architect software and saved in a general folder. This file is then imported to OMICRON Test Universe software to configure the CMC test equipment or test set. The same file is also uploaded or sent to the respective SEL 311L relays. This is done to ensure that the test set is able to subscribe the messages published by the relays. The test set will inject fault currents into the relays and subscribe to messages published by the relays. One test set is used to inject two relays and the second test set is used to inject the third relay. The two test sets are then synchronized to inject fault currents simultaneously. Testing of the logical nodes is presented in chapter 6.

4.8.1 IED configuration

Testing of the new CID file was done using OMICRON Test Universe software and CMC test set hardware which is simply referred to as 'Test Set' for the remainder of this document. The OMICRON Test Universe was the ideal software for testing this new IED model as it has been designed for testing protection and measurement devices by both utilities and manufacturers. It consists of state-of-the-art hardware and user-friendly Windows-based software and provides complete flexibility and adaptability to different testing applications.

The flexibility is provided in the diverse software packages, while the adaptability is achieved in how the components of a software package can be combined and utilized. Each software package contains a selection of function-oriented test modules. The test modules can operate stand-alone for single tests or be "embedded" with other modules into a Control Centre test document (a test plan) for complete, multi-functional tests. One of Test Universe function-oriented test modules is Generic Object Oriented Substation Events (GOOSE) Configuration module.

The GOOSE Configuration module sets up test set with the NET-1 option to send and receive GOOSE messages. GOOSE messages are events that are directly embedded into the data packets transmitted via Ethernet in the substation network.

OMICRON has integrated the GOOSE features into the test set in a way that the status information in the messages on the network are mapped to the binary inputs and outputs of the test set. The same ten binary inputs and eight binary outputs, which are used by most of OMICRON's test modules, are available for the GOOSE mapping.

The mapping of operate and restraint elements GOOSE messages from the CID file to the test set binary inputs is performed via the GOOSE Configuration module and is kept completely outside of the other test modules.

The operate and restraint signals are subscribed and used for testing the protection function. Figure 4.21 shows the example of a relay publishing the Red phase differential protection operated element (PRO.PDIF87L1.Op.phsA) GOOSE message and the test set subscribing to this message mapping it to binary input 1
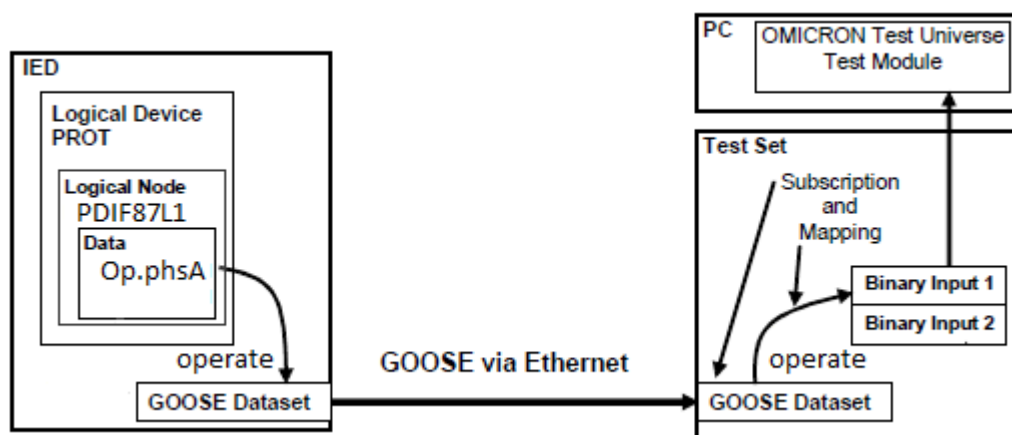
Figure 4.21: **Publishing and subscription of operate element**

Figure 4.22 shows the example of a relay publishing the Red phase differential protection restraint element (PRO.R87LPDIF4.Op.phsA) GOOSE message and the test set subscribing to this message, mapping it to binary input 2.
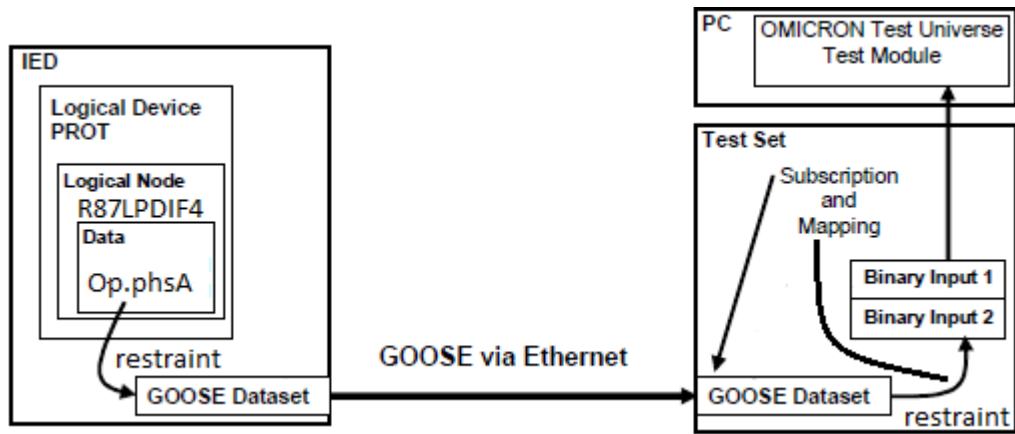
Figure 4.22: Publishing and subscription of restraint element

Figure 4.23 shows the test bench setup with two test sets synchronized via IRIGB, connected to an Ethernet switch and protection relays which are also inter-connected with fibre optic cables for differential protection communication purpose.

One PC is used to control both test sets and communicates with all three relays.
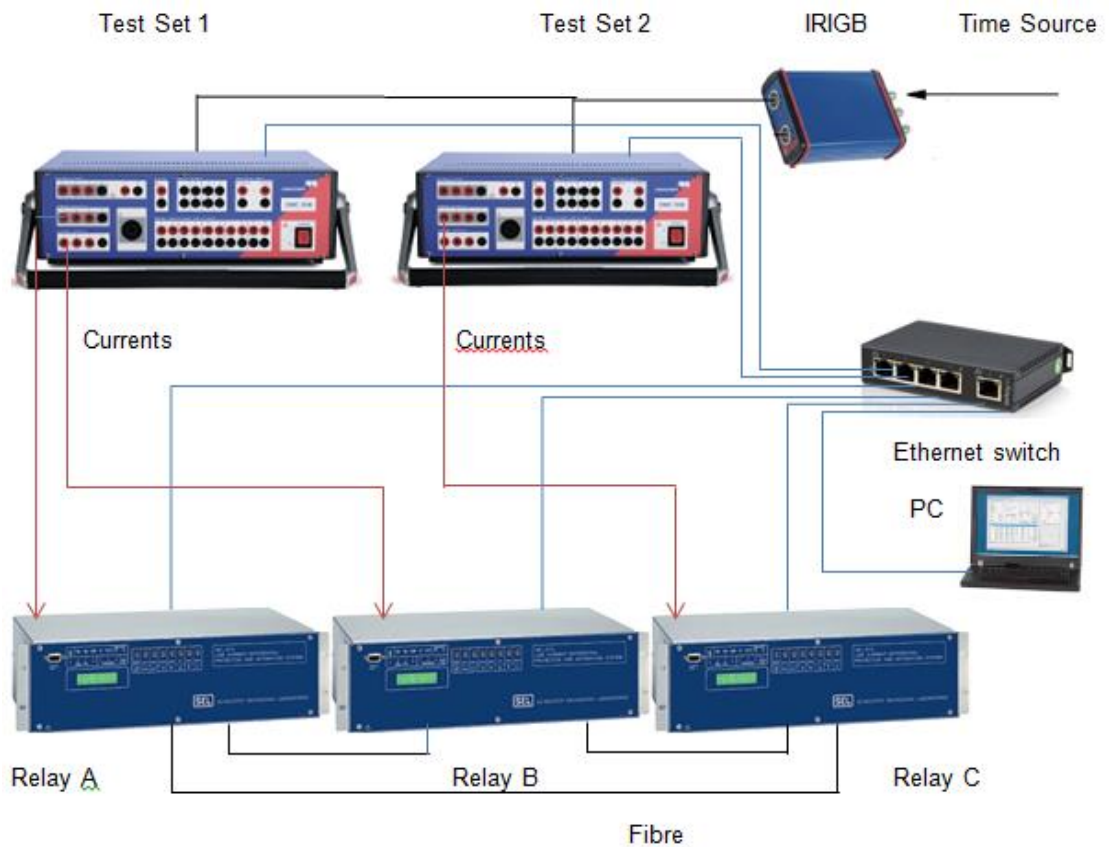
Figure 4.23: Test-bench setup

The IED contains (among other logical devices) a logical device "PRO", which serves as a container for all protection-related sub functions (logical nodes). One of these

logical nodes is given by "D87LPDIF1 and R87LPDIF4" of the type 87L (differential Protection), which contains data such as the Operate and Restraint information.

These data are mapped in the relay into the dataset which is sent out with the published GOOSE messages.

The test set subscribes to these GOOSE messages and maps the data items from the received dataset to binary inputs of the test set. This is accomplished by the GOOSE Configuration module. All further processing in the protection testing (Test Modules of the OMICRON Test Universe) refers to these mapped binary inputs.

IEDs were configured to publish operate and restraint information GOOSE messages using AcSELerator Architect. The AcSELerator Architect software provides a Microsoft Windows -compatible Graphical User Interface (GUI) with which engineers can select, edit, and create IEC 61850 reports and GOOSE messages for the design and commissioning of IEC 61850 substations containing SEL intelligent electronic devices (IEDs).

The AcSELerator Architect can be used to:
- Organize and configure all SEL IEDs in a substation project
- Configure incoming and outgoing Generic Object Oriented Substation Event (GOOSE) messages
- Read non-SEL IED Capability Description (ICD) and Configured IED Description (CID) files and determine the available IEC 61850 messaging options
- Load device settings and IEC 61850 Configured IED Description (CID) files into SEL IEDs
- Generate ICD files that will provide SEL IED descriptions to other manufacturers' tools so that these tools can use SEL GOOSE messages and reporting features
- Configure protection, logic, control, and communication settings of all SEL IEDs in the substation. The IEDs were added to a project. Since only two IED Relay A and relay B) were IEC 61850 compliant, the two IEDs were configured through the use of properties, configuration of GOOSE receive and transmit messages, and configuration of datasets (dataset 13 in this case) as shown in Figure 4.24
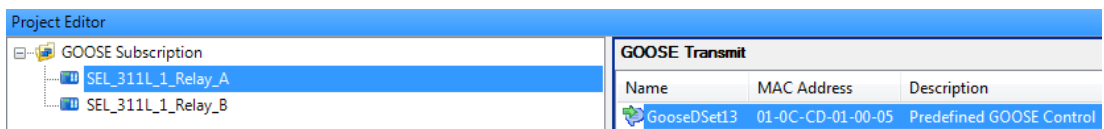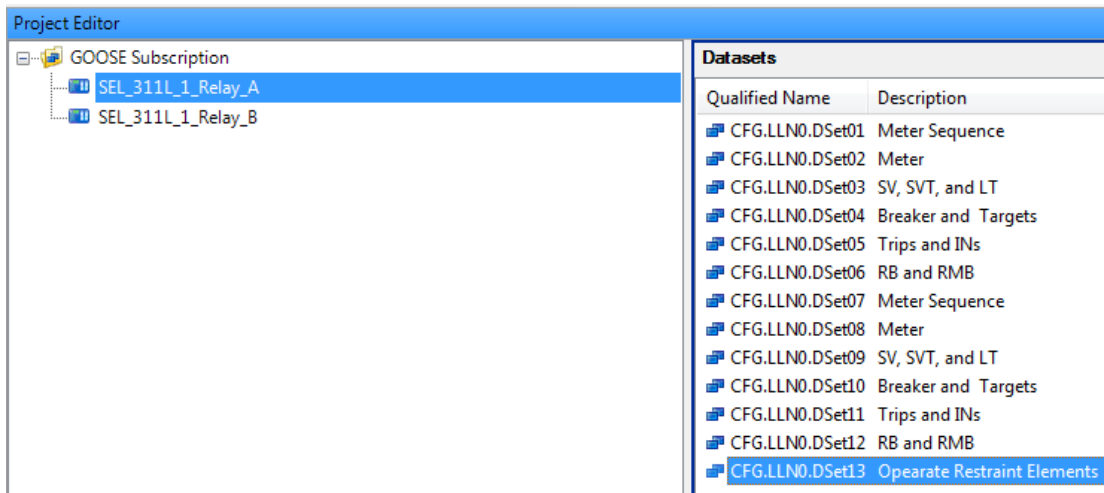
Figure 4.24: Dataset 13 for relay A similar to relay B

Dataset 13 is then configured to publish the following elements as shown on Figure 4.25.

- Red Phase operate element (PRO.D87LPDIF1.Op.phsA)
- White Phase operate element (PRO.D87LPDIF1.Op.phsB)
- Blue Phase operate element (PRO.D87LPDIF1.Op.phsC)
- Zero sequence operate element (PRO.D87LPDIF1.Op.neut)
- Negative sequence operate element (PRO.D87LPDIF1.Op.neg.)
- Red Phase restraint element (PRO.R87LPDIF4.Op.phsA)
- White Phase restraint element (PRO.R87LPDIF4.Op.phsB)
- Blue Phase restraint element (PRO.R87LPDIF4.Op.phsC)
- Zero sequence restraint element (PRO.R87LPDIF4.Op.neut)
- Negative sequence restraint element (PRO.R87LPDIF4.Op.neg)
- General trip element (PRO.TRPPTRC1.Tr.general)
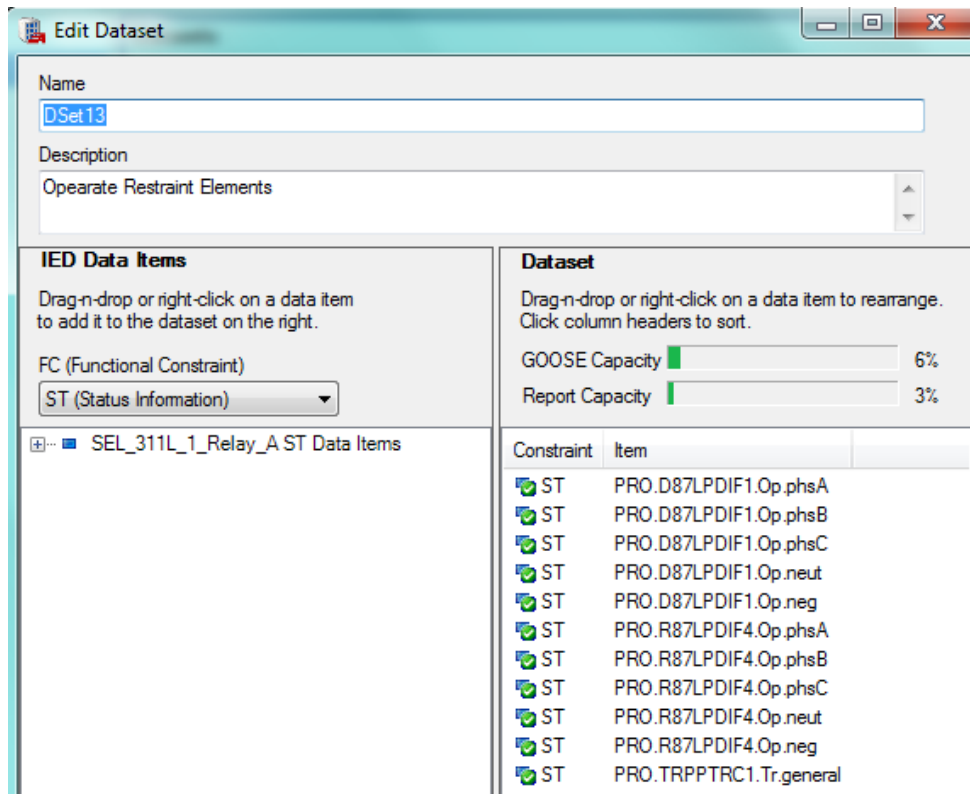
Figure 4.25: Published operate and restraint elements as well as general trip

Following the ICD configuration, the resulting configuration (port settings and CID files) was transferred to SEL IEDs via File Transfer Protocol (FTP) as shown in the following Figure 4.26. AcSELerator Architect software was used to transfer the CID file to the relays. IED Settings are discussed in chapter 5.
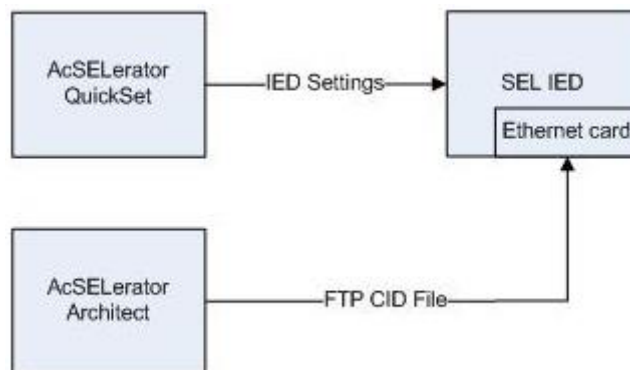
Figure 4.26: CID file and setting transfer to the relay

Figure 4.27 shows CID file transfer to the relay using AcSELerator Architect software. Only relay A is shown, the principle applies to relay B as well. Due to availability of resources, relay C was not IEC 61850 compatible otherwise the same process would apply to the third relay.
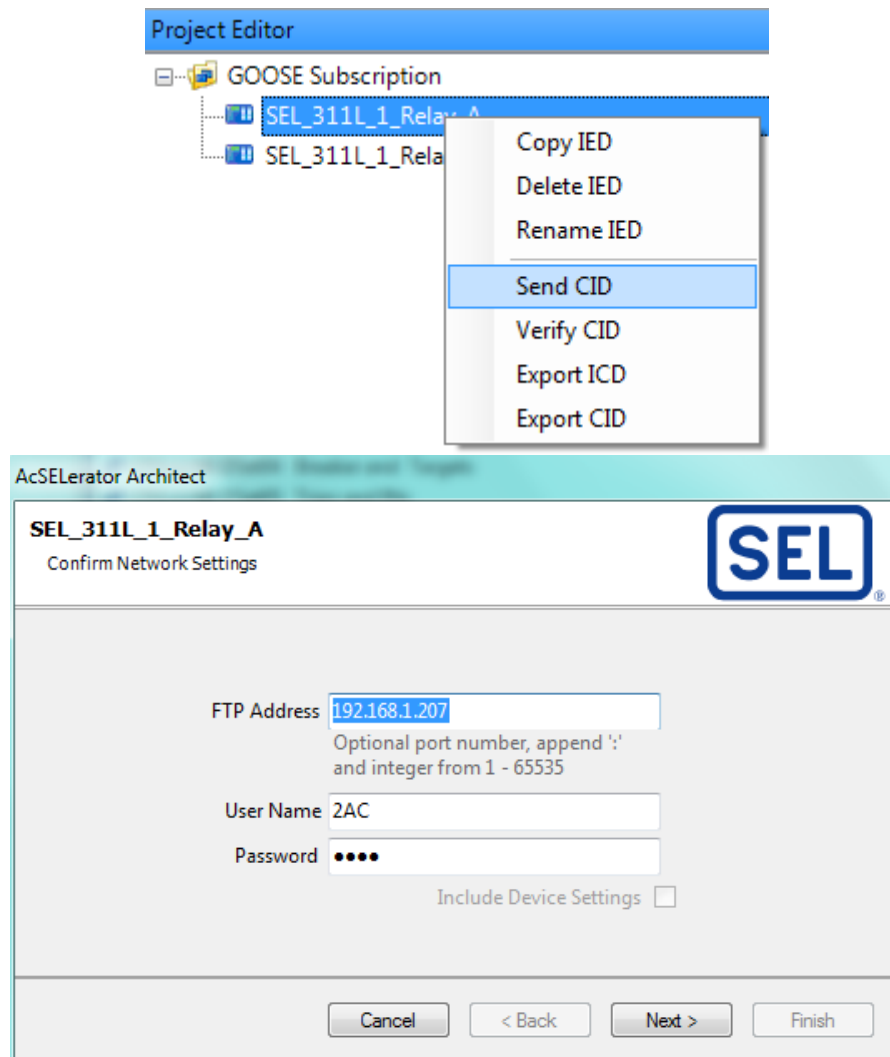
Figure 4.27: Transfer of CID file to relay A

4.8.2 Test set configuration

Figure 4.27 indicates the workflow of the four basic methods to configure the test set. The test set can be configured using:

• The SCL file from the engineering process (system configurator)

• An SCL file created from the IED's self-description

• Online GOOSE sniffing

• Manual configuration of the subscription

In this case the test set was configured using SCL file from the engineering process (system configurator) as shown with notification 1 in Figure 4.28 This method assumes that an SCL file is available. An SCL file was created from a system configuration tool during the engineering process.
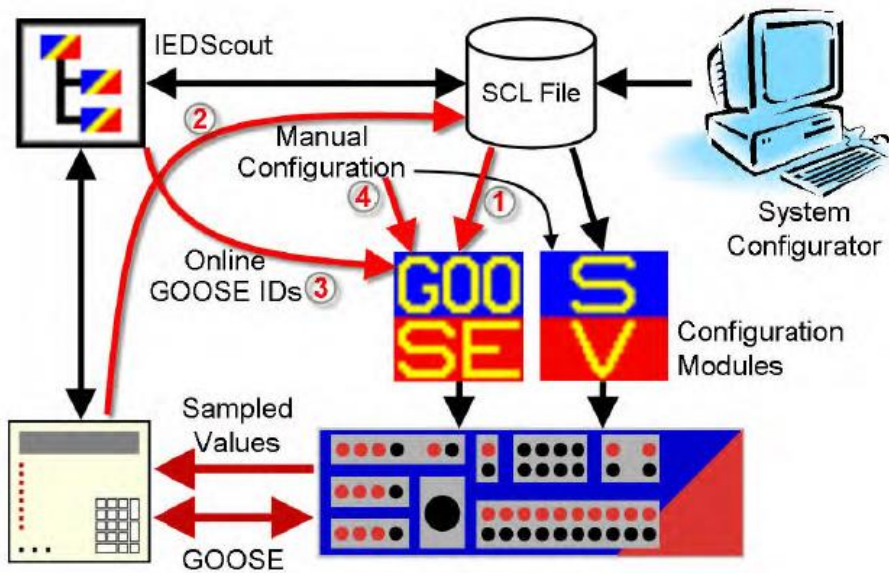
Figure 4.28: Workflow to configure the test set

Using GOOSE Configuration module the SCL-file was imported by selecting 'File' - 'Import Configuration as shown in Figure 4.29. The SCL-file is parsed and all contained GOOSE definitions are offered in a further dialog. This way, all configured GOOSEs from the SCL-file are added in the GOOSE Configuration module without any typing.
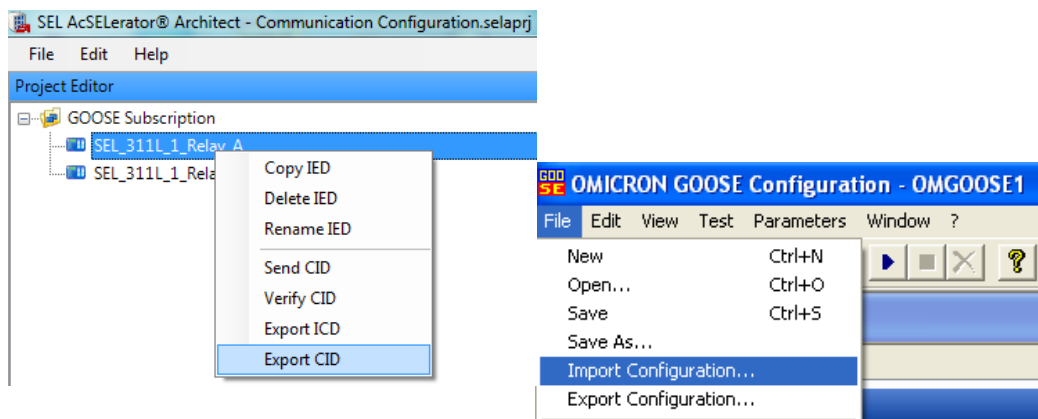
Figure 4.29: Importing of CID file to configure the test set using GOOSE configuration module

The GOOSE messages are then individually selected for subscription. GOOSE messages are mapped to respective input of the test set as shown in Figure 4.30.
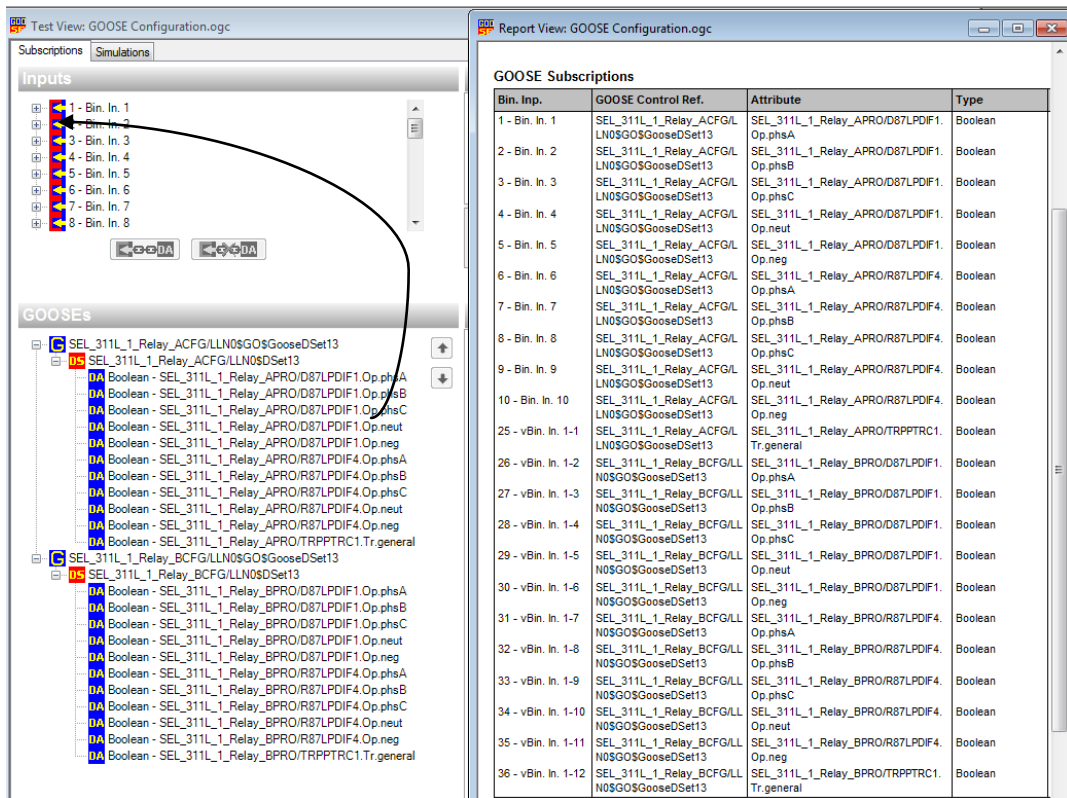
Figure 4.30: Mapping data from the GOOSE to binary inputs of the test set

After the SCL file has been imported, the GOOSEs have to be mapped to the binary inputs of the Test Set. The binary input to be mapped is selected and the data item from the received GOOSE is moved by Drag & Drop to this input. This action is repeated until all mappings have been established.

The test set provides ten binary inputs and up to 360 virtual inputs for the mapping. The mapped data can come from up to 128 subscribed GOOSE messages on Figure 2.30.

By pressing the start button in GOOSE configuration module in Test Universe sofware, the GOOSE configuration is transferred to the test set.

The progress bar indicates the progress of the configuration process. The "Test State" indicates if the new configuration could be successfully applied which in this case was indicated as successful.

4.9   Conclusion

Overview of IEC 61850-7-4 standard as guidelines applicable to the development of PDIF logical Node is presented in in this chapter. Brief description of XML Marker program functions used in modelling the SEL 311L Intelligent Electronic Device (IED) is discussed.

59

The standard SEL 311L relay model is presented and analysed. Using the standard model of IED Configuration Description file (ICD), restraint elements for Phase A, Phase B, Phase C, Zero Sequence and Negative sequence are developed. Because testing of restraint elements is only possible on fully functional differential protection, this requires setting up of all differential functions in the relays which is done in chapter 5.

Testing of the newly developed Logical Nodes with restraint elements is done in chapter 6 in conjunction with evaluation of newly developed test method for 3 terminal alpha plane differential protection characteristic.

CHAPTER FIVE

ENGINEERING PROCESS FOR SEL311L CONFIGURATION

5.1   Introduction

Due to the availability of resources, SEL-311L relays with different nominal currents were used for this research. Two relays were rated at 1 Amp nominal current and the third relay was rated at 5 Amp nominal current. This chapter demonstrates the proper current transformer ration (CTR_X), differential protection pickup (87LPP), negative sequence protection pickup (87L2P), and zero sequence protection pickup (87LGP) settings adjustments when using SEL-311L Relays with different nominal currents for line differential protection (a 5 A relay on one end of the transmission line and a 1 A relay on the other end of the line). The principle is discussed for 2 terminal application and is also applicable on 3 terminal application. After the adjusted settings are entered, both relays report the correct primary currents and the local and remote currents are on the appropriate base to assert or deassert the differential protection operate elements (87LOPn). Differential protection settings parameters and communication channel interface are discussed.

The points that are covered in the chapter are: Part 5.2 describes the element settings for compensated current transformer ratio, part 5.3 details the relay settings parameters, part 5.4 shows SEL311L communication settings 5.5 gives the Conclusion.

5.2   SEL-311L Element settings

Each SEL-311L allows the user to enter the local current transformer ratio (CTR) and the remote CTR (the CTR and CTR_X settings, respectively). To obtain primary currents, the local current is multiplied by CTR, while the remote (Channel X) current is multiplied by CTR_X. Then each of these currents is divided by the maximum CTR (CTRmax) to obtain the local and remote secondary currents referenced to CTRmax. The addition of these two currents is the difference current (see Figure 5.1).
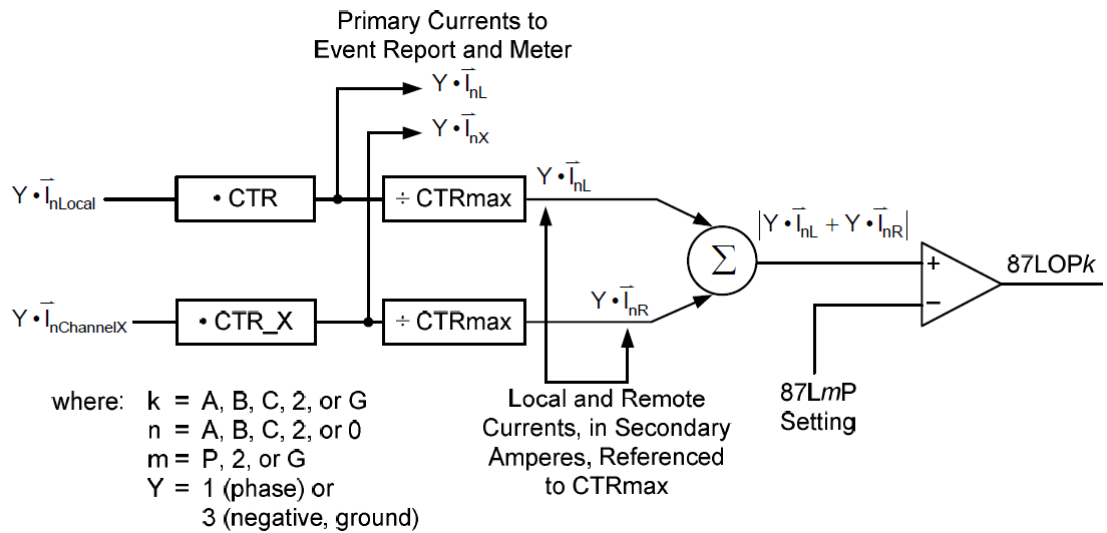
Figure 5.1: Phase, negative sequence and ground differential elements processing for channel X

The SEL-311L compares the difference level current 87LmP settings (where m = P for A-, B-, and C-phase, 2 for negative-sequence, or G for zero-sequence differential) with the difference current in secondary amperes. The comparison allows the relay to decide to assert or deassert the various differential operate 87LOPk elements (where k = A for A-phase, B for B-phase, C for C-phase, 2 for negative-sequence, or G for zero-sequence differential).

In a two-terminal application, local current is sent through the Tx channel, is received by the Rx channel of the remote relay, and becomes the Channel X current of the remote relay. The current is transmitted in per unit, using the nominal current of the sending relay as the base. This current is then converted by the receiving relay to secondary amperes using its own base. This presents a problem with an application where two relays are rated at 5 A and 1 A. The 5 A relay divides its transmitted (local) current by 5 and multiplies its received (Channel X) current by 5, while the 1 A relay divides its transmitted current by 1 and multiplies its received current by 1, as shown in Figure 5.2.
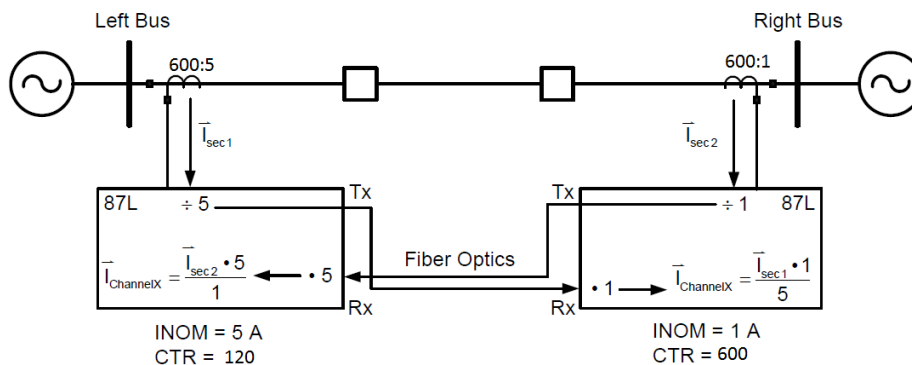
Figure 5.2: Two-terminal relay application with different nominal current ratings

62

In the example in Figure 5.3, if 3,000 A flow from the left bus to the right bus, the left relay receives 5A secondary current while the right relay receives 0.75A secondary current. These currents are then converted to per unit and sent to the opposite relay, resulting in Channel X values of 3.75A secondary current and 1A secondary current at the left and right relays, respectively.
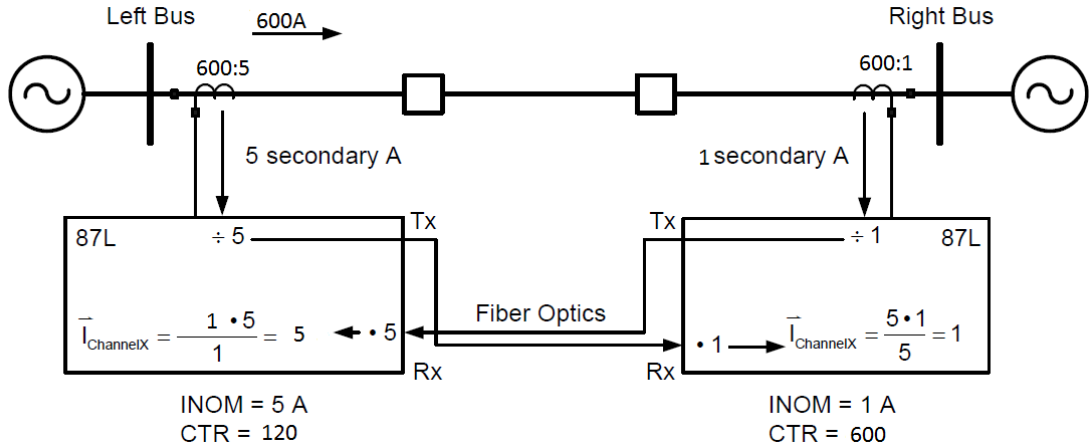
Figure 5.3: Two-Terminal Application With 600 A Flowing Through the Line

If the traditional approach is followed and the values of 600 and 120 are selected for CTR_X in the left and right relays in Figure 5.3, respectively, the left relay will process 600 A as the Channel X current (5 times more than expected), while the right relay will process 120A as the Channel X current (5 times less than expected). This is shown in Figure 5.4.
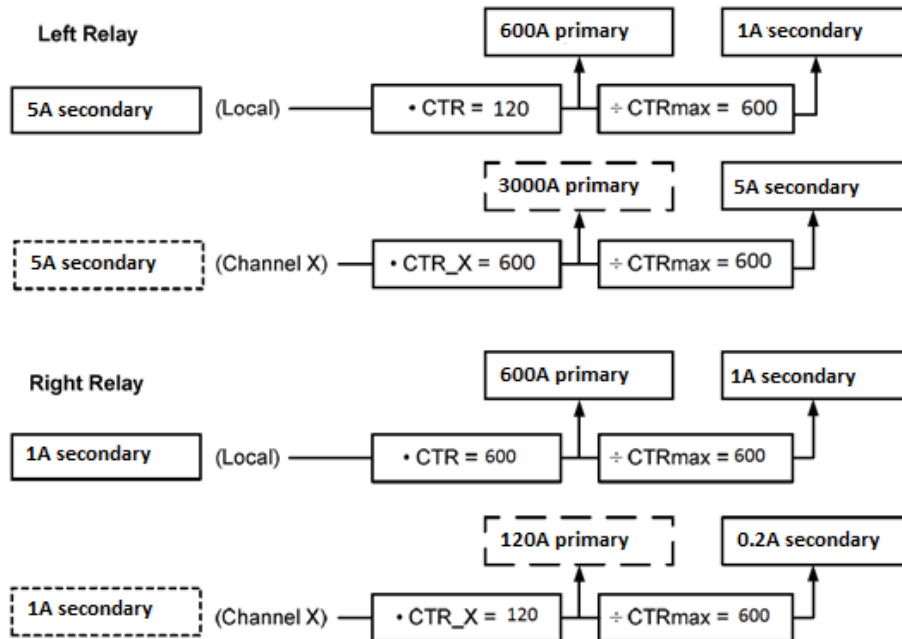
Figure 5.4: Local and channel X currents processed by the left and right relays with CTR_X uncompensated

This mismatch happens because of the following:

- The left relay divides its transmitted current by 5. When the current is received by the right relay, it is multiplied by 1.
- The right relay divides its transmitted current by 5. When the current is received by the left relay, it is multiplied by 5.
- The following compensation is needed:
- Because the left relay receives a Channel X current that is 5 times higher than expected, its original CTR_X needs to be divided by 5. In Figure 5.3, set CTR_X in the left relay to 3000/5 = 600.
- Because the right relay receives a Channel X current that is 5 times lower than expected, its original CTR_X needs to be multiplied by 5. In Figure 5.3, set CTR_X in the right relay to 600 • 5 = 3000.

These settings are shown in Table 5.1 for CTR_X compensation for current transfer and receive correction. This new approach results in correct primary current calculations by both relays.

Table 5.1: CTR_X Compensation for current transfer and receive correction

	Left Relay (5A)	Right Relay (1A)
Ratio	600:5	600:1
CTR	120	600
Compensated CTR_X	3000/5	600*5=3000

After the CTR_X compensation is made, the correct primary value (600 A) is calculated, as shown in Figure 5.5. However, the CTRmax at the left relay (CTRmax = 600) is now 5 times smaller than at the right relay (CTRmax = 3000). Therefore, the current in secondary amperes at the left relay (5 A) is 5 times larger than at the right relay (1 A).
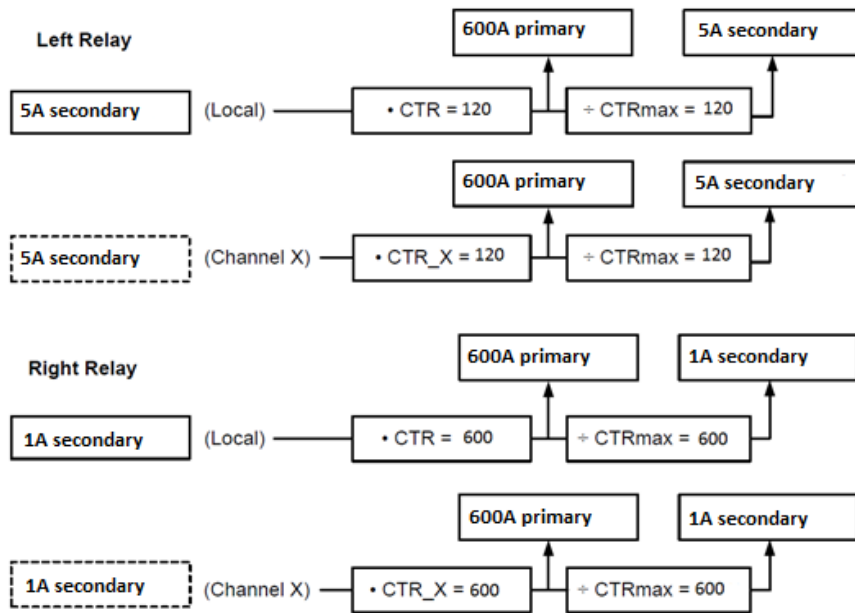
Figure 5.5: Local and channel X currents processed by the left and right relays with CTR_X compensated

If an A-phase-to-ground fault happens in the Figure 5.5 example, the left relay will process the logic shown in Figure 5.1 with a resulting secondary difference current of 10A, as shown in Figure 5.6. Because the 87LPP setting is 6, the Relay Word bit 87LOPA in the left relay will assert. The logic processed in the right relay is also shown in Figure 5.6, yielding a secondary difference current of 2 A. Because the 87LPP setting is 1.2, the Relay Word bit 87LOPA in the right relay will assert.
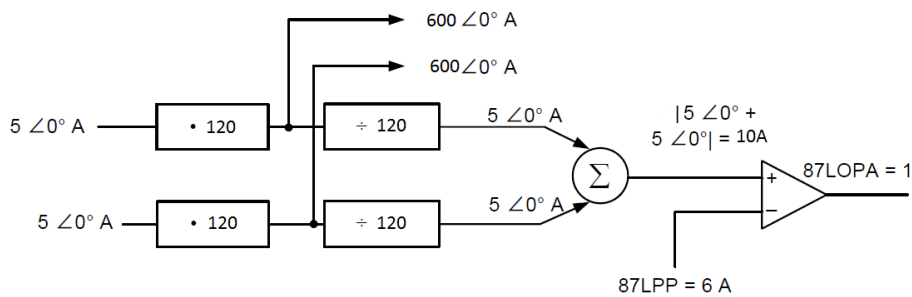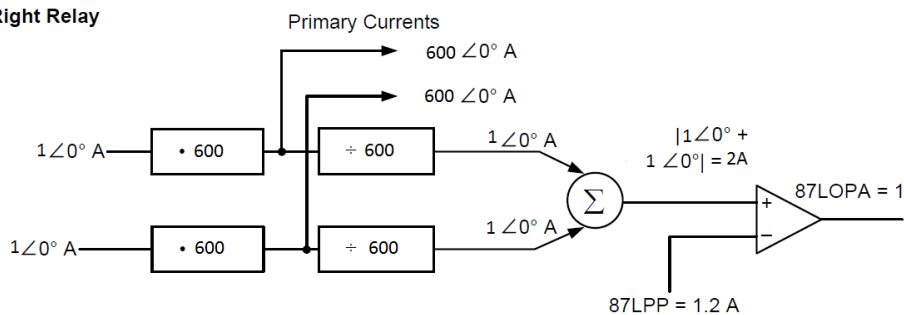
Figure 5.6: Secondary difference currents in the left and right relays

The difference current in primary amperes required to assert 87LOPk is obtained using the following equation:

Difference Current = 87LmP •CTRmax   (5.1)

In this example, 87LmP is five times larger in the left relay than in the right relay. However, CTRmax is five times larger in the right relay than in the left relay. Because of this inverse relationship, the difference current in primary amperes required to assert 87LOPk is the same in both relays. Table 5.2 shows the primary phase difference current, and Table 5.3 shows the primary negative- and zero-sequence current for this example.

Table 5.2: **Primary phase difference current**

	87LPP	CTRmax	Difference Current
Left Relay	6	120	720A
Right Relay	1.2	600	720A

Table 5.3: **Primary negative and zero sequence current**

	87LPP	CTRmax	Difference Current
Left Relay	0.5	120	60A
Right Relay	0.1	600	60A

The same principle applies to the 3 terminal application as shown on Figure 5.7.
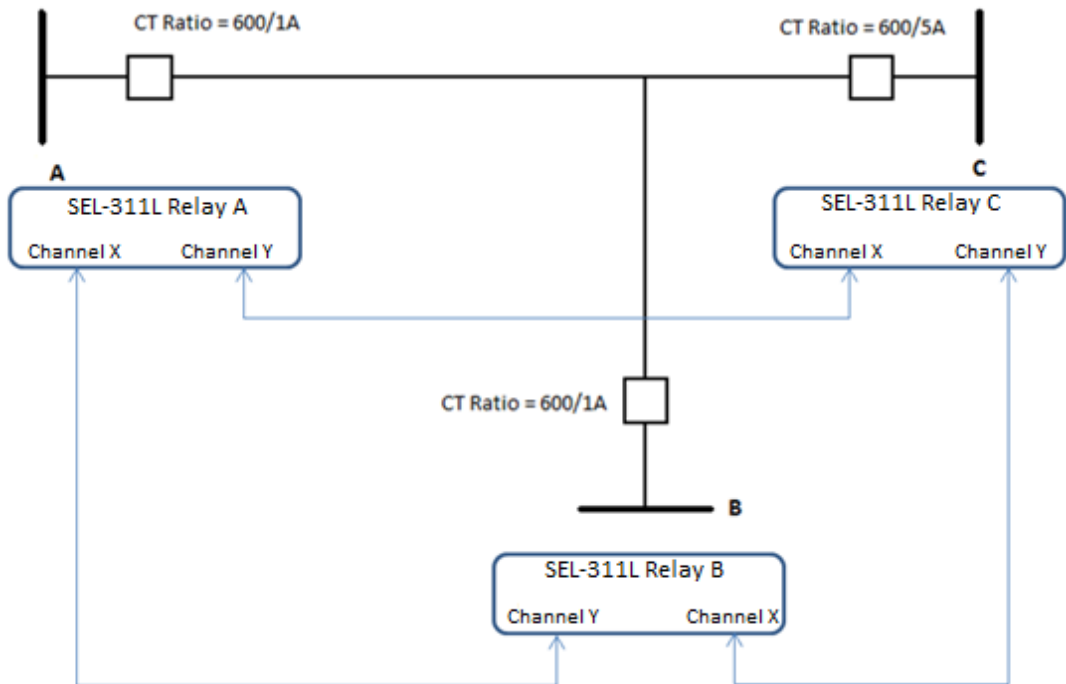
Figure 5.7: **3 terminal application using relays with different nominal currents**

5.3   Settings parameters

To apply these settings and other settings parameters to the relays, AcSElerator Quickset software was used. AcSELerator Quickset Software is a tool used to design, deploy, and manage devices for power system protection, control, metering, and monitoring. Quickset has smart drivers that automatically verify if settings are within an acceptable range. For this purpose, SEL311L settings driver was installed.

General settings for relay A was set as shown on Figure 5.8 with relay identifier set to SEL-311L A, local current transformer ratio (CTR) set to 600 as discussed and application set to 311L for differential protection.

Figure 5.8: Relay A general settings including local CT ratio

Further, the line current differential protection setting was set as shown on Figure 5.9 Number of terminals was set to 3 for 3 terminal transmission line protection, CTR at terminal connected to channel X and Y set to 600, channel X transmit and receive address set to 1 and 2 respectively as well as channel Y transmit and receive address set to 3 and 4 respectively.

Figure 5.9: Relay A line current differential settings including remote CT ratios

The differential protection (87L) pickup settings are set as shown on Figure 5.10. Phase differential protection pickup (87LPP) was set to 1.2A, negative sequence protection pickup (87L2P) set to 0.1A, zero sequence protection pickup (87LGP) set to 0.1A, alpha plane restraint region outer radius (87LR) set to 6 and the alpha plane restraint region angle (87LANG) set to 195 degrees.

Figure 5.10: Relay A 87L settings

General settings for relay B was set as shown on Figure 5.11 with relay identifier set to SEL-311L B, local current transformer ratio (CTR) set to 600 as discussed and application set to 311L for differential protection.

Figure 5.11: Relay B general settings including local CT ratio

The line current differential protection setting for relay B are shown on Figure 5.12 Number of terminals was set to 3 for 3 terminal transmission line protection, CTR at terminal connected to channel X and Y set to 600, channel X transmit and receive address set to 5 and 6 respectively as well as channel Y transmit and receive address set to 2 and 1 respectively.

Line Current Differential Settings

Line Current Differential Configuration Settings

E87L Number of 87L Terminals
3   Select: 2, 3, 3R, N

EHST High Speed Tripping
N   Select: 1-6, N

EHSDTT Enable High Speed Direct Transfer Trip
N   Select: Y, N

EDD Enable Disturbance Detect
N   Select: Y, N

ETAP Tapped Load Coordination
N   Select: Y, N

EOCTL Enable Open CT Logic
N   Select: Y, N

PCHAN Primary 87L Channel
Y   Select: X, Y

EHSC Hot-Standby Channel Feature
N   Select: Y, N

CTR_X CTR at Terminal Connected to Channel X
600   Range = 1 to 6000

TA_X Channel X Transmit Address
1   Select: 1-16

RA_X Channel X Receive Address
2   Select: 1-16

CTR_Y CTR at Terminal Connected to Channel Y
600   Range = 1 to 6000

TA_Y Channel Y Transmit Address
3   Select: 1-16

RA_Y Channel Y Receive Address
4   Select: 1-16

Figure 5.12: Relay B line current differential settings including remote CT ratios

The differential protection (87L) pickup settings are set as shown on Figure 5.13. Phase differential protection pickup (87LPP) was set to 1.2A, negative sequence protection pickup (87L2P) set to 0.1A, zero sequence protection pickup (87LGP) set to 0.1A, alpha plane restraint region outer radius (87LR) set to 6 and the alpha plane restraint region angle (87LANG) set to 195 degrees.

87L Settings

Minimum Difference Current Enable Level Settings

87LPP Phase 87L (Amps secondary)

1.20   Range = 0.20 to 2.00, OFF

87L2P 3I2 Negative-Sequence 87L (Amps secondary)

0.10   Range = 0.10 to 1.00, OFF

87LGP Ground 87L (Amps secondary)

0.10   Range = 0.10 to 1.00, OFF

CTALRM Ph. Diff. Current Alarm Pickup (Amps secondary)

0.10   Range = 0.10 to 2.00

Restraint Region Characteristic Settings

87LR Outer Radius

6.0   Range = 2.0 to 8.0

87LANG Angle (degrees)

195   Range = 90 to 270

Figure 5.13: Relay B 87L settings

General settings for relay C are shown on Figure 5.14 with relay identifier set to SEL-311L C, local current transformer ratio (CTR) set to 120 as discussed and application set to 311L for differential protection.

General Settings

Relay Identifier Labels

RID Relay Identifier (30 chars)

SEL-311L C

TID Terminal Identifier (30 chars)

311L STUDY

Current Transformer Ratio and Application Settings

CTR Local Phase (IA,IB,IC) CT Ratio, CTR:1

120   Range = 1 to 6000

APP Application

311L   Select: 87L, 87L21, 87L21P, 311L

EADVS Advanced Settings Enable

Y   Select: Y, N

Figure 5.14: Relay C general settings including local CT ratio

The line current differential protection setting for relay C are shown on Figure 5.15 Number of terminals was set to 3 for 3 terminal transmission line protection, CTR at terminal connected to channel X and Y set to 120, channel X transmit and receive address set to 4and 3 respectively as well as channel Y transmit and receive address set to 6 and 5 respectively.

Figure 5.15: **Relay C line current differential settings including remote CT ratios**

The differential protection (87L) pickup settings are shown on Figure 5.16. Phase differential protection pickup (87LPP) was set to 6A, negative sequence protection pickup (87L2P) set to 0.5A, zero sequence protection pickup (87LGP) set to 0.5A, alpha plane restraint region outer radius (87LR) set to 6 and the alpha plane restraint region angle (87LANG) set to 195 degrees.

Figure 5.16: Relay C 87L settings

5.4 SEL-311L communication Settings

The SEL-311L Relay provides:

- Line current differential communications
- Communications with EIA-232 and EIA-485 serial ports
- Communications with Ethernet ports

For the purpose of this project, only line current differential protection communication and communication with Ethernet ports are discussed as these are the two methods applicable in development of new logical nodes as well as the new test method for 3 terminal differential protection. These two methods of communication are discussed in 5.4.2 and 5.4.3 respectively.

5.4.1   Line current differential communications

A communications interface and protocol are required for communicating with the relay. A communications interface is the physical connection on a device. A communications protocol is a language used to perform operations and collect data.

The relays have two line current differential interfaces. Each interface is factory configured as one of the following:

- EIA-422 (Electronic Industries communication standard)
- CCITT G.703(Comité Consultatif International Téléphonique et Télégraphique)
- IEEE Standard C37.94 850nm Multimode Fibre-Optic
- Interface
- IEEE Standard C37.94 Modulated 1300nm Single-mode Fibre-Optic Interface
- 1300 nm Single or Multimode Fibre-Optic Interface
- 1550 nm Single-mode Direct Fibre-Optic Interface

Channel configuration settings support optimization of the interface for the channel in a particular application. For this research, IEEE Standard C37.94 850nm Multimode fibre-Optic was used. IEEE Standard C37.94 defines a direct relay-to-multiplexer interface over inexpensive multimode fibre-optic cable. This prevents problems associated with grounding electrical interfaces. It also provides excellent noise immunity. The Standard defines the data structure and encoding, and also defines the physical interface (ST connector, 850nm light wavelength, 50 or 62μm multimode fibre) ensuring that all C37.94 compliant relays interface with all C37.94 compliant multiplexers.

The SEL-311L is available with two options that are based on the IEEE C37.94 interface. The first option uses the interface as defined by the IEEE standard, i.e. ST connector, 850nm wavelength, and 50 or 62μm multimode fibre. The second option uses the data structure and encoding defined by C37.94, as well as ST connectors, but uses a 1300 nm wavelength, and 9μm single-mode fibre. The first option was used in this application.

The IEEE C37.94 interface is suitable for distances up to 2 km (850 nm multimode fibre) or 15 km (1300 nm single-mode fibre) either between the relay and the multiplexer or directly between relays. For longer haul direct fibre applications using multimode or single-mode fibre, the 1300 nm or 1500 nm fibre-optic interfaces is used. The relays were connected back-to-back with direct fibre in a lab environment as shown on Figure 5.17 to implement the three terminal scheme.
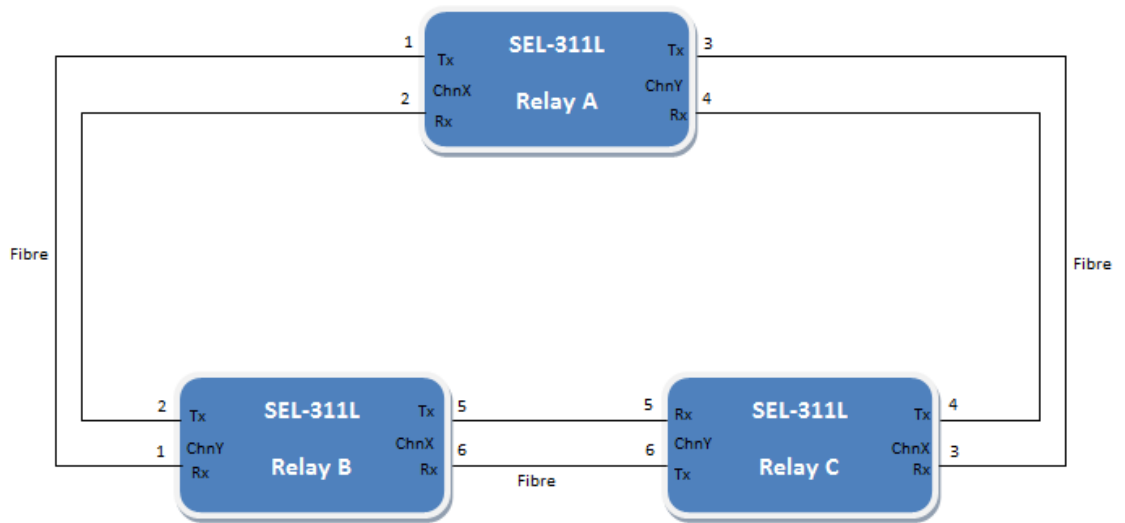
Figure 5.17: Line current differential communication channel connections for the 3 terminal protection scheme

5.4.2 Line current differential communication channel settings

For secure communication between the relays, the following settings were made.

Timing source for channel X (TIMRX) was set to external (E) and Timing source for channel Y (TIMRY) set to external (E) in one relay, and TIMRX = internal (I) and TIMRY = I for Channel Y in the other relay. The relay with TIMRY = E synchronizes to the relay with setting TIMRY = I, providing error free operation.

Address checking function for communication channels X and Y on all relays was also enabled by setting address check (EADDCX) and EADDCY to Y respectively. Transmitted messages contain an address field. When EADDCX = Y, the transmitting relay places the address defined by channel X transmit address setting (TA_X) or setting TA_Y for Channel Y in the transmitted message. The receiving relay checks to ensure that the address contained in the message matches the local channel X receive address (RA_X) setting or RA_Y setting for Channel Y. If the received address does not match the receive address setting, the relay discards the message as if it were corrupted.

Address checking serves two purposes;

- The first purpose is to avoid misoperations due to inadvertent loopbacks in the network or multiplexer equipment. An inadvertent loopback might also occur if light from a fibre optic transmitter reflects off a surface and returns to a receiver. To effectively detect inadvertent loopbacks, set RA_X different than TA_X.

- The second purpose is to avoid misoperations due to misrouted communications links.

Channel loss monitoring function was also used, by setting channel X continuous drop out alarm (RBADXP) and channel X packet loss alarm (AVAXP) (RBADYP and AVAYP for Channel Y) together detectS channel loss and degradation. When no acceptable packets have been received for longer than setting RBADXP (in seconds), Relay Word bit RBADX asserts. This asserts channel X alarm Relay Word bit (CHXAL) and illuminates front-panel LED 87CH FAIL. When the number of packets corrupted or lost from the previous 10,000 packets exceeds setting AVAXP, channel X packet loss Relay Word bit (AVAX) asserts. This asserts Relay Word bit CHXAL, and illuminates front-panel LED 87CH FAIL. Together, AVAXP and RBADXP detect short-term interruptions and long term degradation of the communications circuit. After the problem is repaired, Relay Word bit AVAX resets itself in less than 15 seconds, and RBADX resets itself instantly. Settings AVAYP and RBADYP and Relay Word bits AVAY and RBADY operate the same for Channel Y.

Channel delays monitoring function was used for secured data exchange. Setting channels X one way channel delay alarm (DBADXP) (DBADYP for Channel Y) detects longer than expected channel delays. Such increased delays might be caused by channel reroutes on a switched network. When the estimated one-way channel delay exceeds setting DBADXP (in milliseconds), channel X one way channel delay Relay Word bit (DBADX) asserts. This asserts Relay Word bit CHXAL, and illuminates front-panel LED 87CH FAIL.

These settings were applied to the respective using AcSELerator Quickset software. Figure 5.18 shows relay A channel X communication settings as follows:

- EADDCX   = Y
- TA_X   = 1
- RA_X   = 2
- RDBAXP   = 1
- AVAXP   = 10
- DBADXP   = 10
- TIMRX   = I

Figure 5.18: Relay A communication channel X settings

Figure 5.19 shows relay A channel Y communication settings as follows:

- EADDCY   = Y
- TA_Y   = 3
- RA_Y   = 4
- RDBAYP   = 1
- AVAYP   = 10
- DBADYP   = 10
- TIMRY   = E

Figure 5.19: Relay A communication channel Y settings

Figure 5.20 shows relay B channel X communication settings as follows

- EADDCX   = Y
- TA_X   = 5
- RA_X   = 6
- RDBAXP   = 1
- AVAXP   = 10
- DBADXP   = 10
- TIMRX   = I

Channel X

EADDCX Channel X Address Check
Y   Select: Y, G, N

TA_X Channel X Transmit Address
5   Select: 1-16

RA_X Channel X Receive Address
6   Select: 1-16

RBADXP Continuous Dropout Alarm (Seconds)
1   Range = 1 to 1000

AVAXP Packets Lost in Last 10,000 Alarm
10   Range = 1 to 5000

DBADXP One Way Channel Delay Alarm (msec.)
10   Range = 1 to 24

RC422X RS422 Receive Clock Edge (R=Rising, F=Falling)
R   Select: R, F

TC422X RS422 Transmit Clock Edge (R=Rising, F=Falling)
R   Select: R, F

TIMRX Timing Source (I=Internal, E=External)
I   Select: I, E

Figure 5.20: Relay B communication channel X settings

Figure 5.21 shows relay B channel Y communication settings as follows:

- EADDCY   = Y
- TA_Y   = 2
- RA_Y   = 1
- RDBAYP   = 1
- AVAYP   = 10
- DBADYP   = 10
- TIMRY   = E

Figure 5.21: Relay B communication channel Y settings

Figure 5.22 shows relay C channel X communication settings as follows

- EADDCX   = Y
- TA_X   = 4
- RA_X   = 3
- RDBAXP   = 1
- AVAXP   = 10
- DBADXP   = 10
- TIMRX   = I

Figure 5.22: Relay C communication channel X settings

Figure 5.23 shows relay C channel Y communication settings as follows:

- EADDCY = Y
- TA_Y = 6
- RA_Y = 5
- RDBAYP = 1
- AVAYP = 10
- DBADYP = 10
- TIMRY = E

Figure 5.23: Relay C communication channel Y settings

5.4.3 Ethernet Interfaces

Ethernet interface is one of the methods of communication applied in this project. It is used as a communication interface between relays and test equipment, relays and a computer as well as computer and test equipment.

The SEL-311L provides optional dual failover Ethernet ports with two physical layer options. Both ports (Port 5 and Port 6) are configured with Port 5 settings. The physical layer options are the following:

- Two 10/100BASE-T ports that support 10/100 Mbps rates on RJ-45 connectors
- Two 100BASE-FX ports that support 100 Mbps rates on LC connectors

The SEL-311L is optionally equipped with two 100BASE-TX copper or 100BASE-FX fibre-optic Ethernet ports. The two Ethernet ports are used in redundant network architectures. The relay can use a single Ethernet port even though it is equipped with two ports. For this research, the following settings were made to configure the relays in redundant Ethernet network on failover mode using the internal failover switch to connect the relay to redundant networks as shown in Figure 5.24.
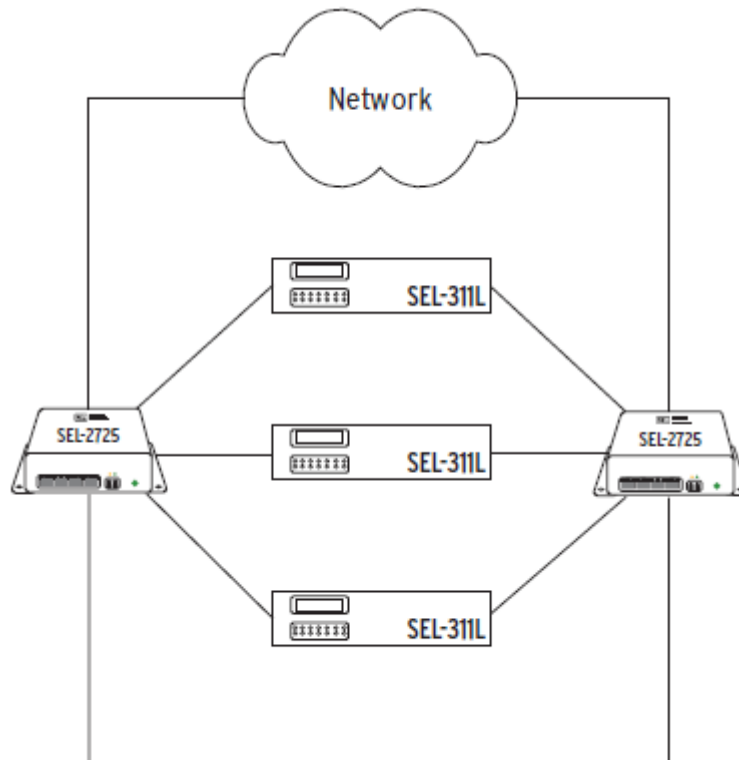
Figure 5.24: **Failover network topology**

Figure 5.25 shows the Ethernet settings for relay A as follows;

- IPADDR   = 192.168.1.207 (IP Address)
- SUBNETM   = 255.255.255.0 (subnet ask)
- DERRTR   = 192.168.1.1 (default router)
- ETCPKA   = Y (enable TCP keep alive)
- KAIDLE   = 10 sec (TCP keep alive idle range)
- KAINTV   = 1sec (TCP keep alive interval range)
- KACNT   = 6 sec (TCP keep alive count range)
- NETMODE   = FAILOVER (operating mode)
- FTIME   = 0.1sec (fail over time out)
- E61850   = Y (enable IEC 61850 protocol)
- EGSE   = Y (enable IEC 61850 GSE)

Ethernet Settings

Ethernet IP Addresses

IPADDR IP Address (xxx.xxx.xxx.xxx)

192.168.1.207

SUBNETM Subnet Mask (xxx.xxx.xxx.xxx)

255.255.255.0

DEFRTR Default Router (xxx.xxx.xxx.xxx)

192.168.1.1

TCP Keep-Alive Settings

ETCPKA Enable TCP Keep-Alive (Y,N)

Y   Select: Y, N

KAIDLE TCP Keep-Alive Idle Range (1-20 s)

10   Range = 1 to 20

KAINTV TCP Keep-Alive Interval Range (1-20 s)

1   Range = 1 to 20

KACNT TCP Keep-Alive Count Range (1-20 s)

6   Range = 1 to 20

NETMODE Settings

NETMODE Operating Mode (FIXED, FAILOVER)

FAILOVER   Select: FIXED, FAILOVER

FTIME Failover Time-out (OFF, 0.10-65.00 sec)

0.10   Range = 0.10 to 65.00, OFF

IEC 61850 Settings

E61850 Enable IEC 61850 Protocol (Y,N)

Y   Select: Y, N

EGSE Enable IEC 61850 GSE (Y,N)

Y   Select: Y, N

Figure 5.25: Relay A Ethernet settings

Figure 5.26 shows the Ethernet setting for relay B as follows;

- IPADDR   = 192.168.1.208 (IP Address)
- SUBNETM   = 255.255.255.0 (subnet ask)
- DERRTR   = 192.168.1.1 (default router)
- ETCPKA   = Y (enable TCP keep alive)
- KAIDLE   = 10 sec (TCP keep alive idle range)
- KAINTV   = 1sec (TCP keep alive interval range)

- KACNT = 6 sec (TCP keep alive count range)
- NETMODE = FAILOVER (operating mode)
- FTIME = 0.1sec (fail over time out)
- E61850 = Y (enable IEC 61850 protocol)
- EGSE = Y (enable IEC 61850 GSE)

Ethernet Settings

Ethernet IP Addresses

IPADDR IP Address (xxx.xxx.xxx.xxx)
192.168.1.208

SUBNETM Subnet Mask (xxx.xxx.xxx.xxx)
255.255.255.0

DEFRTR Default Router (xxx.xxx.xxx.xxx)
192.168.1.1

TCP Keep-Alive Settings

ETCPKA Enable TCP Keep-Alive (Y,N)
Y   Select: Y, N

KAIDLE TCP Keep-Alive Idle Range (1-20 s)
10   Range = 1 to 20

KAINTV TCP Keep-Alive Interval Range (1-20 s)
1   Range = 1 to 20

KACNT TCP Keep-Alive Count Range (1-20 s)
6   Range = 1 to 20

NETMODE Settings

NETMODE Operating Mode (FIXED, FAILOVER)
FAILOVER   Select: FIXED, FAILOVER

FTIME Failover Time-out (OFF, 0.10-65.00 sec)
0.10   Range = 0.10 to 65.00, OFF

IEC 61850 Settings

E61850 Enable IEC 61850 Protocol (Y,N)
Y   Select: Y, N

EGSE Enable IEC 61850 GSE (Y,N)
Y   Select: Y, N

Figure 5.26: Relay B Ethernet settings

Figure 5.27 shows the typical Ethernet setting for relay C as follows;

- IPADDR = 192.168.1.209 (IP Address)
- SUBNETM = 255.255.255.0 (subnet ask)

- DERRTR   = 192.168.1.1 (default router)
- ETCPKA   = Y (enable TCP keep alive)
- KAIDLE   = 10 sec (TCP keep alive idle range)
- KAINTV   = 1sec (TCP keep alive interval range)
- KACNT   = 6 sec (TCP keep alive count range)
- NETMODE   = FAILOVER (operating mode)
- FTIME   = 0.1sec (fail over time out)
- E61850   = Y (enable IEC 61850 protocol)
- EGSE   = Y (enable IEC 61850 GSE)

Ethernet Settings

Ethernet IP Addresses

IPADDR IP Address (xxx.xxx.xxx.xxx)

192.168.1.209

SUBNETM Subnet Mask (xxx.xxx.xxx.xxx)

255.255.255.0

DEFRTR Default Router (xxx.xxx.xxx.xxx)

192.168.1.1

TCP Keep-Alive Settings

ETCPKA Enable TCP Keep-Alive (Y,N)

Y   ▼   Select: Y, N

KAIDLE TCP Keep-Alive Idle Range (1-20 s)

10   Range = 1 to 20

KAINTV TCP Keep-Alive Interval Range (1-20 s)

1   Range = 1 to 20

KACNT TCP Keep-Alive Count Range (1-20 s)

6   Range = 1 to 20

NETMODE Settings

NETMODE Operating Mode (FIXED, FAILOVER)

FAILOVER   ▼   Select: FIXED, FAILOVER

FTIME Failover Time-out (OFF, 0.10-65.00 sec)

0.10   Range = 0.10 to 65.00, OFF

IEC 61850 Settings

E61850 Enable IEC 61850 Protocol (Y,N)

Y   ▼   Select: Y, N

EGSE Enable IEC 61850 GSE (Y,N)

Y   ▼   Select: Y, N

Figure 5.27: Relay C Ethernet settings

86

On start up the relays communicate using Port 5. If any relay detects a link failure on Port 5, and the link status on Port 6 is healthy, the relay activates Port 6 after time FTIME. If the link status on Port 5 returns to normal before time FTIME, the failover timer resets and operation continues on Port 5. Setting FTIME = OFF allows fast port switching (with no intentional delay). Fast port switching can occur within one processing interval (typically 4 ms to 5 ms) and can help with IEC 61850 GOOSE performance. After failover, while communicating via Port 6, if the relay detects a link failure on Port 6, and the link status on Port 5 is healthy, the relay activates Port 5 after time FTIME.

Differential protection and communication settings parameters were transferred to SEL IEDs as shown in the following Figure 5.28. AcSELerator Quickset software was used to transfer the settings to the relays.
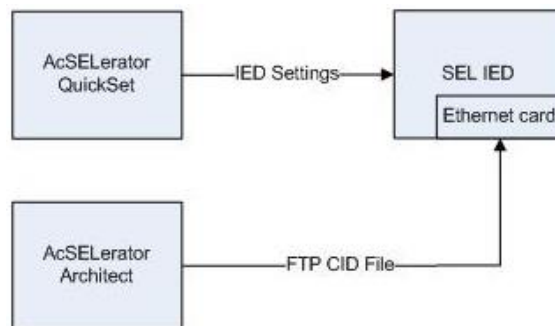
Figure 5.28: Settings transfer to the relay

5.5   Conclusion

This chapter has addressed the situation of using SEL-311L relays with different nominal currents for line differential protection (a 5 A relay on one side and a 1 A relay on the opposite side). After the adjusted settings are entered, both relays report the correct primary currents and the local and remote currents are on the appropriate base to assert or deassert the 87LOPn elements. This was achieved by the CT ratio CTR_X compensation. First the traditional approach with uncompensated CT ratio and its outcomes was demonstrated, and then the new approach of CT ratio compensation and its outcomes were demonstrated.

This chapter also discussed line current differential communications. Critical settings for secure data exchange applicable to back-to-back relay connections were discussed. These include time synchronization, address checking, data packets loss and channel delays. Relay configuration in redundant Ethernet network using FAILOVER mode using the internal failover switch to connect the relay to redundant networks was also discussed. A combination of these settings directly contributed to successful results which is discussed and shown in chapter 6. Chapter 6 discusses

the alpha plane differential protection characteristic and the developed test methods for 3 terminal alpha plane characteristic using newly developed restrain element logical nodes.

CHAPTER SIX

NOVEL METHOD FOR FUNCTIONAL TESTING OF 3 TERMINAL DIFFERENTIAL PROTECTION

6.1 Introduction

This chapter first discusses the principle of alpha plane differential protection characteristic. The principle is presented in its simplest form in two terminal differential protection application which is basically the ratio of remote to local current. According to the literature, the SEL-311L relay applies the alpha plane concept of two-terminal application to three-terminal lines by combining (vectorily adding) currents from two of the terminals to produce the remote current. It was also discovered that there is an additional check logic that the SEL-311L relay applies in case of infeed and outfeed. This additional check logic is discussed in 6.2.

Once the additional logic was discovered, the test method for 3 terminal alpha plane differential protection was developed and this method is discussed in 6.3. The three terminal alpha plane differential protection characteristic and additional check logic are tested in conjunction with the newly developed logical nodes. Ten case studies on this method are described in 6.3. The results on each case study are discussed an analysed.

6.2 3 Terminal Alpha Plane Characteristic

The SEL-311L Relay contains five line current differential elements: one for each phase, and one each for negative-sequence and ground current. The phase elements provide high-speed protection for high current faults. Negative-sequence and ground elements provide sensitive protection for unbalanced faults without compromising security. Figure 6.1 shows the SEL-311L Relay Line Current Differential Elements
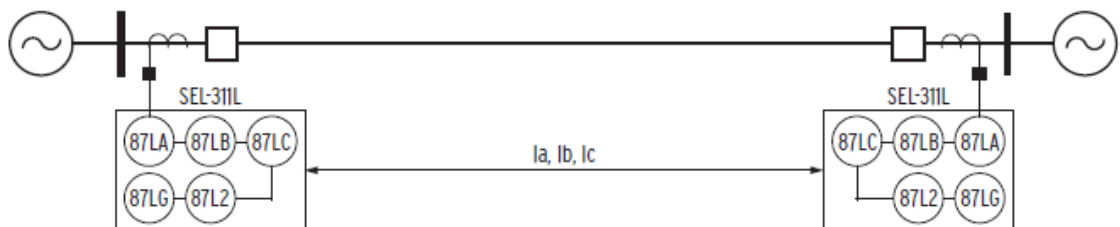
Figure 6.1: SEL-311L relay line current differential elements

The SEL-311L Relay exchanges time-synchronized Ia, Ib, and Ic samples between two or three line terminals. Each relay calculates negative sequence (3I2) and zero sequence (3I0) for all line terminals. Current differential elements 87LA, 87LB, 87LC, 87L2, and 87LG in each relay compare Ia, Ib, Ic, 3I2, and 3I0 (IG) from each line

terminal. All relays perform identical line current differential calculations in a peer-to-peer architecture to avoid transfer trip delays. Phase differential elements 87LA, 87LB, and 87LC reliably detect three-phase faults. The negative-sequence element 87L2 detects internal unbalanced faults and is restrained when all three of the phase currents from any terminal exceed 3 x Inom. Figure 6.2 shows the alpha plane, which represents the phasor or complex ratio of remote (I_R) to local (I_L) complex currents. There is a separate alpha plane for every current (phase, negative-sequence, zero-sequence, etc).
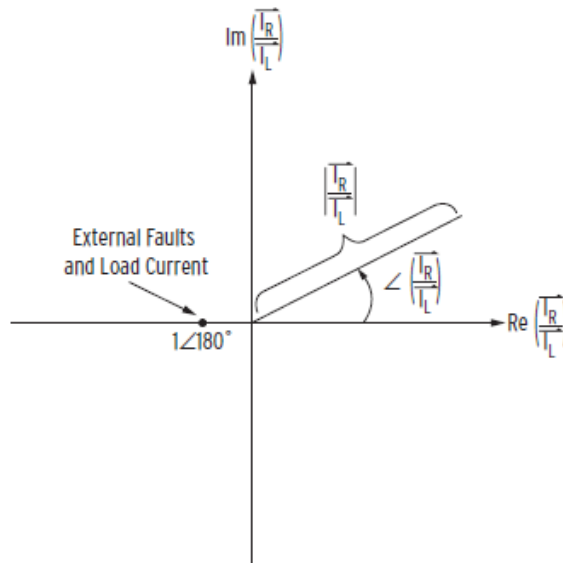
Figure 6.2: **Alpha plane represents complex ratio of remote-to-local complex currents**

Arbitrarily assign current flowing into the protected line to have zero angle, and current flowing out of the protected line to have angle 180 degrees. Five Amps of load current flowing from the local to the remote relay produces an A-phase current of $5\angle0°$ at the local relay, and $5\angle180°$ at the remote relay. The ratio of remote to local current is:

$$\frac{\bar{I}_{AR}}{\bar{I}_{AL}} = \frac{5\angle180°}{5\angle0°} = 1\angle180°$$

(6.1)

$$\frac{\bar{I}_{BR}}{\bar{I}_{BL}} = \frac{5\angle60°}{5\angle-120°} = 1\angle180°$$

(6.2)

$$\frac{\bar{I}_{CR}}{\bar{I}_{CL}} = \frac{5\angle-60°}{5\angle120°} = 1\angle180°$$

(6.3)

On the phase alpha plane, $1\angle180°$ plots one unit to the left of the origin, as shown in Figure 6.2. The other two phases also reside at $1\angle180°$ on their respective alpha planes. In fact, all through-load current plots at $1\angle180°$ regardless of magnitude and

regardless of angle with respect to the system voltages. Likewise, an external fault has equal and opposite current at the two line ends, and so external faults also plot at $1\angle 180°$. The SEL-311L Line Current Differential Relay surrounds the point $1\angle 180°$ on the alpha plane with a restraint region, as shown in Figure 6.3. The relay trips when the alpha plane ratio travels outside the restraint region, and the difference current is above a settable threshold. The relay restrains when the alpha plane ratio remains inside the restraint region, or when there is insufficient difference current.
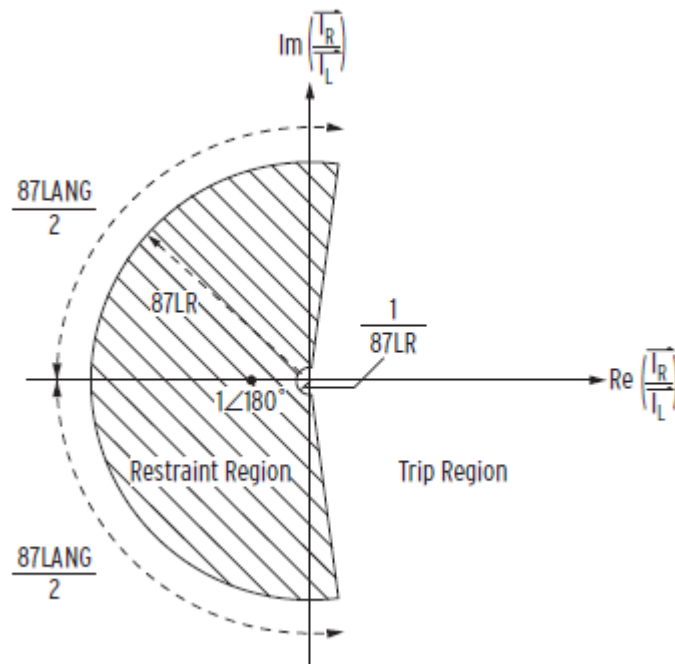
Figure 6.3: SEL-311L relay restraint region surrounds external faults

The shape of the restraint region is described by two settings, as shown in Figure 6.3. Setting 87LANG determines the angular extent of the restraint region. Setting 87LR determines the outer radius of the restraint region. The inner radius is the reciprocal of 87LR. All three types of elements (phase, negative-sequence, and zero-sequence) further qualify trips with a differential pickup setting. For example, setting 87LPP qualifies trips generated by the phase current differential elements 87LA, 87LB, and 87LC. If the Red-phase current ratio travels outside the restraint characteristic, and the Red-phase difference current exceeds setting 87LPP, then element 87LA asserts, indicating an internal fault. Differential pickup settings 87LGP and 87L2P provide similar supervision for the ground current differential element 87LG and the negative-sequence current differential element 87L2, respectively.

Three settings control operation of the phase 87L elements. Refer to Figure 6.3.

- 87LANG The angular extent of the restraint region.

- 87LR The outer radius of the restraint region (the inner radius is the reciprocal of 87LR).
- 87LPP The difference current which qualifies tripping when the alpha plane ratio lies outside the restraint region.

Settings 87LANG and 87LR are common for all differential elements. There are not separate restraint region settings for each type of element.
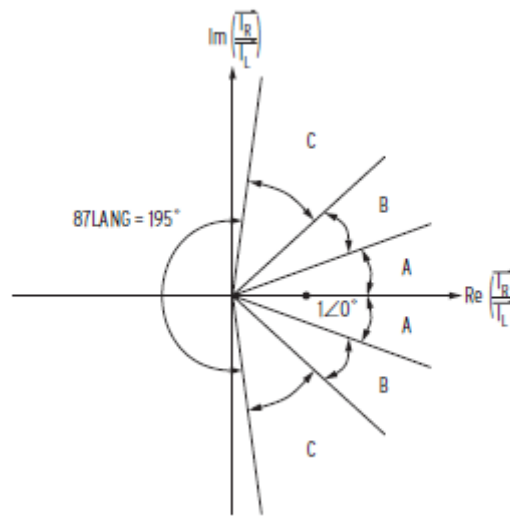
Figure 6.4: Alpha Plane Angel Setting 87LANG Is Based on Maximum Alpha Plane Angle for an External Fault

From Figure 6.4:

- 87LANG = 195°
- A: 20° shift caused by source angle and source impedance angle.
- B: 21.6° shift caused by 2 ms channel asymmetry.
- C: 40° shift caused by CT saturation.

Consider a three-phase fault at midline on a homogenous system with no load flow. The remote and local currents are equal in magnitude and phase. The vector ratio of remote to local currents is $1\angle 0°$. $1\angle 0°$ plots one unit to the right of the origin, as shown in Figure 6.4. If the system is non-homogenous then the line-end current angles differ, and hence the angle of the current ratio is not zero. If the source impedance angles differ by 10 degrees, and there is an angular difference of 10 degrees between the sources, then the angle between remote and local currents can approach 20 degrees.

If the internal fault is not at midline, or if the sources do not have equal strength, the alpha plane ratio moves away from 1∠0°to the right or left. In the limit, either the remote or the local current approaches zero during weak-infeed. If the remote current approaches zero, the ratio moves toward the origin from the right half-plane. If the local current approaches zero, the ratio moves toward the far right end of the right half plane. Therefore, for an internal three-phase fault the phase current ratio lies in the right hand plane within +/-20 degrees of the positive real axis as shown in Figure 6.4 for the source and impedance angles assumed above.

Considering a data alignment error caused by unequal delays in transmit and receive channels. In a unidirectional SONET ring with 20 nodes, the transmit and receive times might be different by 2 ms, assuming adjacent nodes in one direction and 19 intervening nodes in the other direction (an extreme case). The SEL-311L relay estimates the one-way channel delay as half the round trip delay. In this situation, the round trip delay is about 2 ms (100 μs one way, 2 ms the other way, for a total round trip of about 2 ms). In this extreme case both SEL-311L Relays estimate a one-way channel delay of 1 ms, and each relay uses local currents measured 1 ms earlier to align the local data with the received remote data. Thus, both relays have a 1 ms data alignment error (one relay leading, the other lagging). This causes the angle of the alpha plane ratio to be in error by about 22 degrees on a 60 Hz system. In one relay, the error is positive (counter clockwise on the alpha plane); in the other
relay the error is negative (clockwise on the alpha plane). Depending on the angular shift at a particular relay, this error could add to or subtract from the angles caused by the system non-homogeneity and load angle discussed above. Assuming the
angles add, as a worst case. For an internal fault, the alpha plane angle could be as much as +/-(20 + 22) = +/-42 degrees.

Considering CT saturation, a severely saturated CT might temporarily cause the fundamental component of the secondary current to lead the primary current by as much as 40 degrees. Considering CT saturation, system non-homogeneity, load angle, and asymmetrical channel delay, the alpha plane angle for phase currents could be as much as +/-(40 + 22 + 20) = +/-82 degrees for an internal three-phase fault.

Three-phase fault protection places the highest constraints on setting 87LANG, because of source angle considerations. 87LANG is set considering maximum load angle, system non-homogeneity, asymmetrical channel delay and CT saturation. 87LANG is set to 360 - (82 · 2) = 196 degrees. The recommended factory default setting by the manufacturer (SEL) is 195 degrees which is used in this research.

Even if the installation cannot experience these conditions, it is advised to consider leaving 87LANG = 195 degrees. Extensive testing at SEL company demonstrates that this setting provides a good balance of security and dependability.

87LR defines the outer radius of the restraint region, and the reciprocal of 87LR defines the inner radius of the restraint region. 87LR is set to exclude from the restraint region all internal three-phase faults, including those with zero-infeed. An 87LR setting of 6 gives an outside radius of 6 and an inside radius of 1/6. This comfortably excludes zero-infeed conditions from the restraint region.

87LPP is set to reliably detect all internal three-phase faults. 87LPP is set above line charging current. 87LPP is set above maximum expected load current to prevent misoperation when a ganged set of CT test switches is left shorted at one line end. The factory default setting for 87LPP is 1.2 times nominal secondary current (6 A for a 5 A relay or 1.2 A for a 1 A relay) and does not need to be changed except for special conditions. The settings defined above are factory default.

According to the literature, the SEL-311L relay applies the alpha plane concept of two-terminal application to three-terminal lines by combining (vectorly adding) currents from two of the terminals to produce the remote current. The remaining (uncombined) current becomes the local current when calculating the alpha plane ratio of the remote to the local currents. In other words, the SEL-311L Relay converts the three-terminal line to an electrically equivalent two-terminal line, and then applies two-terminal protection algorithms. All of the considerations described in the two-terminal discussion apply to three-terminal protection also.

For internal faults with no outfeed and for external faults with no CT saturation, there is no wrong way to choose which two currents to combine into the remote current, because all three possibilities result in the correct trip/restrain decision.

The SEL-311L Relay processes all 87L elements using all three possible combinations of remote current. Table 6.1 shows the three possibilities.

Table 6.1: Three possible combinations of remote and local currents at relay R.

Currents Combinations	1	2	3
I_{Remote}	$I_B + I_C$	$I_A + I_C$	$I_A + I_B$
I_{Local}	I_A	I_B	I_C

For example, consider the fault depicted in Figure 6.5. For this internal fault, the relay at terminal B experiences outfeed. Fault current flows from Terminal C, through Terminal B, through the parallel line, and to the fault through Terminal A. Assume the fault involves ground. All three relays process the 87LG elements using three possible combinations of remote ground current. The relay at B produces three trip/restrain decisions for the 87LG element. One trip/restrain decision uses the ground current from Terminal B as the local current and vectorily adds the ground currents from Terminals A and C to produce the remote ground current (column 2 in Table 6.1). The relay at B produces another trip/restrain decision using the ground current from Terminal C as the local ground current and combining the ground currents from Terminals A and B as the remote ground current (column 3 in Table 6.1). The relay at B produces the third trip/restrain decision using the ground current from Terminal A as the local current and combining the ground currents from Terminals B and C as the remote ground current (column 1 in Table 6.1). Then the relay trips or operates the 87L element if all three permutations declare the fault as internal and restrains if all three permutations declare the fault as external.
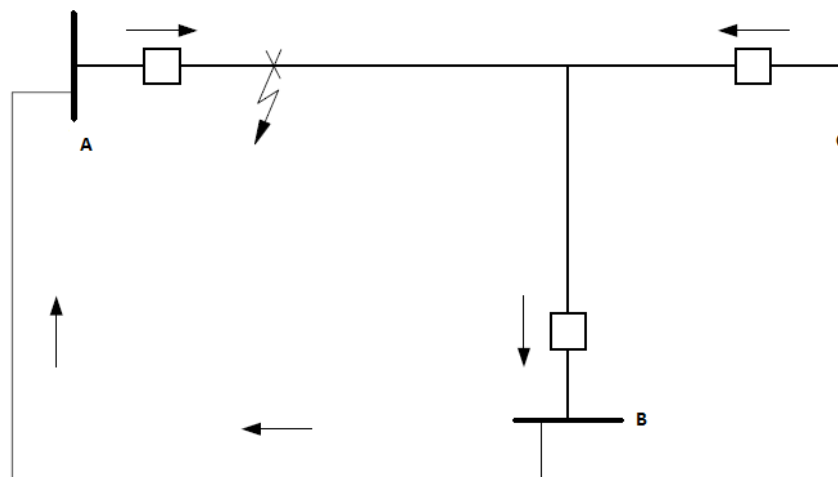
Figure 6.5: Internal fault on three-terminal line producing outfeed at one terminal

During the research, it was also discovered that if at least one or more terminals see the fault as internal, additional check logic is used so as to ensure that the fault is within the protective zone. This logic exists in the relays but is not in the relay manual which also formed basis of this research as is was found that the relays do not

operate as described in the manual. Figure 6.6 shows the additional trip/restraint check logic. Once the logic has established that one of the permutations has detected the fault as internal it will now determine which of the three currents is the largest and which current is the second largest (middle value). It will then check the angle between these two currents. If the angle difference between the largest and second largest (middle) current is greater than 90 degrees, the fault is external and the element is blocked from operating. If the angle is less than 90 degrees, the fault is internal and the 87L element is allowed to trip.
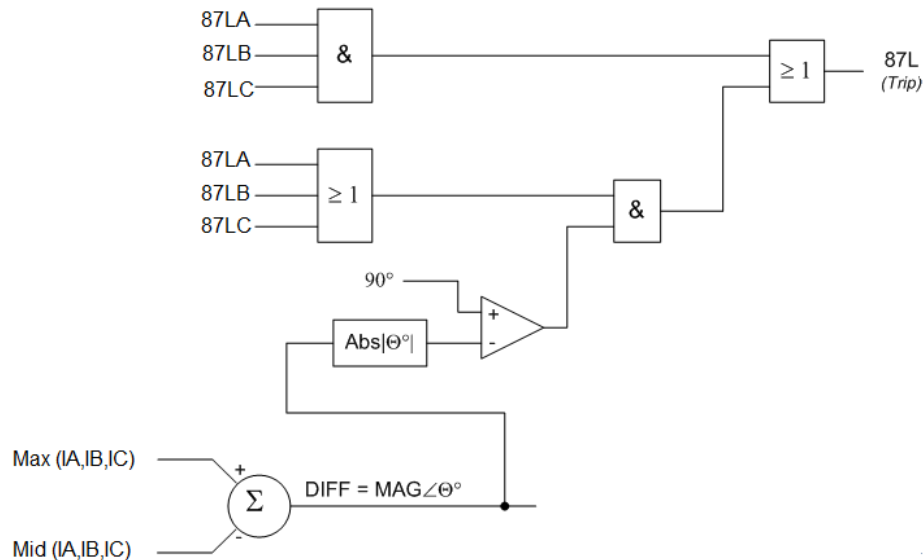
Figure 6.6: Additional trip/restraint check logic

6.3 Development of a method for testing 3 terminal alpha plane using newly developed logical nodes

Once the additional logic was discovered, the test method for 3 terminal alpha plane differential protection was developed. The test is 3 fold:

- to prove functionality of the 3 terminal alpha plane characteristic with additional logic
- to prove the functionality of the developed test method
- to prove the functionality of newly developed logical nodes

All the tests are carried out simultaneously. 8 case studies represented by 8 test point as shown on Figure 6.7 and additional 2 case studies represented by the additional check logic are carried out.

6.4 Test bed setup

To prepare the test bed for testing, the following steps to configure the relays and the OMICRON devices communication and protection settings are followed;

- the CID files with new logical nodes are transferred to the relevant relays and the OMICRON devices to establish communication between the relays and OMICRON devices

- selection of alpha plane parameters (radius and angle) according to the specification of the protection scheme

- determination of tests points for testing of the alpha plane

- calculation of the amount of current to be injected simultaneously by the OMICRON devices to the relays in line with the test points

- programing of the relays settings parameters

- development of test OMICRON control centre test file using Test Universe software to control the OMICRON devices

- synchronisation of the 2 OMICRON devises using CMIRIG-B time synchronising device

The Alpha Plane tests are designed to test the Alpha Plane Restraint region defined by the SEL 311L settings 87LR and 87LANG. To test this restraint characteristic, a set of eight test points are calculated and executed in different test modules for each Alpha Plane. Figure 6.6 shows the relative positions of the test points in the Alpha Plane Restraint region.
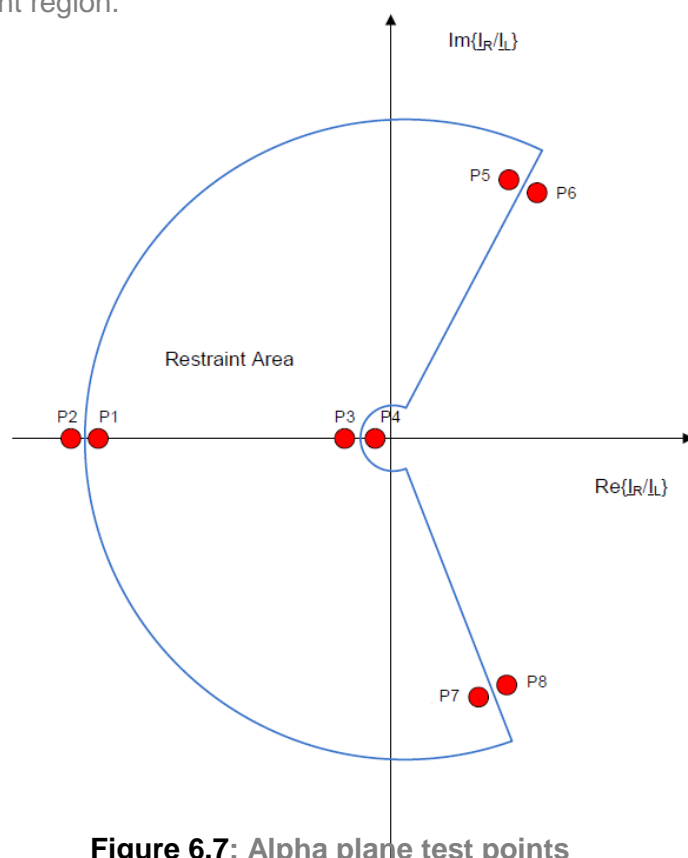
Figure 6.7: Alpha plane test points

97

Test points with even numbers are placed in the trip region, whereas test points with odd numbers are placed in the restraint region.

From the test module's view, the binary inputs are configured in the hardware configuration and applied for the testing. The mapping of the Binary input signals are verified using 'State Sequencer' test module in line with Alpha Plane Operate and Restraint regions as discussed below.

For testing three terminal 311L, two criteria was established in line with the algorithm as discussed in 6.2.

- Internal fault without out-feed

If each of the permutation sees the fault internal i.e. in each case the I_L/I_R ratio goes outside the blocking zone and enters the operating zone then the element trip without any further checks

- Internal fault with out-feed

If at least one terminal sees the fault as internal, the additional check logic in Figure 6.6 is followed.

With alpha (α) set to 6∠195°, a set of eight test points calculated.

The eight test points are:

- P1: α= 5.5 ∠180°
- P2: α = 6.5∠180°
- P3: α = 0.3∠180°
- P4: α = 0.05∠180°
- P5: α = 5.5∠87.5°
- P6: α = 5.5 ∠77.5°
- P7: α = 5.5 ∠-87.5°
- P8: α = 5.5 ∠-77.5°

To achieve these alpha values, a set of currents to be injected on all three relays were calculated as follows;

6.5   Calculation of test points

Ten case studies represented by eight points in Figure 6.7 and infeed/outfeed lcheck logic are carried out for external and internal faults. For alpha value to be at certain point, a certain amount of secondary current must be injected simultaneously on all 3 relays. These secondary currents are calculated for all points and tabulated on Table 6.2, Table 6.3 and Table 6.4. Calculation is shown for one external fault at point 1 and

one internal fault at point 2, the same calculations apply to all other internal and external fault points.

In line with the permutations in Table 6.1, it can be seen that in all permutations, one relay is the reciprocal of the other two. For this case study, two relays are assumed to be in one point of Figure 6.7 and the position of the third relay in the alpha plane is calculated and the same is done for all eight points.

IA represents Red Phase current for relays A, IB represents Red Phase current for relays B, IC represents Red Phase current for relays C, α_A represents Red Phase Alpha value for relay A, α_B represents Red Phase Alpha value for relay B and α_C represents Red Phase Alpha value for relay C.

For point 1 assuming αA = αB = 5.5∠180° and αC = 0.31∠180° (reciprocal of αA & αB)

From equation (6.1), – equation (6.2) and equation (6.3) it can be seen that IA, IB and IC are the variables. These are solved using simultaneous equation solution method as follows:

$$\alpha A = \frac{I_B + I_C}{I_A}$$

$$\alpha B = \frac{I_A + I_C}{I_B}$$

$$\alpha C = \frac{I_A + I_B}{I_C}$$

$$\therefore \quad \frac{I_B + I_C}{I_A} = 5.5\angle 180° \tag{6.4}$$

$$\frac{I_A + I_C}{I_B} = 5.5\angle 180° \tag{6.5}$$

$$\frac{I_A + I_B}{I_C} = 0.31\angle 180° \tag{6.6}$$

From equation (6.1) $I_A = \frac{I_B + I_C}{5.5\angle 180°}$ (6.7)

From equation (6.2) $I_B = \frac{I_A + I_C}{5.5\angle 180°}$ (6.8)

From equation (6.3) $I_C = \frac{I_A + I_B}{0.31\angle 180°}$ (6.9)

Substituting equation (6.7) and equation (6.8) to equation (6.9)

$$I_C = \left(\frac{I_B + I_C}{5.5\angle 180°} + \frac{I_A + I_C}{5.5\angle 180°} \right) \div 0.31\angle 180° \tag{6.10}$$

$I_A = 1.705 I_C - 2 I_C - I_B$

$$I_A = -I_B - 0.295I_C \tag{6.10}$$

Equation (6.7) = equation (6.10)

$$\frac{I_B + I_C}{5.5\angle 180°} = -I_B - 0.295I_C$$

$$I_B - 5.5I_B = 1.623I_C - I_C$$

$$I_B = -0.138I_C \tag{6.11}$$

Substituting equation (6.11) to equation (6.10)

$$I_A = -(-0.138I_C) - 0.295I_C$$

$$I_A = 0.138I_C - 0.295I_C$$

$$I_A = -0.157\ I_C$$

If $I_A = 1\angle 180°A$

$$\therefore I_c = 6.4\angle 0°A$$

$$\&\ I_B = 0.88\angle 180°A \cong I_A$$

For point 2 assuming $\alpha A = 6.5\angle 180°$ and $\alpha B = \alpha C = 0.2\angle 0°$ (reciprocal of αA)

$$\alpha A = \frac{I_B + I_C}{I_A}$$

$$\alpha B = \frac{I_A + I_C}{I_B}$$

$$\alpha C = \frac{I_A + I_B}{I_C}$$

From equation (5.1) – (5.3) and assumed values of αA, αB, αC the following can be derived.

$$\therefore$$

$$\frac{I_B + I_C}{I_A} = 6.5\angle 180° \tag{6.12}$$

$$\frac{I_A + I_C}{I_B} = 0.2\angle 0° \tag{6.13}$$

$$\frac{I_A + I_B}{I_C} = 0.2\angle 0° \tag{6.14}$$

From equation (6.1) $I_A = \frac{I_B + I_C}{6.5\angle 180°}$ (6.15)

From equation (6.2) $I_B = \frac{I_A + I_C}{0.2\angle 0°}$ (6.16)

From equation (6.3) $I_C = \frac{I_A + I_B}{0.2\angle 0°}$ (6.17)

Substituting equation (6.15) and equation (6.16) to equation (6.17)

$$I_C = \left(\frac{I_B + I_C}{6.5\angle 0°} + \frac{I_A + I_C}{0.2\angle 0°} \right) \div 0.2\angle 0°$$

$I_A = 0.04\ I_C - I_C\ 0.031\ I_B\ 0.031\ I_C$

$I_A = 0.031\ I_B - 0.929\ I_C$ (6.18)

Equation (6.15) = equation (6.18)

$$\frac{I_B + I_C}{6.5 \angle 180°} = 0.031 I_B - 0.929 I_C$$

$I_B + 0.202\ I_B = 5.039\ I_C$

$I_B = 4.192\ I_C$ (6.19)

Substituting equation (6.19) to equation (6.18)

$I_A = 0.031 \times 4.192\ I_C - 0.929\ I_C$

$I_A = 0.13\ I_C - 0.929\ I_C$

$I_A = -0.799\ I_C$

If $I_C = 1 \angle 180°$A

$\therefore\ I_B = 4.192 \angle 180°$A

& $I_A = 0.799 \angle 0°$A

Table 6.2 shows the amount of currents that are injected simultaneously on each relay for relay A equivalent alpha value.

Table 6.2: Simultaneous injected analogue values for relay A for point 1 to point 8

Relay A			
Alpha α	Relay A current (Amps)	Relay B current (Amps)	Relay C current (Amps)
P1: α= 5.5∠180°	1∠180°	1∠180°	6.4∠0°
P2: α= 6.5∠180°	0.799∠0°	4.192∠180°	1∠180°
P3: α= 0.3∠180°	6.5∠0°	1∠180°	1∠180°
P4: α= 0.05∠180°	4.192∠180°	0.799∠0°	1∠180°
P5: α= 5.5∠87.5°	1∠180°	1∠180°	5.548∠-82°
P6: α= 5.5∠77.5°	1∠180°	5.66∠-112°	0.948∠-9.9°
P7: α= 5.5∠-87.5°	1∠180°	5.547∠82°	1∠180°
P8: α= 5.5∠-77.5°	1∠180°	5.66∠112°	0.948∠9.9°

Table 6.3 shows the amount of currents that are injected simultaneously on each relay for relay B equivalent alpha value.

Table 6.3: Simultaneous injected analogue values for relay B for point 1 to point 8

Relay B			
Alpha α	Relay A current (Amps)	Relay B current (Amps)	Relay C current (Amps)
P1: α= 5.5∠180°	1∠180°	1∠180°	6.4∠0°
P2: α= 6.5∠180°	4.192∠180°	0.799∠0°	1∠180°
P3: α= 0.3∠180°	1∠180°	6.5∠0°	1∠180°
P4: α= 0.05∠180°	0.799∠0°	4.192∠180°	1∠180°
P5: α= 5.5∠87.5°	1∠180°	1∠180°	5.548∠-82°
P6: α= 5.5∠77.5°	5.66∠-112°	1∠180°	0.948∠-9.9°
P7: α= 5.5∠-87.5°	5.547∠82°	1∠180°	1∠180°
P8: α= 5.5/-77.5°	5.66/112°	1/180°	0.948/9.9°

Table 6.4 shows the amount of currents that are injected simultaneously on each relay for relay C equivalent alpha value.

Table 6.4: Simultaneous injected analogue values for relay C for point 1 to point 8

Relay C			
Alpha α	Relay A current (Amps)	Relay B current (Amps)	Relay C current (Amps)
P1: α= 5.5∠180°	6.4∠0°	1∠180°	1∠180°
P2: α= 6.5∠180°	1∠180°	4.192∠180°	0.799∠0°
P3: α= 0.3∠180°	1∠180°	1∠180°	6.5∠0°
P4: α= 0.05∠180°	1∠180°	0.799∠0°	4.192∠180°
P5: α= 5.5∠87.5°	5.548∠-82°	1∠180°	1∠180°
P6: α= 5.5∠77.5°	0.948∠-9.9°	5.66∠-112°	1∠180°
P7: α= 5.5∠-87.5°	1∠180°	5.547∠82°	1∠180°
P8: α= 5.5∠-77.5°	0.948∠9.9°	5.66∠112°	1∠180°

6.6 Performing the test

Subsequent to the preparation of the test bed, the following steps are followed to carry out the test;

- Power up the test scheme
- Inject the fault current simultaneously to the relays for the first test point
- Read the OMICRON test report on the Test Universe software from the PC. The report include the feedback for the logical nodes performance and the performance of the alpha plane

- Check the status of the test ; if passed, continue to the next step, if not passed, verify the communication and protection settings
- Continue until all test points are finished
- Test the infeed and outfeed logic in line with the logic as described in 6.2
- Print the report

6.6.1 Case study 1 – relay A and B point 1

Using values from Table 6.2, the results from Figure 6.8 and Figure 6.9 have shown that;

- Relay A and B point 1 was tested simultaneously as shown with notification 1 on Figure 6.7.
- $1\angle180°$A on red phase with balanced angles and equal magnitudes for all phases was injected on relay A and B as shown with notification 2 on Figure 6.7, and $32\angle0°$A (= 6.4 x I $_{nominal}$) on red phase with balanced angles and equal magnitudes for all phases was injected on relay C as shown with notification 2 on Figure 6.9 since relay C secondary current rating was 5A.
- This external fault was simulated for 1 second as shown with notification 3 on Figure 6.8 and Figure 6.9.
- Restraint elements R87LA, R87LB and R87LC (notification 4 on Figure 6.8) picked-up almost instantaneously (just above 13ms) as shown with notification 5 on Figure 6.8. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC (notification 4 on Figure 6.8) picked-up 1 second later when the internal fault was simulated subsequent to 1 second external fault as shown with notification 5 on Figure 6.8. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.
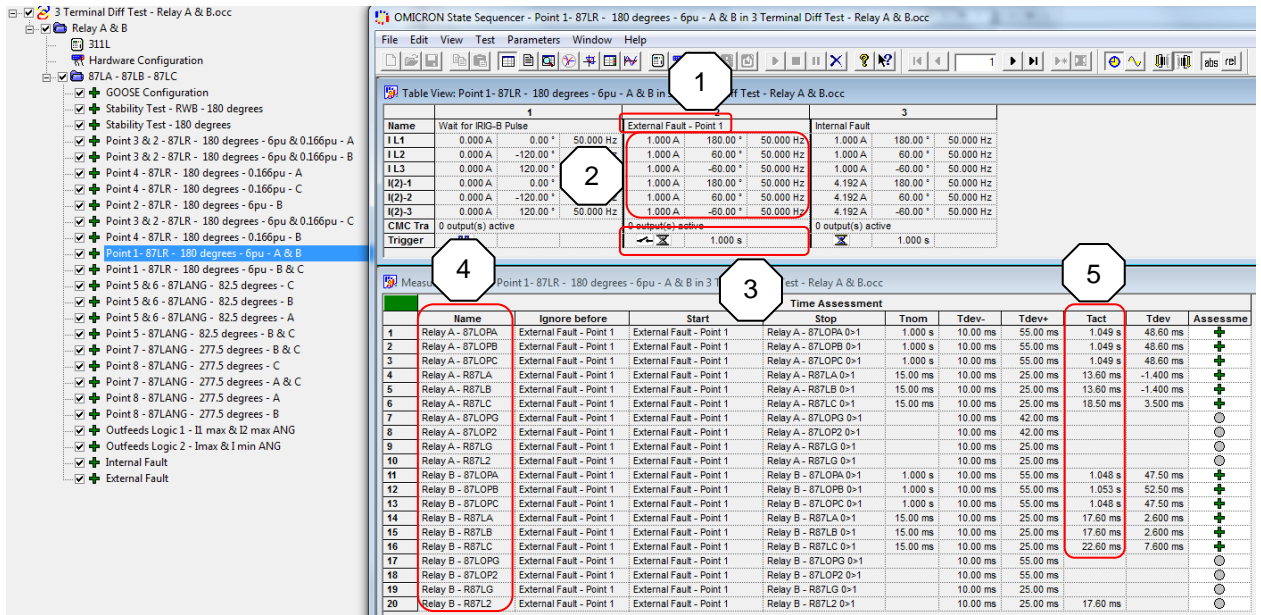
Figure 6.8: Injected analogue values and test results for relay A and B for point 1

Figure 6.9: Injected analogue values and test results for relay C

Figure 6.10 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET₁

SEL-311L A                      Date: 10/31/2014      Time: 12:48:40.508
311L STUDY
        ①
Local              A          B          C          3I0        3I2        I1
I MAG (A Pri)   597.984    597.793    597.400      1.887      1.805    597.725
I ANG (DEG)       -0.10    -120.10     120.10    -129.30     -18.60      0.00
Channel X          A          B          C          3I0        3I2        I1
I MAG (A Pri)   597.750    596.473    598.456      2.775      2.975    597.559
I ANG (DEG)       -0.60    -120.60     119.20     58.90      -1.70     -0.70
Channel Y          A          B          C          3I0        3I2        I1
I MAG (A Pri)  3824.561   3819.937   3814.480     18.628     15.786   3819.653
I ANG (DEG)      179.70      59.80     -60.00     92.60     148.20    179.80
Vector Sum         A          B          C          3I0        3I2        I1
I MAG (A Pri)  2628.838   2625.685   2618.704     19.534     11.616   2624.394
I ANG (DEG)      179.60      59.80     -59.80     91.70     138.70    179.80
Alpha Plane        A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS    ②     5.390      5.390      5.380      0.000      0.000      5.390
ANG (DEG)        179.60     179.80     179.70      0.00       0.00     179.70
↵
=>MET₁

SEL-311L B                      Date: 10/31/2014      Time: 13:20:21.170
311L STUDY
        ③
Local              A          B          C          3I0        3I2        I1
I MAG (A Pri)   598.914    596.901    597.581      2.064      1.210    597.799
I ANG (DEG)       -0.10    -120.00     119.90      5.00       6.20      0.00
Channel X          A          B          C          3I0        3I2        I1
I MAG (A Pri)  3818.339   3825.214   3832.049     12.732     10.373   3825.199
I ANG (DEG)      179.40      59.50     -60.40      9.70      46.40    179.50
Channel Y          A          B          C          3I0        3I2        I1
I MAG (A Pri)   598.555    599.147    597.584      3.924      1.746    598.427
I ANG (DEG)       -0.20    -120.10     120.10   -108.10       2.50      0.00
Vector Sum         A          B          C          3I0        3I2        I1
I MAG (A Pri)  2620.926   2629.221   2636.922     13.464     12.712   2629.041
I ANG (DEG)      179.10      59.20     -60.50     -6.00      37.30    179.20
Alpha Plane        A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS           5.370      5.400      5.410      0.000      0.000      5.390
ANG (DEG) ④      179.40     179.40     179.50      0.00       0.00     179.40
L
=>MET₁

SEL-311L C                      Date: 10/31/2014      Time: 04:34:51.796
311L STUDY
        ⑤
Local              A          B          C          3I0        3I2        I1
I MAG (A Pri)  3825.938   3826.165   3823.966      9.496      5.331   3825.354
I ANG (DEG)       -0.10    -120.10     120.00    -112.90     -58.40      0.00
Channel X          A          B          C          3I0        3I2        I1
I MAG (A Pri)   597.242    599.312    596.729      3.985      1.415    597.761
I ANG (DEG)      179.60      59.60     -60.20     63.10     -67.40    179.70
Channel Y          A          B          C          3I0        3I2        I1
I MAG (A Pri)   598.146    595.616    598.534      3.443      2.110    597.432
I ANG (DEG)     -179.90      60.20     -60.00    -129.40     81.10   -179.90
Vector Sum         A          B          C          3I0        3I2        I1
I MAG (A Pri)  2630.561   2631.251   2628.707      8.849      5.254   2630.173
I ANG (DEG)        0.00    -120.00     120.00    -117.40     -45.60      0.00
Alpha Plane        A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS    ⑥     0.310      0.310      0.310      0.000      0.000      0.310
ANG (DEG)        179.90     179.90     179.80      0.00       0.00     179.80
```

Figure 6.10: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.10 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 597.984∠-0.1°A, White Phase current = 597.793∠-120.1°A and Blue Phase current = 597.4∠120.1A°.
- Relay B Red Phase current = 597.75∠0.6°A, White Phase current = 596.473∠-120.6°A and Blue Phase current = 598.456∠119.2°A.
- Relay C Red Phase current = 3824.561∠179.7°A, White Phase current = 3819.937∠59.8°A and Blue Phase current = 3814.48∠-60°A.
- Relay A then calculated its alpha values as show with notification 2 on Figure 6.10).
- Relay A Red Phase Alpha α = 5.39∠179.6°, White Phase Alpha α = 5.39∠179.8° and Blue Phase Alpha α = 5.38∠179.7° as shown with notification 2 on Figure 6.10.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively (notification 3 on Figure 6.10).

Observed from relay B and shown with notification 3 on Figure 6.9 it can be seen that:

- Relay A Red Phase current = 598.555∠-0.2°A, White Phase current = 599.147∠-120.1°A and Blue Phase current = 597.584∠120.1°A.
- Relay B Red Phase current = 598.914∠-0.1°A, White Phase current = 596.901∠-120°A and Blue Phase current = 597.581∠119.9°A.
- Relay C Red Phase current = 3818.339∠179.4°A, White Phase current = 3825.214∠59.5°A and Blue Phase current = 3832.049∠-60.4°.

  Relay B then calculated its alpha values as show on (notification 4 on Figure 6.9).
- Relay B Red Phase Alpha α = 5.37∠179.4°, White Phase Alpha α = 5.4∠179.4° and Blue Phase Alpha α = 5.4∠179.4° as shown with notification 4 on Figure 6.10.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively (notification 5 on Figure 6.10).

Observed from relay C and shown with notification 5 on Figure 6.10 it can be seen that:

- Relay A Red Phase current = 597.242∠179.6°A, White Phase current = 599.312∠59.6°A and Blue Phase current = 596.729∠-60.2°A.
- Relay B Red Phase current = 598.146∠-179.9°A, White Phase current = 595.616∠60.2°A and Blue Phase current = 598.534∠-60°A.
- Relay C Red Phase current = 3825.938∠-0.1°A, White Phase current = 3826.165∠-120.1°A and Blue Phase current = 3823.966∠120°A.
- Relay C then calculated its alpha values as show on (notification 6 on Figure 6.10).
- Relay C Red Phase Alpha α = 0.31∠179.9°A, White Phase Alpha α = 0.31∠179.9°A and Blue Phase Alpha α = 0.31∠179.9°A as shown with notification 6 on Figure 6.10.

6.6.2 Case study 2 – Relay A point 2

Using values from Table 6.2, the results from Figure 6.11 and Figure 6.12 show that;

- Relay A point 2 and Point 3 were tested on the same test module as shown with notification 1 on Figure 6.11
- The external fault was simulated for 10 second as shown with notification 3 on Figure 6.11 and Figure 6.12 and thereafter the internal fault was simulated for 1 second.
- For point 2, 0.799∠0°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 4.192∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay B as shown with notification 2 on Figure 6.11
- and 5∠180°A (= 1 x $I_{nominal}$) was injected on relay C as shown with notification 2 on Figure 6.12.
- Restraint elements R87LA, R87LB and R87LC on (as shown with notification 2 on Figure 6.11) picked-up almost instantaneously (just above 12ms) as shown with notification 5 on Figure 6.11. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC (as show with notification 4 on Figure 6.11) picked-up 10 seconds later when the internal fault was simulated subsequent to 10 seconds external fault as show with notification 5 on Figure 6.11. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.

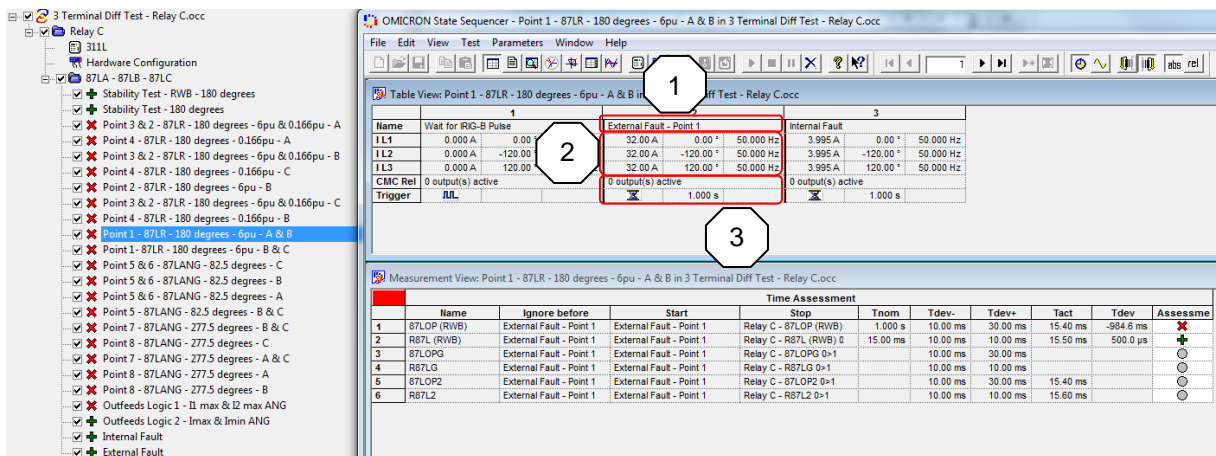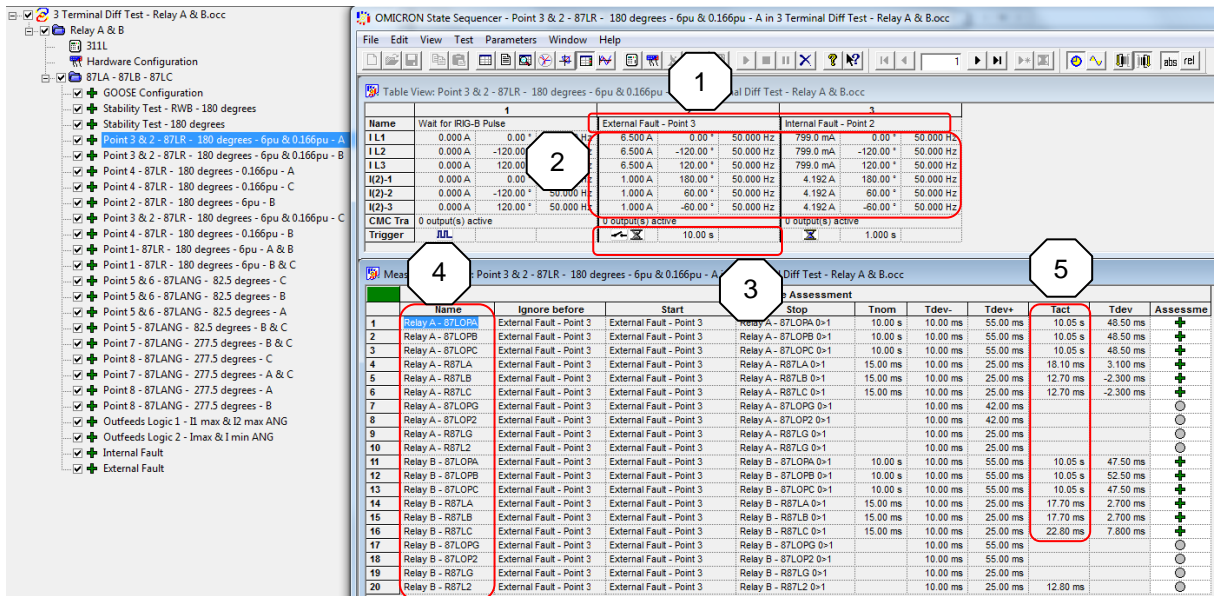**Figure 6.11**: Injected analogue values and test results for relay A for point 2 and 3

Figure 6.12: Injected analogue values and test results for relay C

Figure 6.13 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET₁

SEL-311L A                    Date: 10/30/2014    Time: 14:14:30.184
311L STUDY

Local            A          B          C        3I0        3I2         I1
I MAG (A Pri)  477.640    477.197    477.374    1.470      2.811     477.403
I ANG (DEG)     -0.10     -120.10     120.10  -135.50    -21.80       0.00
Channel X        A          B          C        3I0        3I2         I1
I MAG (A Pri) 2503.238   2500.917   2502.489    5.764      7.418    2502.212
I ANG (DEG)    179.90      60.00     -59.90     57.00    149.80      180.00
Channel Y        A          B          C        3I0        3I2         I1
I MAG (A Pri)  597.228    596.784    599.191    1.895      3.625     597.733
I ANG (DEG)   -179.90      60.30     -59.60      9.90     87.60     -179.70
Vector Sum       A          B          C        3I0        3I2         I1
I MAG (A Pri) 2622.823   2620.498   2624.299    5.720      7.290    2622.531
I ANG (DEG)    179.90      60.00     -59.80     46.20    120.00      179.90
Alpha Plane      A          B          C      ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS         6.490      6.490      6.490      0.000      0.000      6.490
ANG (DEG)     179.90     179.80     179.90      0.00       0.00     179.90

=>MET₁

SEL-311L B                    Date: 10/30/2014    Time: 14:44:41.394
311L STUDY

Local            A          B          C        3I0        3I2         I1
I MAG (A Pri) 2508.460   2505.276   2504.384    3.326      3.059    2506.040
I ANG (DEG)     -0.10     -120.10     120.00    -26.80      4.90       0.00
Channel X        A          B          C        3I0        3I2         I1
I MAG (A Pri)  600.049    597.931    597.308    3.091      1.846     598.429
I ANG (DEG)     -0.20     -120.00     119.90    -32.80    -35.10      -0.10
Channel Y        A          B          C        3I0        3I2         I1
I MAG (A Pri)  477.566    476.762    478.343    2.436      2.300     477.557
I ANG (DEG)    179.70      59.60     -60.20    -55.10    128.70      179.70
Vector Sum       A          B          C        3I0        3I2         I1
I MAG (A Pri) 2630.946   2626.457   2623.349    8.670      3.277    2626.920
I ANG (DEG)     0.00     -119.90     119.90    -36.50     17.70       0.00
Alpha Plane      A          B          C      ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS         0.040      0.040      0.040      0.000      0.000      0.040
ANG (DEG)      0.60       0.50       0.30       0.00       0.00       0.10

=>MET₁

SEL-311L C                    Date: 10/30/2014    Time: 05:58:41.496
311L STUDY

Local            A          B          C        3I0        3I2         I1
I MAG (A Pri)  597.871    598.246    597.649    2.347      0.629     597.922
I ANG (DEG)     -0.20     -120.00     120.00  -109.00    -27.90       0.00
Channel X        A          B          C        3I0        3I2         I1
I MAG (A Pri)  477.042    477.427    478.396    3.538      2.828     477.619
I ANG (DEG)    179.40      59.50     -60.20     21.90    126.60      179.50
Channel Y        A          B          C        3I0        3I2         I1
I MAG (A Pri) 2512.748   2503.924   2503.011   13.954      8.887    2506.559
I ANG (DEG)     -0.60     -120.40     119.50    -30.40     17.10      -0.50
Vector Sum       A          B          C        3I0        3I2         I1
I MAG (A Pri) 2633.570   2624.732   2622.248   16.589      8.679    2626.851
I ANG (DEG)     -0.50     -120.20     119.50    -28.60     31.90      -0.30
Alpha Plane      A          B          C      ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS         3.400      3.380      3.380      0.000      0.000      3.390
ANG (DEG)      0.60       0.60       0.80       0.00       0.00       0.70
```

Figure 6.13: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.13 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 477.640∠-0.1°A, White Phase current = 477.197∠-120.1°A and Blue Phase current = 477.374∠120.0°A.
- Relay B Red Phase current = 2503.238∠179.9°A, White Phase current = 2500.917∠60°A and Blue Phase current = 2502.489∠-59.9°A.
- Relay C Red Phase current = 597.228∠-179.7°A, White Phase current = 596.784∠60.3°A and Blue Phase current = 599.191∠-59.6°A.
- Relay A then calculated its alpha values as show with notification 2 on Figure 13
- Relay A Red Phase Alpha α = 6.49∠179.9°, White Phase Alpha α = 6.49∠179.9° and Blue Phase Alpha α = 6.49∠179.9° as shown with notification 2 on Figure 6.13.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively (notification 3 on Figure 6.13).

Observed from relay B and shown with notification 3 on Figure 6.13 it can be seen that:

- Relay A Red Phase current = 477.566∠179.7°A, White Phase current = 476.762∠59.6°A and Blue Phase current = 478.343∠-60.2°A.
- Relay B Red Phase current = 2508.460∠-0.1°A, White Phase current = 2505.276∠-120.1°A and Blue Phase current = 2504.384∠120°A.
- Relay C Red Phase current = 600.049∠-0.2°A, White Phase current = 597.931∠-120°A and Blue Phase current = 597.308∠119.9°A.
- Relay B then calculated its alpha values as show with notification 4 on Figure 6.13.
- Relay B Red Phase Alpha α = 0.040∠0.6°, White Phase Alpha α = 0.040∠0.5° and Blue Phase Alpha α = 0.040∠0.3° as shown with notification 4 on Figure 6.13.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively (notification 5 on Figure 6.13).

Observed from relay C and shown with notification 5 on Figure 6.13 it can be seen that:

- Relay A Red Phase current = 477.042∠179.4°A, White Phase current = 477.427∠59.5°A and Blue Phase current = 478.396∠-60.2°A.
- Relay B Red Phase current = 2512.748∠-0.6°, White Phase current = 2503.924∠-120.4°A and Blue Phase current = 2503.011∠119.5°A.
- Relay C Red Phase current = 597.871∠-0.2°A, White Phase current = 598.246 ∠-120°A and Blue Phase current = 597.649∠120°A.
- Relay C then calculated its alpha values as show with notification 6 on Figure 6.13.
- Relay C Red Phase Alpha α = 3.4∠0.6°, White Phase Alpha α = 3.380∠0.6° and Blue Phase Alpha α = 3.380∠0.8° as shown with notification 6 on Figure 6.16.

6.6.3 Case study 3 – Relay A point 3

Using values from Table 6.2, the results from Figure 6.14 and Figure 6.15 show that;

- Relay A point 2 and Point 3 were tested on the same test module as shown with notification 1 on Figure 6.14.
- The external fault was simulated for 10 second as shown with notification 3 on Figure 6.14 and Figure 6.15 and thereafter the internal fault was simulated for 1 second.
- For point 3, 6.5∠0°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 1∠180°A was injected on relay B as shown with notification 2 on Figure 6.10, and 5∠180°A (= 1 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.15.
- Restraint elements R87LA, R87LB and R87LC on (as shown with notification 2 on Figure 6.14) picked-up almost instantaneously (just above 12ms) as shown with notification 5 on Figure 6.14. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC (as show with notification 4 on Figure 6.14) picked-up 10 seconds later when the internal fault was simulated subsequent to 10 seconds external fault as show with notification 5 on Figure 6.14. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.

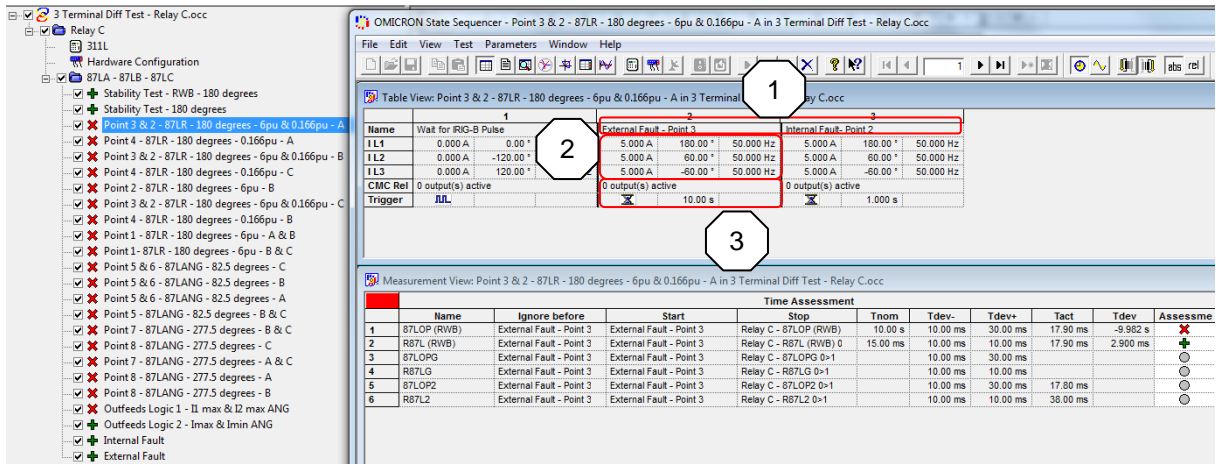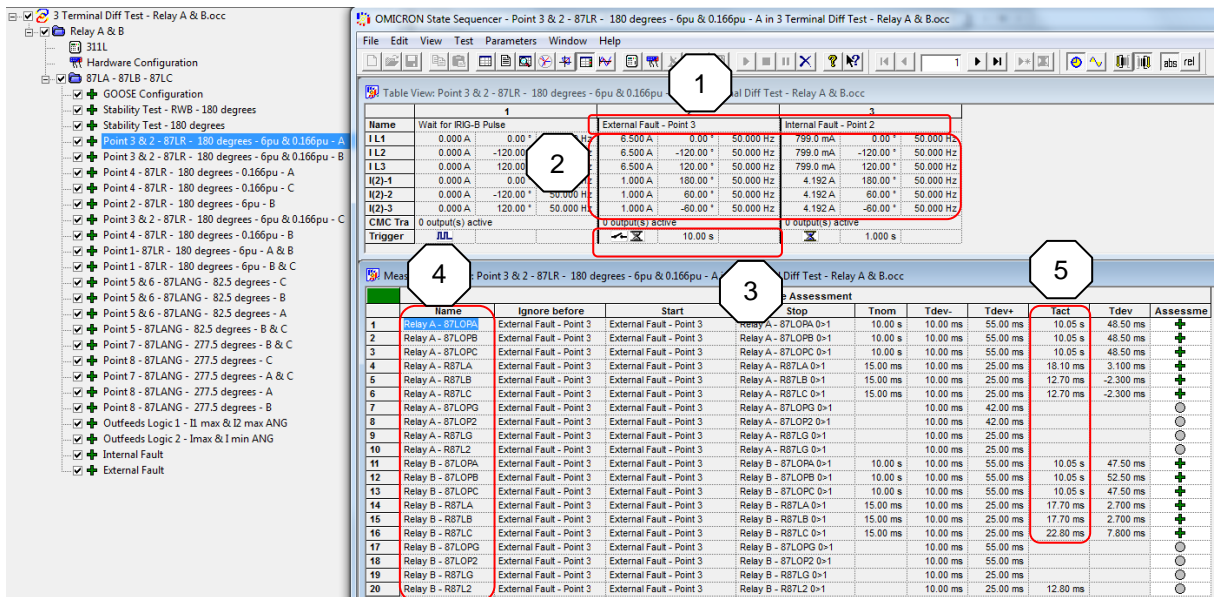**Figure 6.14**: Injected analogue values and test results for relay A for point 2 and 3

Figure 6.15: Injected analogue values and test results for relay C

Figure 6.16 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

met⌐

```
SEL-311L A                    Date: 10/30/2014    Time: 14:10:59.433
311L STUDY

Local            A          B          C         3I0       3I2        I1
I MAG (A Pri)  3886.964   3886.943   3885.764   10.795    11.552    3886.554
I ANG (DEG)      -0.10     -120.10     120.10   -135.70    -12.70       0.00
Channel X        A          B          C         3I0       3I2        I1
I MAG (A Pri)   596.372    597.868    597.431    2.642     2.654     597.223
I ANG (DEG)     -179.80      60.00     -59.80    -20.20   -112.80    -179.90
Channel Y        A          B          C         3I0       3I2        I1
I MAG (A Pri)   598.555    598.523    598.087    2.927     1.238     598.387
I ANG (DEG)     180.00       60.20     -59.70    88.00    102.30    -179.80
Vector Sum       A          B          C         3I0       3I2        I1
I MAG (A Pri)  2692.048   2690.564   2690.257    7.550    10.669    2690.949
I ANG (DEG)      -0.10     -120.10     119.90   -132.90    -20.60       0.00
Alpha Plane      A          B          C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           0.300      0.300      0.300    0.000     0.000       0.300
ANG (DEG)       179.70     179.70     179.70    0.00      0.00       179.70
```
=>MET⌐

```
SEL-311L B                    Date: 10/30/2014    Time: 14:41:25.771
311L STUDY

Local            A          B          C         3I0       3I2        I1
I MAG (A Pri)   598.218    597.086    597.097    1.395     0.919     597.467
I ANG (DEG)       0.00     -120.00     119.90    3.30     43.50        0.00
Channel X        A          B          C         3I0       3I2        I1
I MAG (A Pri)   597.421    597.784    599.566    2.017     3.214     598.257
I ANG (DEG)      -0.30     -120.10     119.90   -175.00   -104.00      -0.20
Channel Y        A          B          C         3I0       3I2        I1
I MAG (A Pri)  3882.243   3884.889   3886.100    5.431     9.894    3884.410
I ANG (DEG)     180.00       60.10     -59.90    82.80     37.90     180.00
Vector Sum       A          B          C         3I0       3I2        I1
I MAG (A Pri)  2686.611   2690.022   2689.447    5.293     8.495    2688.691
I ANG (DEG)    -179.90       60.10     -59.80    89.30     25.00    -179.90
Alpha Plane      A          B          C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           5.490      5.500      5.500    0.000     0.000       5.500
ANG (DEG)       179.90     179.90     179.90    0.00      0.00       179.90
```
=>MET⌐

```
SEL-311L C                    Date: 10/30/2014    Time: 05:55:50.504
311L STUDY

Local            A          B          C         3I0       3I2        I1
I MAG (A Pri)   597.653    597.503    597.438    1.569     1.442     597.531
I ANG (DEG)      -0.10     -120.00     120.00   -103.80    -77.60       0.00
Channel X        A          B          C         3I0       3I2        I1
I MAG (A Pri)  3888.753   3868.161   3889.217   20.558    29.042    3882.040
I ANG (DEG)     179.50       59.30     -60.50    -85.30    144.00     179.50
Channel Y        A          B          C         3I0       3I2        I1
I MAG (A Pri)   598.657    597.153    598.804    2.277     1.414     598.204
I ANG (DEG)      -0.70     -120.60     119.30    43.60   -111.00      -0.70
Vector Sum       A          B          C         3I0       3I2        I1
I MAG (A Pri)  2692.462   2673.568   2693.007   20.658    27.694    2686.333
I ANG (DEG)     179.40       59.00     -60.40    -81.60    148.70     179.40
Alpha Plane      A          B          C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           5.500      5.470      5.500    0.000     0.000       5.490
ANG (DEG)       179.60     179.30     179.50    0.00      0.00       179.40
```

Figure 6.16: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.16 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 3886.964∠-0.1°A, White Phase current = 3886.943∠-120.1°A and Blue Phase current = 3885.764∠120.1°A.
- Relay B Red Phase current = 596.372∠-179.8°A, White Phase current = 597.868/60°A and Blue Phase current = 597.431∠59.8°A.
- Relay C Red Phase current = 598.555∠180°A, White Phase current = 598.523∠60.2°A and Blue Phase current = 598.087∠-59.7°A.
- Relay A then calculated its alpha values as shown with notification 2 on Figure 6.16.
- Relay A Red Phase Alpha α = 0.3∠179.9°, White Phase Alpha α = 0.3∠179.9° and Blue Phase Alpha α = 0.3∠179.9°.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively as shown with notification 3 on Figure 6.16.

Observed from relay B and shown with notification 3 on Figure 6.15 it can be seen that:

- Relay A Red Phase current = 3882.243∠180°A, White Phase current = 3884.889∠60.1°A and Blue Phase current = 3886.100∠-59.9°A.
- Relay B Red Phase current = 598.218∠0°A, White Phase current = 597.086∠-120°A and Blue Phase current = 597.097∠119.9°A.
- Relay C Red Phase current = 597.421∠-0.3°A, White Phase current = 597.784∠-120.1°A and Blue Phase current = 599.566∠119.9°A.
- Relay B then calculated its alpha values as shown with notification 4 on Figure 6.16.
- Relay B Red Phase Alpha α = 5.49∠179.9°, White Phase Alpha α = 5.5∠179.9° and Blue Phase Alpha α = 5.5∠179.9°.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively as shown with notification 5 on Figure 6.16.

Observed from relay C and shown with notification 5 on Figure 6.16 it can be seen that:

- Relay A Red Phase current = 3888.753∠179.5°A, White Phase current = 3868.161∠59.3°A and Blue Phase current = 3889.217∠-60.5°A.
- Relay B Red Phase current = 598.657∠-0.7°A, White Phase current = 597.153∠-120.6°A and Blue Phase current = 598.804∠119.3°.
- Relay C Red Phase current = 597.653∠-0.1°A, White Phase current = 597.503∠-120°A and Blue Phase current = 597.438∠120°A.
- Relay C then calculated its alpha values as show with notification 6 on Figure 6.16.
- Relay C Red Phase Alpha α = 5.500∠179.6°, White Phase Alpha α = 5.470∠179.3° and Blue Phase Alpha α = 5.500∠179.5° as shown with notification 6 on Figure 6.16.

6.6.4 Case study 4 – Relay A point 4

Using values from Table 6.2, the results from Figure 6.17 and Figure 6.18 show that;

- Relay A point 4 was as shown with notification 1 on Figure 6.17.
- 4.192∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 0.799∠0°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay B as shown with notification 2 on Figure 6.16.and 5∠180° amps (= 1 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.18.
- The external fault was simulated for 10 second as shown with notification 3 on Figure 6.17 and Figure 6.18.
- Restraint elements R87LA, R87LB and R87LC on (notification 4 on Figure 6.17.) picked-up almost instantaneously (just above 16ms) as shown with notification 5 on Figure 6.17. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 1 on Figure 6.17.) picked-up 10 seconds later when the internal fault was simulated subsequent to 10 seconds external fault as shown with notification 5 on Figure 6.17. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.

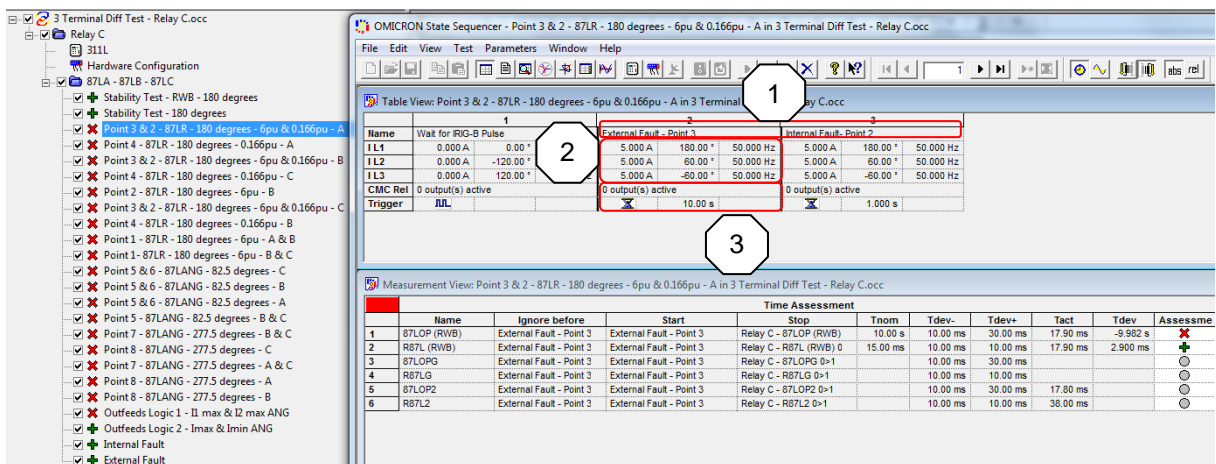**Figure 6.17**: Injected analogue values and test results for relay A for point 4

Figure 6.18: Injected analogue values and test results for relay C

Figure 6.19 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET┐

SEL-311L A                    Date: 11/01/2014    Time: 12:37:53.627
311L STUDY
```
```
Local          A         B         C        3I0       3I2        I1
I MAG (A Pri) 2506.047  2505.551  2504.909    6.921     8.289  2505.500
I ANG (DEG)     -0.10    -120.10    120.10  -139.40    -20.50      0.00
Channel X       A         B         C        3I0       3I2        I1
I MAG (A Pri)  477.190   476.423   476.576    0.864     1.607   476.729
I ANG (DEG)   -179.90     60.00    -60.00   -91.70   -158.00    180.00
Channel Y       A         B         C        3I0       3I2        I1
I MAG (A Pri)  596.498   597.240   596.523    2.353     0.800   596.753
I ANG (DEG)      0.30   -119.70    120.50  -145.60     -6.90      0.40
Vector Sum      A         B         C        3I0       3I2        I1
I MAG (A Pri) 2625.348  2626.358  2624.845    9.849     7.933  2625.513
I ANG (DEG)      0.00   -120.00    120.10  -137.10    -26.90      0.00
Alpha Plane     A         B         C     ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS         0.040     0.040     0.040     0.000     0.000     0.040
ANG (DEG)       1.30      1.70      2.00      0.00      0.00      1.70
=>MET┐
```
②

```
SEL-311L B                    Date: 11/01/2014    Time: 13:08:21.307
311L STUDY
```
③
```
Local          A         B         C        3I0       3I2        I1
I MAG (A Pri)  478.364   477.210   477.337    1.597     0.387   477.637
I ANG (DEG)      0.00   -120.00    119.90    8.90     41.30      0.00
Channel X       A         B         C        3I0       3I2        I1
I MAG (A Pri)  598.199   596.888   597.586    0.365     0.906   597.557
I ANG (DEG)    179.80     59.80    -60.10   141.20   -105.10    179.80
Channel Y       A         B         C        3I0       3I2        I1
I MAG (A Pri) 2504.288  2512.860  2514.326   14.694     4.000  2510.490
I ANG (DEG)    179.90     59.80    -60.10    -2.30     36.00    179.90
Vector Sum      A         B         C        3I0       3I2        I1
I MAG (A Pri) 2624.124  2632.541  2634.574   15.977     3.720  2630.411
I ANG (DEG)    179.80     59.70    -60.10    -0.40     27.70    179.80
Alpha Plane     A         B         C     ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS         6.480     6.510     6.510     0.000     0.000     6.500
ANG (DEG)     179.80    179.80    180.00      0.00      0.00    179.90
```
④
```
=>MET┐

SEL-311L C                    Date: 11/01/2014    Time: 04:22:28.181
311L STUDY
```
⑤
```
Local          A         B         C        3I0       3I2        I1
I MAG (A Pri)  597.750   597.954   597.123    1.793     0.664   597.609
I ANG (DEG)     -0.10   -120.00    120.00   -93.80    -14.60      0.00
Channel X       A         B         C        3I0       3I2        I1
I MAG (A Pri) 2502.231  2495.233  2493.781    4.713    16.323  2497.079
I ANG (DEG)     -0.50   -120.60    119.60   -84.50     -5.40     -0.50
Channel Y       A         B         C        3I0       3I2        I1
I MAG (A Pri)  478.682   475.701   478.094    3.202     2.402   477.492
I ANG (DEG)    179.70     59.70    -60.30  -140.70    120.40    179.70
Vector Sum      A         B         C        3I0       3I2        I1
I MAG (A Pri) 2621.288  2617.461  2612.799    8.772    15.684  2617.178
I ANG (DEG)     -0.40   -120.40    119.50  -104.10      1.40     -0.40
Alpha Plane     A         B         C     ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS         3.380     3.370     3.370     0.000     0.000     3.370
ANG (DEG)       0.40      0.50      0.30      0.00      0.00      0.40
```
⑥

Figure 6.19: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.19 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 2506.047∠-0.1°A, White Phase current = 2505.551∠-120.1°A and Blue Phase current = 2504.909∠120.1°A.
- Relay B Red Phase current = 477.190/-179.9°, White Phase current = 476.423∠60°A and Blue Phase current = 476.576∠59.8°A.
- Relay C Red Phase current = 596.498∠0.3°A, White Phase current = 597.240/-119.7°A and Blue Phase current = 596.523∠120.5°A.
- Relay A then calculated its alpha values as shown with notification 2 on Figure 6.19.
- Relay A Red Phase Alpha α = 0.04∠1.3°, White Phase Alpha α = 0.04∠1.7° and Blue Phase Alpha α = 0.04∠2° as shown with notification 2 on Figure 6.19.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.19 it can be seen that:

- Relay A Red Phase current = 2504.288∠179.9°A, White Phase current = 2512.860∠59.8°A and Blue Phase current = 2514.326∠-60.1°A.
- Relay B Red Phase current = 478.364∠0°A, White Phase current = 477.210∠-120°A and Blue Phase current = 477.337∠119.9°A.
- Relay C Red Phase current = 597.421∠-0.3°A, White Phase current = 597.784∠-120.1°A and Blue Phase current = 599.566∠119.9°A.
- Relay B then calculated its alpha values as shown with notification 4 on Figure 6.18.
- Relay B Red Phase Alpha α = 6.480∠179.8°, White Phase Alpha α = 6.51∠179.8° and Blue Phase Alpha α = 6.510∠180° as shown with notification 4 on Figure 6.18.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.19 it can be seen that:

- Relay A Red Phase current = 2502.231∠-0.5°A, White Phase current = 2495.233∠-120.6°A and Blue Phase current = 2493.781∠119.6°A.
- Relay B Red Phase current = 478.682∠179.7°A, White Phase current = 475.701∠59.7°A and Blue Phase current = 478.094∠-60.3°A.
- Relay C Red Phase current = 597.750∠-0.1°A, White Phase current = 597.954∠-120°A and Blue Phase current = 597.123/120°A.
- Relay C then calculated its alpha values as shown with notification 6 on Figure 6.19.
- Relay C Red Phase Alpha α = 3.380∠0.4°, White Phase Alpha α = 3.370∠0.5° and Blue Phase Alpha α = 3.370∠0.3° as shown with notification 6 on Figure 6.19.

6.6.5 Case study 5 – Relay A point 5

Using values from Table 6.2, the results from Figure 6.20and Figure 6.21 show that;

- Relay A point 5 and 6 were tested on the same test module as shown with notification 1 on Figure 6.20.
- For point 5, 1∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 1∠180°A was injected on relay B (notification 2 on Figure 6.20) and 27.74∠-82°A (= 5.548 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C (notification 2 on Figure 6.21)
- This external fault was simulated for 1 second as shown with notification 3 on Figure 6.20 and Figure 21.
- Restraint elements R87LA, R87LB and R87LC on (notification 4 on Figure 6.20) picked-up almost instantaneously (just above 12ms) as show notification 5 on Figure 6.20. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 on Figure 6.21) picked-up 10 seconds later when the internal fault was simulated subsequent to 1 second external fault as show notification 5 on Figure 6.20. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.
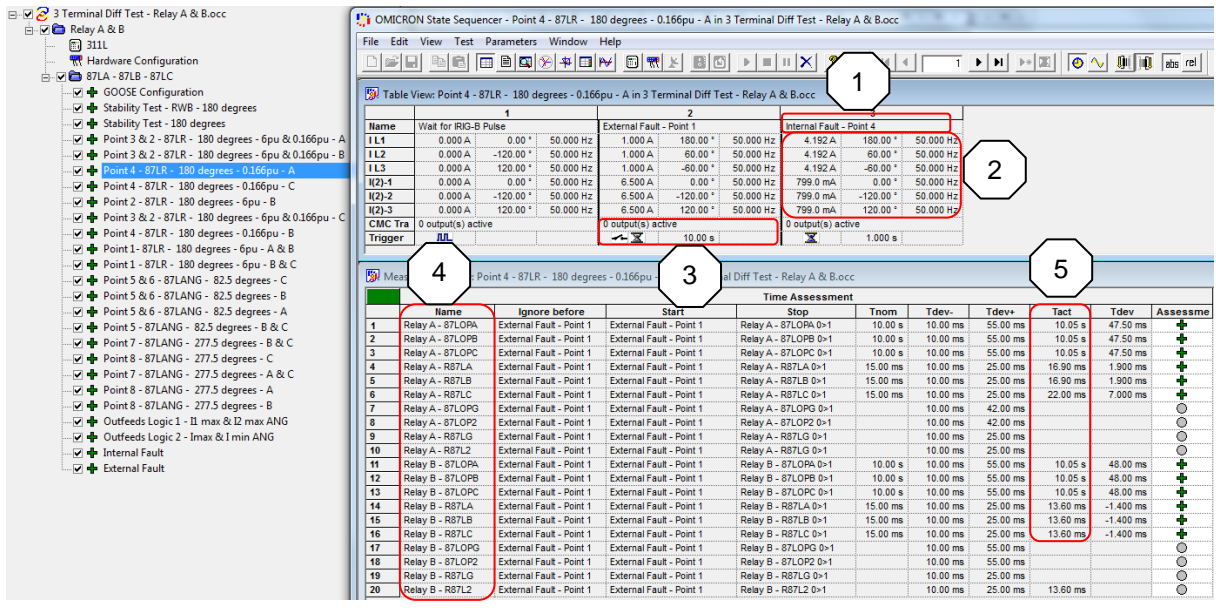
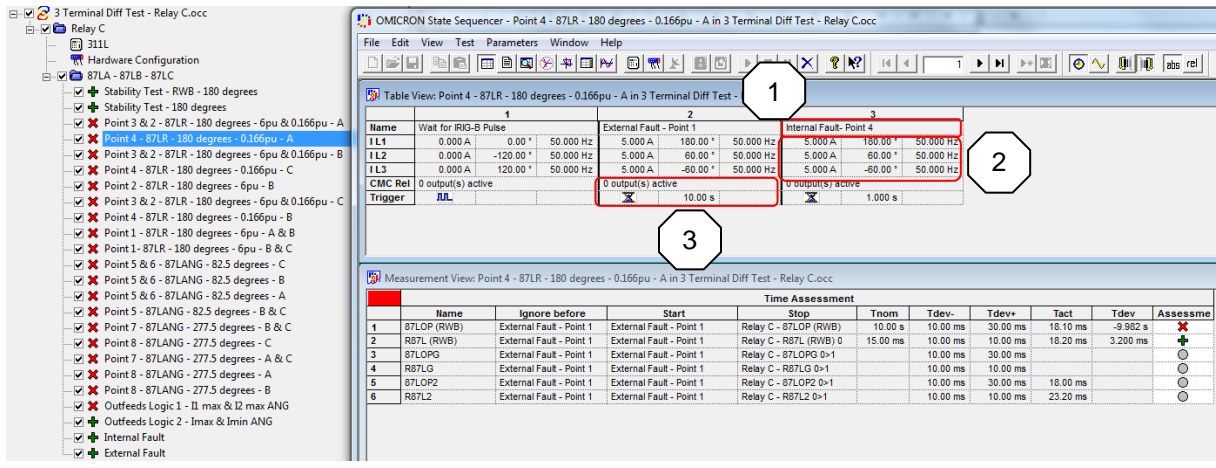**Figure 6.20:** Injected analogue values and test results for relay A point 5 and 6

Figure 6.21: Injected analogue values and test results for relay C

Figure 6.22 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET

SEL-311L A                        Date: 11/01/2014    Time: 14:12:22.105
311L STUDY

Local            A          B          C          3I0        3I2        I1
I MAG (A Pri)  597.594    597.685    597.158      2.123      2.035    597.478
I ANG (DEG)     -0.10     -120.10     120.10    -145.40     -10.60      0.00
Channel X        A          B          C          3I0        3I2        I1
I MAG (A Pri)  600.101    599.215    598.534      2.239      0.606    599.283
I ANG (DEG)     -0.20     -120.10     119.80     -11.30     146.30     -0.20
Channel Y        A          B          C          3I0        3I2        I1
I MAG (A Pri) 3306.988   3318.932   3315.097     13.061     11.397   3313.671
I ANG (DEG)     97.60     -22.30    -142.30     -34.90     -64.50     97.70
Vector Sum       A          B          C          3I0        3I2        I1
I MAG (A Pri) 3362.926   3371.892   3368.032     14.412     12.147   3366.935
I ANG (DEG)     76.90     -42.80    -162.80     -39.20     -58.10     77.00
Alpha Plane      A          B          C        ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS          5.480      5.500      5.490      0.000      0.000      5.490
ANG (DEG)       87.40      87.60      87.40      0.00       0.00      87.50

=>MET

SEL-311L B                        Date: 11/01/2014    Time: 14:42:44.865
311L STUDY

Local            A          B          C          3I0        3I2        I1
I MAG (A Pri)  597.776    597.071    596.898      0.932      0.578    597.248
I ANG (DEG)     -0.10     -120.00     120.00     -40.70     -27.20      0.00
Channel X        A          B          C          3I0        3I2        I1
I MAG (A Pri) 3310.977   3304.443   3317.887     12.615     23.231   3311.101
I ANG (DEG)     97.40     -22.60    -142.50    -144.20     12.10     97.40
Channel Y        A          B          C          3I0        3I2        I1
I MAG (A Pri)  597.728    597.276    597.524      4.031      4.642    597.506
I ANG (DEG)     -0.10     -120.10     120.30    -152.80     -19.50      0.10
Vector Sum       A          B          C          3I0        3I2        I1
I MAG (A Pri) 3370.354   3363.901   3378.986     16.386     27.774   3373.455
I ANG (DEG)     76.70     -43.10    -162.90    -143.10      6.30     76.80
Alpha Plane      A          B          C        ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS          5.490      5.490      5.520      0.000      0.000      5.500
ANG (DEG)       87.10      86.90      87.10      0.00       0.00      87.00

=>MET

SEL-311L C                        Date: 11/01/2014    Time: 05:56:58.595
311L STUDY

Local            A          B          C          3I0        3I2        I1
I MAG (A Pri) 3314.192   3315.537   3313.349      8.085      4.624   3314.358
I ANG (DEG)     -0.10     -120.00     120.00    -113.10     -68.90      0.00
Channel X        A          B          C          3I0        3I2        I1
I MAG (A Pri)  596.457    598.386    596.544      3.540      0.725    597.128
I ANG (DEG)    -98.10     141.90      22.10     130.60     -28.50     -98.00
Channel Y        A          B          C          3I0        3I2        I1
I MAG (A Pri)  598.286    595.882    596.006      1.441      3.022    596.724
I ANG (DEG)    -97.80     142.00      22.20     -50.00     -70.40     -97.90
Vector Sum       A          B          C          3I0        3I2        I1
I MAG (A Pri) 3365.359   3362.135   3365.065      7.414      8.206   3363.168
I ANG (DEG)    -20.60    -140.50      99.40    -127.70     -66.10     -20.50
Alpha Plane      A          B          C        ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS          0.360      0.360      0.350      0.000      0.000      0.360
ANG (DEG)       97.80      97.90      97.90      0.00       0.00      97.90

=>
```

Figure 6.22: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.22 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 597.594∠-0.1°A, White Phase current = 597.685∠-120.1°A and Blue Phase current = 597.158∠120.1°A.
- Relay B Red Phase current = 600.101∠-0.2°A, White Phase current = 599.215∠-120.1°A and Blue Phase current = 598.534∠119.8°A.
- Relay C Red Phase current = 3306.988∠97.6°, White Phase current = 3318.932∠-22.3°A and Blue Phase current = 3315.097∠-142.3°A.
- Relay A then calculated its alpha values as shown with notification 2 on Figure 6.22.
- Relay A Red Phase Alpha α = 5.480∠87.4°, White Phase Alpha α = 5.500∠87.6° and Blue Phase Alpha α = 5.490∠87.4° as shown with notification 2 on Figure 6.22.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.22 it can be seen that:

- Relay A Red Phase current = 597.728∠-0.1°A, White Phase current = 597.071∠-120°A and Blue Phase current = 597.524∠120.8°A.
- Relay B Red Phase current = 597.776∠-0.1°A, White Phase current = 2505.276∠-120.1°A and Blue Phase current = 596.898∠120°A.
- Relay C Red Phase current = 3310.977∠97.4°A, White Phase current = 3304.443∠-22.6°A and Blue Phase current = 3317.887∠-142.5°A.
- Relay B then calculated its alpha values as shown with notification 4 on Figure 6.20.
- Relay B Red Phase Alpha α = 5.480∠87.4°, White Phase Alpha α = 5.500/87.6° and Blue Phase Alpha α = 5.490∠87.4° as shown with notification 4 on Figure 6.20.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.22 it can be seen that:

- Relay A Red Phase current = 596.457∠-98.1°A, White Phase current = 598.386∠141.9°A and Blue Phase current = 596.544∠22.1°A.
- Relay B Red Phase current = 598.286∠-97.8°A, White Phase current = 595.882 ∠142°A and Blue Phase current = 596.006∠22.2°A.
- Relay C Red Phase current = 3314.192∠-0.1°A, White Phase current = 3315.537∠-120°A and Blue Phase current = 3313.349/120°A.
- Relay C then calculated its alpha values as shown with notification 6 on Figure 6.22.
- Relay C Red Phase Alpha α = 0.360∠97.8°, White Phase Alpha α = 0.360∠97.9° and Blue Phase Alpha α = 0.360∠97.9° as shown with notification 6 on Figure 6.22.

6.6.6 Case study 6 – Relay A point 6

Using values from Table 6.2, the results from Figure 6.23 and Figure 6.24 show that;

- Relay A point 5 and 6 were tested on the same test module as shown with notification 1 on Figure 6.23.
- For point 6, 1∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 1∠180°A was injected on relay B (2) and 4.74∠-9.9°A (= 0.948 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C (notification 2 on Figure 6.23).
- This external fault was simulated for 1 second as shown with notification 3 on Figure 6.23 and Figure 24.
- Restraint elements R87LA, R87LB and R87LC on (notification 4 on Figure 6.23) picked-up almost instantaneously (just above 12ms) as show notification 5 on Figure 6.19. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 on Figure 6.23) picked-up 10 seconds later when the internal fault was simulated subsequent to 1 second external fault as show notification 5 on Figure 6.23. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.
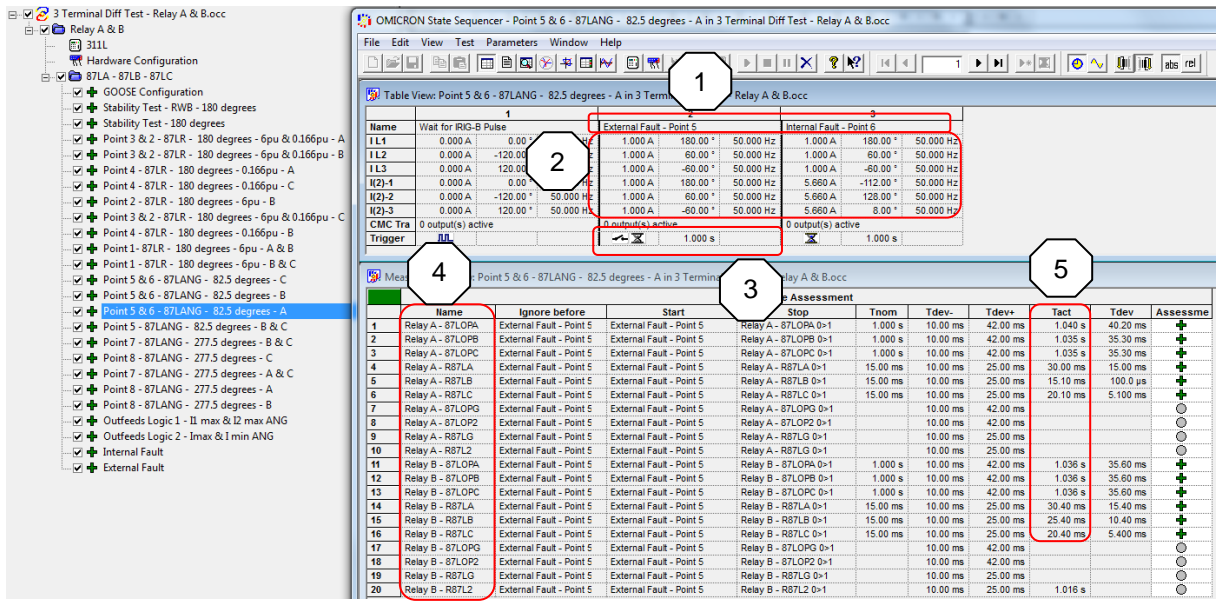
Figure 6.23: Injected analogue values and test results for relay A point 5 and 6
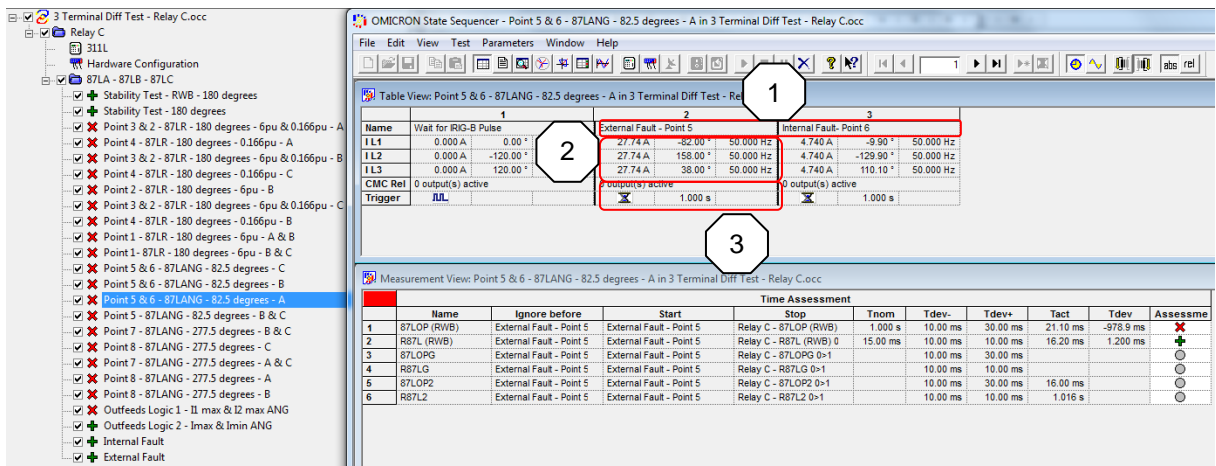

Figure 6.24: Injected analogue values and test results for relay C

Figure 6.25 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET

SEL-311L A                    Date: 11/01/2014    Time: 14:08:42.899
311L STUDY

Local              A         B         C        3I0       3I2        I1
I MAG (A Pri)    597.337   597.428   597.648    2.301     2.193    597.470
I ANG (DEG)       -0.10    -120.10    120.10  -161.00    -30.70      0.00
Channel X          A         B         C        3I0       3I2        I1
I MAG (A Pri)   3398.554  3387.304  3387.893   13.422     9.619   3391.250
I ANG (DEG)       67.60    -52.30   -172.40    61.10     48.40     67.70
Channel Y          A         B         C        3I0       3I2        I1
I MAG (A Pri)    565.921   566.410   568.366    2.736     4.741    566.897
I ANG (DEG)      169.60     49.90    -70.00    22.60     69.60    169.90
Vector Sum         A         B         C        3I0       3I2        I1
I MAG (A Pri)   3507.246  3493.381  3494.366   13.857    14.458   3498.039
I ANG (DEG)       67.50    -52.20   -172.30    60.40     46.50     67.70
Alpha Plane        A         B         C      ZERO-SEQ  NEG-SEQ   POS-SEQ
RADIUS            5.560     5.540     5.540     0.000     0.000     5.550
ANG (DEG)        77.30     77.40     77.10     0.00      0.00     77.30
=>MET

SEL-311L B                    Date: 11/01/2014    Time: 14:39:02.470
311L STUDY

Local              A         B         C        3I0       3I2        I1
I MAG (A Pri)   3386.494  3379.400  3381.005    6.196     4.309   3382.299
I ANG (DEG)       -0.10    -120.00    120.00   -29.60    -11.00      0.00
Channel X          A         B         C        3I0       3I2        I1
I MAG (A Pri)    568.387   566.429   566.507    1.294     4.374    567.107
I ANG (DEG)      101.90    -18.20   -138.10   122.50    111.50    101.90
Channel Y          A         B         C        3I0       3I2        I1
I MAG (A Pri)    599.419   597.491   596.714    0.685     5.178    597.874
I ANG (DEG)      -67.90    172.00     52.20  -111.20    -58.80    -67.90
Vector Sum         A         B         C        3I0       3I2        I1
I MAG (A Pri)   3495.328  3486.832  3490.021    5.152     5.441   3490.727
I ANG (DEG)       -0.10   -119.90    119.90   -30.30    -12.50      0.00
Alpha Plane        A         B         C      ZERO-SEQ  NEG-SEQ   POS-SEQ
RADIUS           0.030     0.030     0.030     0.000     0.000     0.030
ANG (DEG)         0.50      0.20      0.90      0.00      0.00      0.50
=>MET

SEL-311L C                    Date: 11/01/2014    Time: 05:53:04.739
311L STUDY

Local              A         B         C        3I0       3I2        I1
I MAG (A Pri)    567.158   567.074   567.023    1.364     1.023    567.085
I ANG (DEG)       -0.10    -120.00    120.00  -106.10    -77.20      0.00
Channel X          A         B         C        3I0       3I2        I1
I MAG (A Pri)    599.312   598.646   598.182    1.449     2.221    598.713
I ANG (DEG)     -170.40     69.60    -50.20    73.00    178.30   -170.30
Channel Y          A         B         C        3I0       3I2        I1
I MAG (A Pri)   3399.774  3382.136  3386.073   15.293    18.492   3389.328
I ANG (DEG)     -102.20    137.80     17.80   -80.80   -107.80   -102.20
Vector Sum         A         B         C        3I0       3I2        I1
I MAG (A Pri)   3503.454  3484.617  3490.329   15.226    20.055   3492.802
I ANG (DEG)     -102.20    137.70     17.70   -80.50   -112.40   -102.20
Alpha Plane        A         B         C      ZERO-SEQ  NEG-SEQ   POS-SEQ
RADIUS           6.460     6.430     6.440     0.000     0.000     6.440
ANG (DEG)       110.70    110.90    110.90     0.00      0.00    110.80
```

Figure 6.25: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.25 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 597.337∠-0.1°A, White Phase current = 597.428∠-120.1°A and Blue Phase current = 597.648∠120.1°A.
- Relay B Red Phase current = 3398.554∠67.6°A, White Phase current = 3387.304∠-52.3°A and Blue Phase current = 3387.893∠-172.4°A.
- Relay C Red Phase current = 565.921/169.6°A, White Phase current = 566.410∠49.9°A and Blue Phase current = 568.366∠-70°A.
- Relay A then calculated its alpha values as shown with notification 2 on Figure 6.25.
- Relay A Red Phase Alpha α = 5.560∠77.3°, White Phase Alpha α = 5.540∠77.4° and Blue Phase Alpha α = 5.540∠77.1° as shown with notification 2 on Figure 6.25.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.25 it can be seen that:

- Relay A Red Phase current = 599.419∠-67.9°A, White Phase current = 597.071∠-120°A and Blue Phase current = 597.524∠120.8°A.
- Relay B Red Phase current = 3386.494∠-0.1°, White Phase current = 3379.400∠-120°A and Blue Phase current = 3381.005∠120°A.
- Relay C Red Phase current = 568.387∠101.9°A, White Phase current = 566.429∠-18.2°A and Blue Phase current = 566.507∠-132.1°A.
- Relay B then calculated its alpha values as show on as shown with notification 4 on Figure 6.25.
- Relay B Red Phase Alpha α = 0.03∠0.5°, White Phase Alpha α = 0.03∠0.2° and Blue Phase Alpha α = 0.03∠0.9° as shown with notification 4 on Figure 6.25.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.25 it can be seen that:

- Relay A Red Phase current = 599.312∠-170.4°A, White Phase current = 598.646∠69.6°A and Blue Phase current = 598.182∠-50.2°A.
- Relay B Red Phase current = 3399.774∠-102.2°, White Phase current = 595.882∠142°A and Blue Phase current = 596.006∠22.2°A.
- Relay C Red Phase current = 3314.192∠-0.1°A, White Phase current = 3382.136∠137.8°A and Blue Phase current = 3386.073∠17.8°A.
- Relay C then calculated its alpha values as show on as shown with notification 6 on Figure 6.25.
- Relay C Red Phase Alpha α = 6.460∠110.7°, White Phase Alpha α = 6.430∠110.9° and Blue Phase Alpha α = 6.440∠110.9° as shown with notification 6 on Figure 6.25.

6.6.7 Case study 7 – Relay A point 7

Using values from Table 6.4, the results from Figure 6.26 and Figure 6.27 show that;

- Relay A point 7 and 8 as well as point 7 for relay C were tested on the same test module as shown with notification 1 on Figure 6.26.
- For relay A point 7, 1∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 5.547∠82°A was injected on relay B (notification 2 on Figure 6.26.) and 1∠180°A (= 0.948 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.26.
- Same values represent point 7 of relay C
- This external fault was simulated for 10 seconds as shown with notification 3 on Figure 6.26.
- Restraint elements R87LA, R87LB and R87LC on (notification 4 on Figure 6.26.) picked-up almost instantaneously (just above 12ms) as shown with notification 5 on Figure 6.26. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 on Figure 6.26.) picked-up 10 seconds later when the internal fault was simulated subsequent to 10 seconds external fault as shown with notification 5 on Figure 6.26. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.
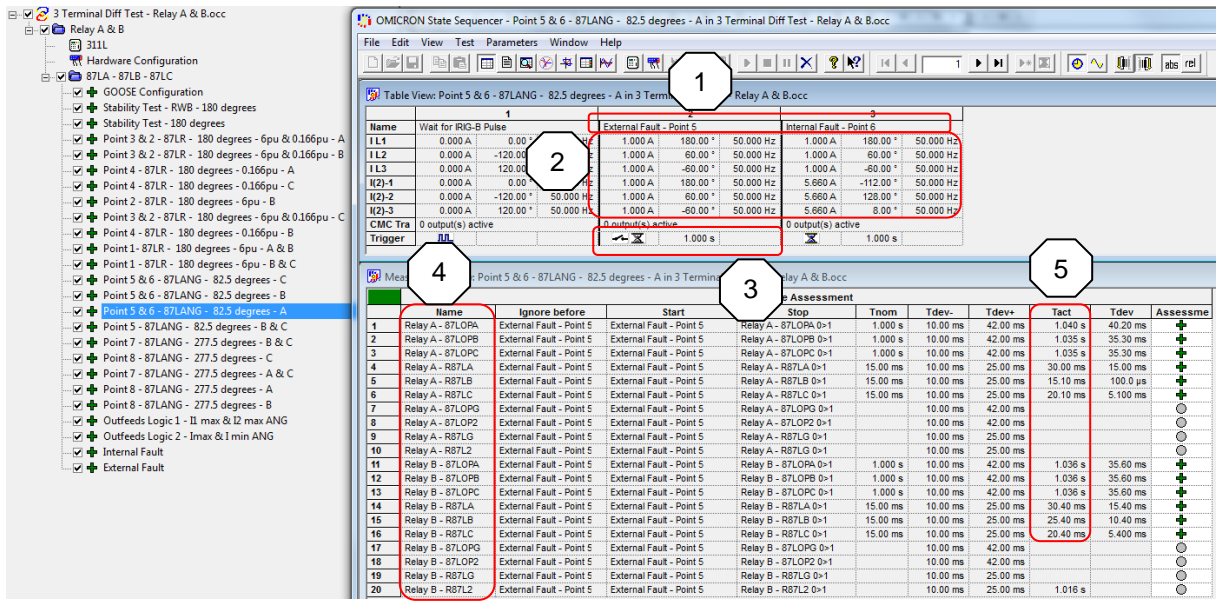
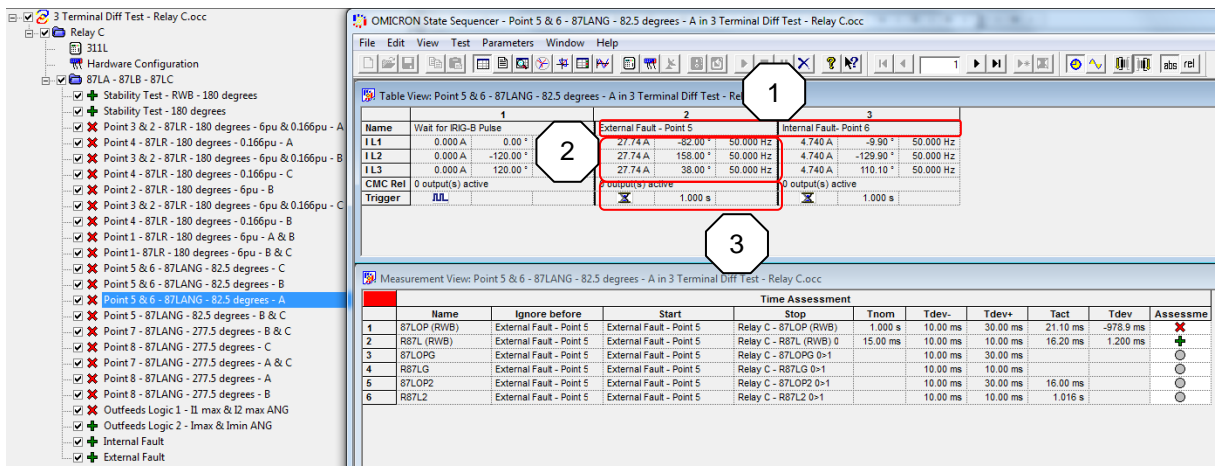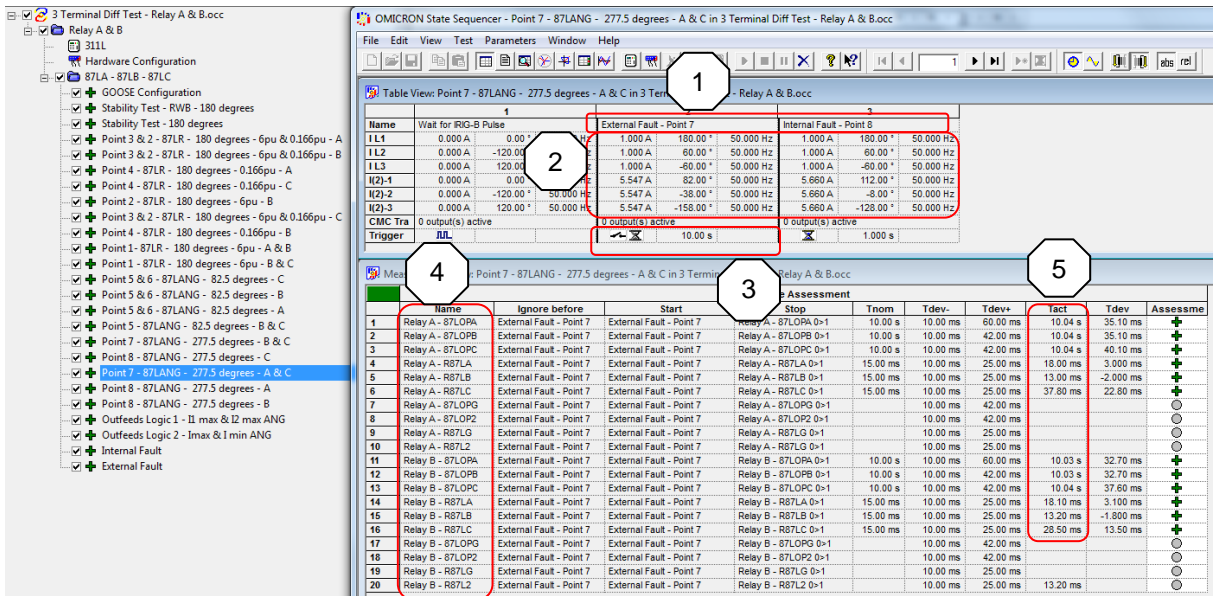**Figure 6.26**: Injected analogue values and test results for relay A point 7 and 8 as well as relay C point 7
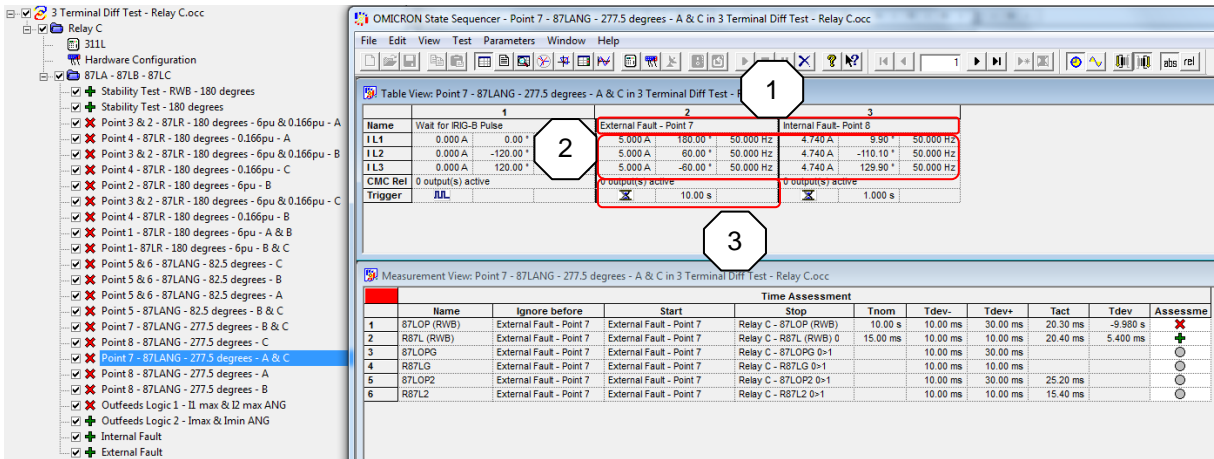
Figure 6.27: Injected analogue values and test results for relay C Point 7

Figure 6.28 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

MET₁

SEL-311L A   Date: 10/30/2014   Time: 12:48:39.913
311L STUDY

Local	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3317.220	3316.480	3314.785	9.121	10.633	3316.159
I ANG (DEG)	-0.10	-120.10	120.10	-138.80	-15.60	0.00
Channel X	A	B	C	3I0	3I2	I1
I MAG (A Pri)	598.988	599.722	596.706	2.049	5.764	598.471
I ANG (DEG)	98.10	-22.00	-142.10	62.40	154.20	98.00
Channel Y	A	B	C	3I0	3I2	I1
I MAG (A Pri)	598.052	598.890	599.593	1.088	0.443	598.845
I ANG (DEG)	98.50	-21.50	-141.50	-83.40	-29.90	98.50
Vector Sum	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3357.111	3359.670	3361.131	7.831	5.465	3359.305
I ANG (DEG)	20.40	-99.30	140.60	-137.60	-5.90	20.50
Alpha Plane	A	B	C	ZERO-SEQ	NEG-SEQ	POS-SEQ
RADIUS	0.360	0.360	0.360	0.000	0.000	0.360
ANG (DEG)	98.30	98.30	98.10	0.00	0.00	98.30

L

SEL-311L B   Date: 10/30/2014   Time: 13:19:05.956
311L STUDY

Local	A	B	C	3I0	3I2	I1
I MAG (A Pri)	598.070	597.413	597.494	0.904	0.843	597.659
I ANG (DEG)	0.00	-120.10	119.90	36.90	38.70	0.00
Channel X	A	B	C	3I0	3I2	I1
I MAG (A Pri)	598.341	597.546	597.550	0.466	1.792	597.812
I ANG (DEG)	-0.10	-120.20	120.00	-167.90	-35.40	-0.10
Channel Y	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3317.991	3319.519	3318.740	8.862	9.562	3318.748
I ANG (DEG)	-98.20	141.70	21.80	49.70	-33.80	-98.20
Vector Sum	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3362.748	3363.866	3365.194	9.375	11.630	3363.254
I ANG (DEG)	-77.50	162.20	42.30	50.20	-30.00	-77.60
Alpha Plane	A	B	C	ZERO-SEQ	NEG-SEQ	POS-SEQ
RADIUS	5.500	5.500	5.500	0.000	0.000	5.500
ANG (DEG)	87.60	87.70	87.50	0.00	0.00	87.60

L

SEL-311L C   Date: 10/30/2014   Time: 04:33:40.809
311L STUDY

Local	A	B	C	3I0	3I2	I1
I MAG (A Pri)	597.756	597.694	597.542	1.317	1.002	597.664
I ANG (DEG)	-0.10	-120.10	120.00	-118.20	-28.10	0.00
Channel X	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3311.294	3308.538	3316.716	17.044	21.325	3312.170
I ANG (DEG)	-98.50	141.60	21.90	99.10	-153.80	-98.30
Channel Y	A	B	C	3I0	3I2	I1
I MAG (A Pri)	599.235	596.602	597.681	1.309	3.670	597.839
I ANG (DEG)	0.00	-120.10	120.00	51.00	-25.90	0.00
Vector Sum	A	B	C	3I0	3I2	I1
I MAG (A Pri)	3351.568	3351.405	3362.616	16.873	18.858	3355.183
I ANG (DEG)	-77.80	162.20	42.40	98.40	-142.30	-77.60
Alpha Plane	A	B	C	ZERO-SEQ	NEG-SEQ	POS-SEQ
RADIUS	5.480	5.480	5.500	0.000	0.000	5.480
ANG (DEG)	87.90	87.90	87.70	0.00	0.00	87.80

L

Figure 6.28: Measured primary currents and calculated alpha values for relay A, B and C

Even though measurements for relay A point 7 were not captured, based on injected secondary values on relay A which are similar to relay C, relay A point 7 measured value were similar to relay C point 7 as show on Figure 6.28.

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.28 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 3317.220∠-0.1°A, White Phase current = 3316.480∠-120.1°A and Blue Phase current = 3314.785∠120.1°A.
- Relay B Red Phase current = 598.988/98.1°A, White Phase current = 599.722∠-22°A and Blue Phase current = 596.706∠-142.1°A.
- Relay C Red Phase current = 598.052∠98.5°, White Phase current = 598.890∠-12.5°A and Blue Phase current = 599.593∠-141.5°A.
- Relay A then calculated its alpha values as shown with notification 2 on Figure 6.28.
- Relay A Red Phase Alpha α = 0.360∠98.3°, White Phase Alpha α = 0.360∠98.3° and Blue Phase Alpha α = 0.360∠98.1° as shown with notification 2 on Figure 6.28.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.28 it can be seen that:

- Relay A Red Phase current = 3317.991∠-98.2°, White Phase current = 3319.519∠141.7°A and Blue Phase current = 597.494∠119.9°A.
- Relay B Red Phase current = 598.070/0°A, White Phase current = 597.413∠-120.1°A and Blue Phase current = 597.494∠119.9°A.
- Relay C Red Phase current = 598.341∠-0.1°A, White Phase current = 597.546∠-120.2°A and Blue Phase current = 597.550∠120°A.
- Relay B then calculated its alpha values as show on as shown with notification 4 on Figure 6.28.
- Relay B Red Phase Alpha α = 5.5/87.6°, White Phase Alpha α = 5.5/87.7° and Blue Phase Alpha α = 5.5/87.5° as shown with notification 4 on Figure 6.28.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.28 it can be seen that:

- Relay A Red Phase current = 3311.294∠-98.5°A, White Phase current = 3308.538∠141.6°A and Blue Phase current = 3316.716∠21.9°A.

- Relay B Red Phase current = 599.235∠0°A, White Phase current = 596.602∠-120.1°A and Blue Phase current = 597.681∠120°A.

- Relay C Red Phase current = 597.756∠-0.1°A, White Phase current = 597.694∠-120.1°A and Blue Phase current = 597.542/120°A.

- Relay C then calculated its alpha values as shown with notification 6 on Figure 6.28.
- Relay C Red Phase Alpha α = 5.480∠87.9°, White Phase Alpha α = 5.480∠87.9° and Blue Phase Alpha α = 5.500∠87.7° as shown with notification 6 on Figure 6.28.
-

6.6.8 Case study 8 – Relay A point 8

Using values from Table 6.2, the results from Figure 6.29 and Figure 6.30 show that;

- Relay A point 7 and 8 as well as point 7 for relay A were tested on the same test module as shown with notification 1 on Figure 6.29.

- This external fault was simulated for 10 seconds as shown with notification 3 on Figure 6.29.

- For relay A point 8, 1∠180°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 5.66∠112°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay B (notification 2 on Figure 6.29.) and 4.74∠9.9°A (= 0.948 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.29.

- Restraint elements R87LA, R87LB and R87LC on (notification 4 on Figure 6.29.) picked-up almost instantaneously (just above 12ms) as shown with notification 5 on Figure 6.29. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.

- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 on Figure 6.29.) picked-up 10 seconds later when the internal fault was simulated subsequent to 10 seconds external fault as shown with notification 5 on Figure

6.29. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.
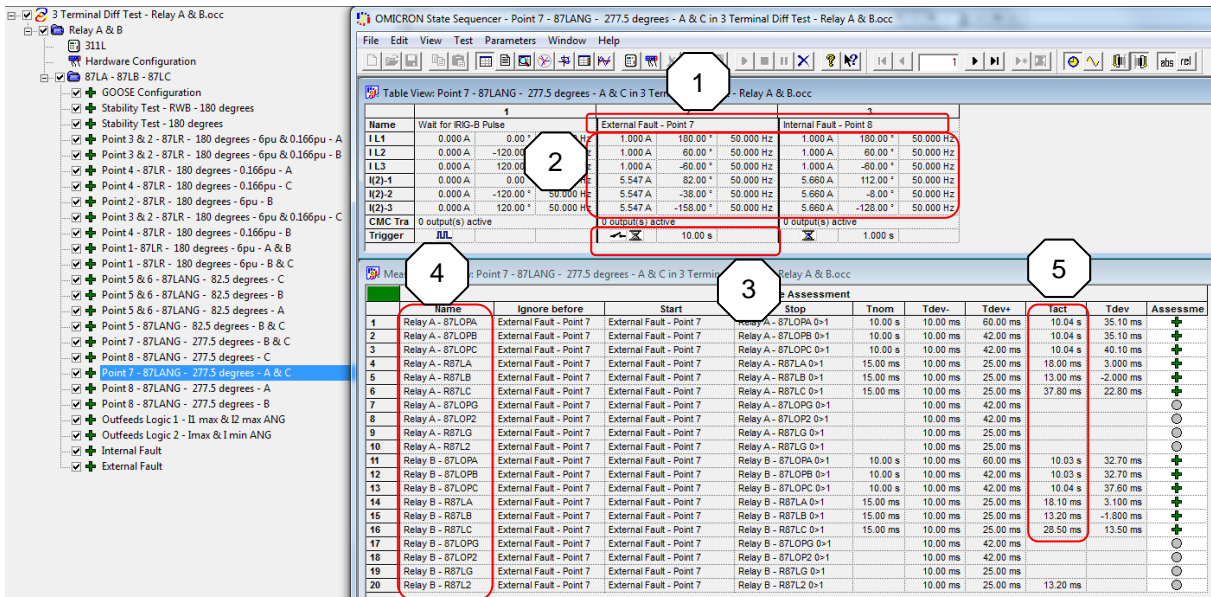
Figure 6.29: Injected analogue values and test results for relay A point 7 and 8 as well as relay C point 7
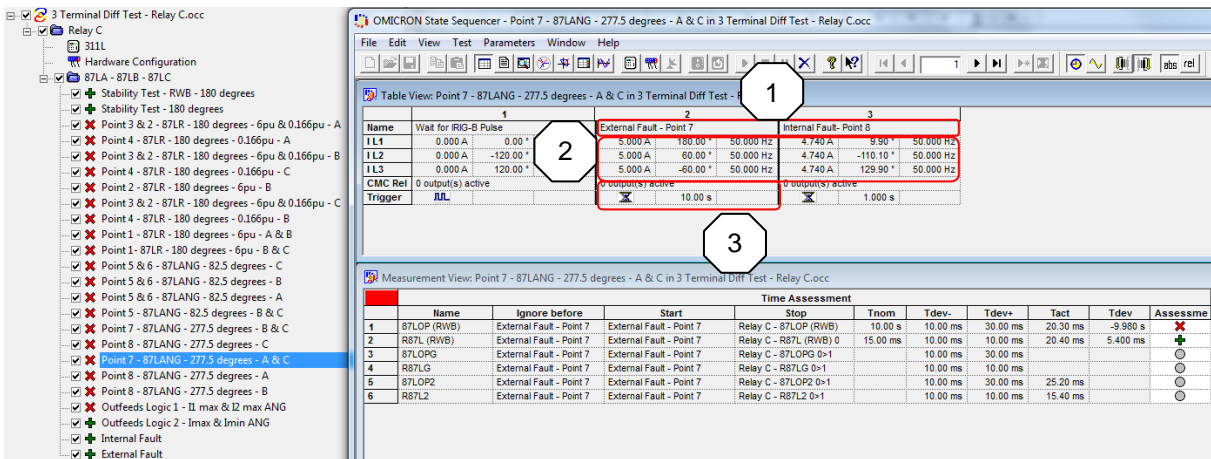
Figure 6.30: Injected analogue values and test results for relay A Point 8

Figure 6.31 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET₁

SEL-311L A                      Date: 11/01/2014     Time: 14:47:32.759
311L STUDY

Local             A         B         C         3I0       3I2        I1
I MAG (A Pri)   597.945   597.360   597.356     1.428     1.803    597.553
I ANG (DEG)      -0.10    -120.10    120.10    -139.40    -11.30      0.00
Channel X         A         B         C         3I0       3I2        I1
I MAG (A Pri)  3391.876  3375.817  3374.812    18.271    17.084   3380.834
I ANG (DEG)     -68.40    171.70     51.70     -79.50    -73.00    -68.30
Channel Y         A         B         C         3I0       3I2        I1
I MAG (A Pri)   567.580   567.867   566.036     1.362     1.970    567.161
I ANG (DEG)    -170.00     70.00    -50.00      92.40   -116.10   -170.00
Vector Sum        A         B         C         3I0       3I2        I1
I MAG (A Pri)  3498.273  3482.153  3480.732    17.671    19.377   3486.406
I ANG (DEG)     -68.30    171.70     51.60     -82.80    -72.20    -68.20
Alpha Plane       A         B         C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           5.560     5.530     5.530      0.000     0.000     5.540
ANG (DEG)        77.80     77.80     78.00      0.00      0.00     77.90
L

=>MET₁

SEL-311L B                      Date: 11/01/2014     Time: 15:17:54.170
311L STUDY

Local             A         B         C         3I0       3I2        I1
I MAG (A Pri)  3387.502  3383.642  3382.591     5.375     4.835   3384.578
I ANG (DEG)      -0.10    -120.00    120.00    -34.10     11.00      0.00
Channel X         A         B         C         3I0       3I2        I1
I MAG (A Pri)   566.550   566.634   566.575     1.959     1.725    566.586
I ANG (DEG)    -101.90    138.10     18.30     117.60   -145.90   -101.90
Channel Y         A         B         C         3I0       3I2        I1
I MAG (A Pri)   597.721   597.528   597.473     0.502     0.401    597.574
I ANG (DEG)      68.30    -51.70    -171.70    -13.90    -21.40     68.30
Vector Sum        A         B         C         3I0       3I2        I1
I MAG (A Pri)  3491.882  3488.052  3487.991     4.265     3.696   3488.979
I ANG (DEG)       0.00   -119.90    119.90     -19.10     -2.80      0.00
Alpha Plane       A         B         C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           0.030     0.030     0.030      0.000     0.000     0.030
ANG (DEG)        0.50      0.30      0.20       0.00      0.00      0.30
L

=>MET₁

SEL-311L C                      Date: 11/01/2014     Time: 06:31:59.818
311L STUDY

Local             A         B         C         3I0       3I2        I1
I MAG (A Pri)   566.553   566.265   565.878     1.668     0.668    566.232
I ANG (DEG)      -0.10    -120.00    120.00    -85.60    -44.40      0.00
Channel X         A         B         C         3I0       3I2        I1
I MAG (A Pri)   597.696   595.017   596.433     1.860     2.591    596.382
I ANG (DEG)     169.80     50.00    -70.00     155.40    103.80    169.90
Channel Y         A         B         C         3I0       3I2        I1
I MAG (A Pri)  3400.587  3388.053  3391.804     7.128    18.318   3393.479
I ANG (DEG)     101.90    -18.00    -138.00     85.00     72.80    102.00
Vector Sum        A         B         C         3I0       3I2        I1
I MAG (A Pri)  3507.661  3493.221  3497.580     6.281    20.248   3500.127
I ANG (DEG)     101.80    -18.00    -138.00     98.60     74.80    101.90
Alpha Plane       A         B         C       ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS           6.470     6.450     6.460      0.000     0.000     6.460
ANG (DEG)       110.70    110.60    110.70      0.00      0.00     110.70
L
```

Figure 6.31: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.31 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = $597.945\angle-0.1°$, White Phase current = $597.360\angle-120.1°$ and Blue Phase current = $597.356\angle120.1°$.
- Relay B Red Phase current = $3391.876\angle-68.4°$, White Phase current = $3375.817\angle171.7°$ and Blue Phase current = $3374.812\angle51.71°$.
- Relay C Red Phase current = $567.580\angle-170°$, White Phase current = $567.867\angle70°$ and Blue Phase current = $566.036\angle-50°$.
- Relay A then calculated its alpha values as show with notification 2 on Figure 6.31.
- Relay A Red Phase Alpha α = $5.560\angle77.8°$, White Phase Alpha α = $5.530\angle77.8°$ and Blue Phase Alpha α = $5.530\angle78°$ as show with notification 2 on Figure 6.31.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.30 it can be seen that:

- Relay A Red Phase current = $597.721\angle68.3°$, White Phase current = $597.528\angle-51.7°$ and Blue Phase current = $597.473\angle-171.7°$.
- Relay B Red Phase current = $3387.502\angle-0.1°$, White Phase current = $3383.642\angle-120°$ and Blue Phase current = $3382.591\angle120°$.
- Relay C Red Phase current = $566.550\angle-101.9°$, White Phase current = $566.634\angle138.1°$ and Blue Phase current = $566.575/18.3°$.
- Relay B then calculated its alpha values as show with notification 4 on Figure 6.30.
- Relay B Red Phase Alpha α = $0.030\angle0.5°$, White Phase Alpha α = $0.030\angle0.3°$ and Blue Phase Alpha α = $0.030\angle0.2°$ as show with notification 4 on Figure 6.30.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.31 it can be seen that:

- Relay A Red Phase current = 597.696∠169.8°, White Phase current = 595.017∠50° and Blue Phase current = 596.433∠-70°.
- Relay B Red Phase current = 599.235∠0°, White Phase current = 595.017∠50° and Blue Phase current = 596.433∠-70°.
- Relay C Red Phase current = 566.553∠-0.1°, White Phase current = 566.265∠-120° and Blue Phase current = 565.878∠120°.
- Relay C then calculated its alpha values as show with notification 6 on Figure 6.31.
- Relay C Red Phase Alpha α = 6.470∠110.7°, White Phase Alpha α = 6.450∠110.6° and Blue Phase Alpha α = 6.460∠110.7° as show with notification 6 on Figure 6.31.

6.6.9 Case study 9 – Infeed check logic

In line with the differential protection infeed/outfeed additional check logic in Figure 6.5, the results from Figure 6.32 and Figure 6.33 show that;

- The infeed and outfeed logic was tested on the same test module as shown with notification 1 on Figure 6.32.
- This external fault was simulated for 10 seconds as shown with notification 3 on Figure 6.32.
- For infeed logic test, 6.5∠0°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 5.5∠91°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay B (notification 2 on Figure 6.32.) and 5∠180°A (= 1 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.33.
- The angle between the biggest current (6.5∠0°A) and second biggest current (5.5∠91°A) is greater than 90°.
- Restraint elements R87LA, R87LB and R87LC for relay A and B (notification 4 and 5 on Figure 6.32.) picked-up for 10.17ms as shown with notification 5 on Figure 6.32. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.
- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 and 5 on Figure 6.32.) picked-up 10 seconds later the phase angle between the biggest and second biggest was dropped below 90° subsequent to 10 seconds external fault as shown with notification 5 on Figure 6.32. This is the indication

135

that the alpha plane differential protection characteristic additional infeed logic operates as required for this test case.
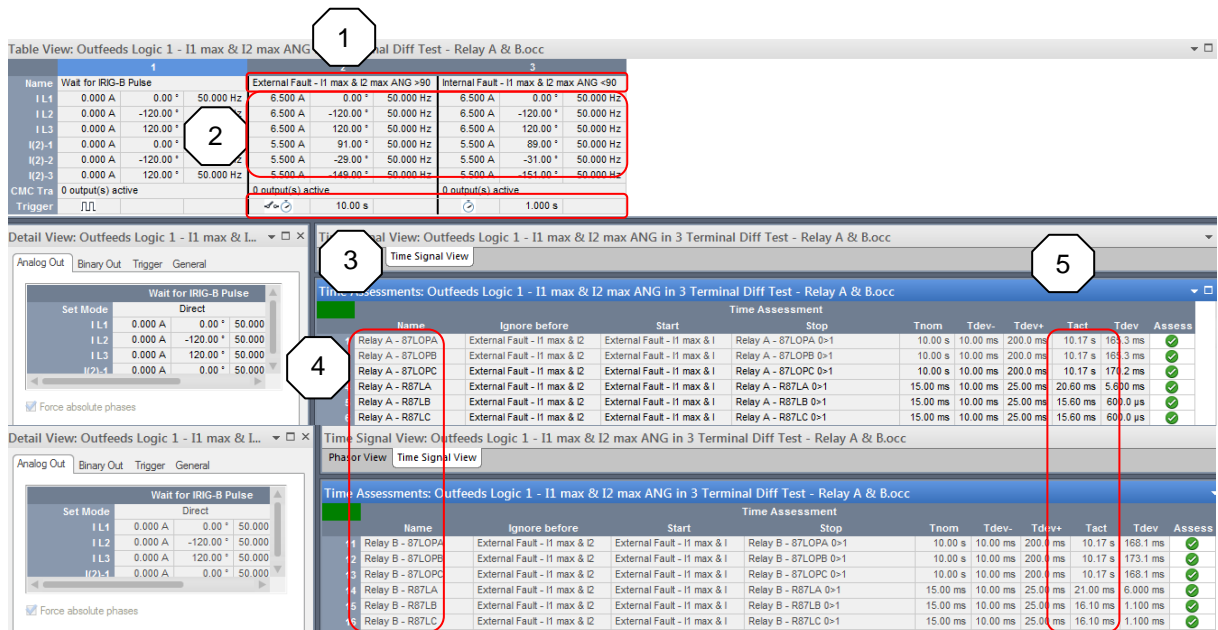
Figure 6.32: Injected analogue values and test results for relay A and B infeed check logic

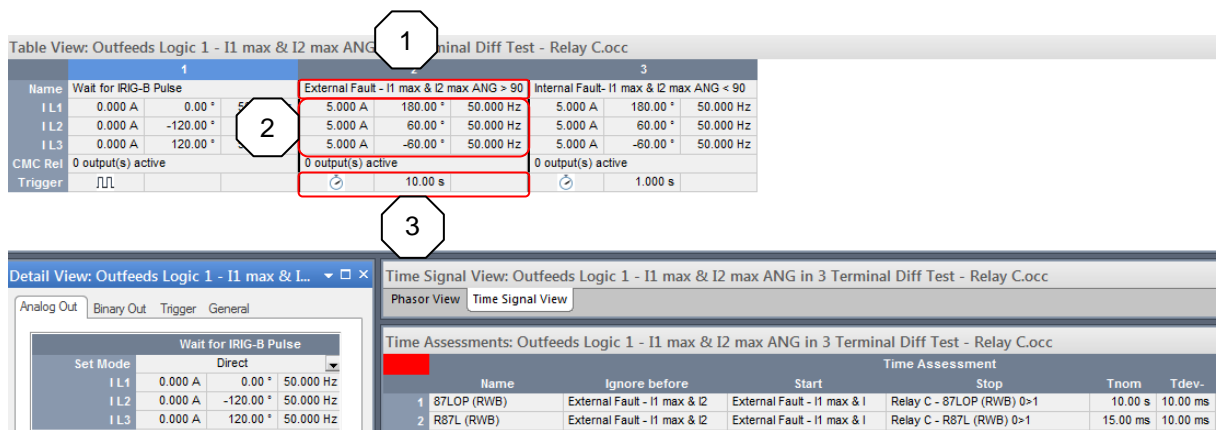**Figure 6.33**: Injected analogue values and test results for relay C infeed check logic

Figure 6.34 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
met¬

SEL-311L A                    Date: 11/08/2014    Time: 11:13:41.245
311L STUDY                                              ①

Local              A          B          C        3I0       3I2        I1
I MAG (A Pri)   3884.734   3884.507   3882.691    10.851    10.712   3883.974
I ANG (DEG)        -0.10    -120.10     120.10   -136.80    -22.10      0.00
Channel X          A          B          C        3I0       3I2        I1
I MAG (A Pri)   3278.472   3286.334   3288.793    10.744     8.465   3284.534
I ANG (DEG)        90.90     -29.10    -149.10    -91.20    -62.40     90.90
Channel Y          A          B          C        3I0       3I2        I1
I MAG (A Pri)    598.047    598.005    597.468     1.564     0.991    597.839
I ANG (DEG)      -179.80      60.30     -59.70     77.20    135.50   -179.70
Vector Sum         A          B          C        3I0       3I2        I1
I MAG (A Pri)   4598.786   4604.380   4613.748    18.377    17.032   4606.608
I ANG (DEG)        45.20     -74.50     165.40   -115.00    -39.40     45.30
Alpha Plane        A          B          C      ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS       ②    0.850      0.860      0.860     0.000     0.000     0.860
ANG (DEG)        101.30     101.20     101.10     0.00      0.00     101.20


=>>MET¬

SEL-311L B                    Date: 11/08/2014    Time: 11:44:11.965
311L STUDY              ③

Local              A          B          C        3I0       3I2        I1
I MAG (A Pri)   3290.092   3286.449   3286.434     5.230     4.701   3287.658
I ANG (DEG)        -0.10    -120.00     120.00    -30.70     -6.90      0.00
Channel X          A          B          C        3I0       3I2        I1
I MAG (A Pri)    597.255    598.026    599.078     2.361     1.911    598.119
I ANG (DEG)        89.30     -30.70    -150.50    -89.10     -6.40     89.40
Channel Y          A          B          C        3I0       3I2        I1
I MAG (A Pri)   3886.320   3888.360   3879.870    23.895    23.261   3884.835
I ANG (DEG)       -91.20     148.70      29.10    122.00    -83.60    -91.10
Vector Sum         A          B          C        3I0       3I2        I1
I MAG (A Pri)   4606.940   4592.494   4604.845    17.268    25.584   4604.646
I ANG (DEG)       -45.70    -165.70      74.50    118.00    -69.00    -45.60
Alpha Plane        A          B          C      ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS       ④    0.990      1.000      0.990     0.000     0.000     0.990
ANG (DEG)         91.10      91.20      90.80     0.00      0.00      91.00


=>MET¬

SEL-311L C                    Date: 11/08/2014    Time: 02:58:41.827
311L STUDY              ⑤

Local              A          B          C        3I0       3I2        I1
I MAG (A Pri)    597.455    598.204    597.761     1.969     0.634    597.806
I ANG (DEG)        -0.10    -120.00     120.00   -119.20    -76.00      0.00
Channel X          A          B          C        3I0       3I2        I1
I MAG (A Pri)   3875.692   3882.488   3880.706    20.774    16.698   3879.621
I ANG (DEG)       179.50      59.30     -60.50    -26.70   -119.20    179.40
Channel Y          A          B          C        3I0       3I2        I1
I MAG (A Pri)   3296.267   3281.970   3279.131     7.749    23.596   3285.787
I ANG (DEG)       -89.00     150.90      31.10    -83.60    -75.80    -89.00
Vector Sum         A          B          C        3I0       3I2        I1
I MAG (A Pri)   4583.545   4569.578   4574.871    26.314    38.137   4570.506
I ANG (DEG)      -134.60     104.90     -14.70    -45.40    -93.20   -134.80
Alpha Plane        A          B          C      ZERO-SEQ   NEG-SEQ   POS-SEQ
RADIUS       ⑥    8.410      8.390      8.390     0.000     0.000     8.400
ANG (DEG)        139.40     139.80     139.70     0.00      0.00     139.60
```

Figure 6.34: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.34 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = $3384.734\angle-0.1°$, White Phase current = $3384.507\angle-120.1°$ and Blue Phase current = $3882.691\angle120.1°$.
- Relay B Red Phase current = $3278.472\angle90.9°$, White Phase current = $3286.334\angle-29.1°$ and Blue Phase current = $3288.793\angle-149.1°$.
- Relay C Red Phase current = $598.047\angle-179.8°$, White Phase current = $598.005\angle60.3°$ and Blue Phase current = $597.468\angle-59.7°$.
- Relay A then calculated its alpha values as show with notification 2 on Figure 6.34.
- Relay A Red Phase Alpha α = $0.85\angle101.3°$, White Phase Alpha α = $0.86\angle101.1°$ and Blue Phase Alpha α = $0.86\angle101.1°$ as show with notification 2 on Figure 6.34.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.34 it can be seen that:

- Relay A Red Phase current = $4606.94\angle-45.7°$, White Phase current = $4592.494\angle-165.7°$ and Blue Phase current = $4604.845\angle74.5°$.
- Relay B Red Phase current = $3290.092\angle-0.1°$, White Phase current = $3286.449\angle-120°$ and Blue Phase current = $3286.434\angle120°$
- Relay C Red Phase current = $597.255/89.3°$, White Phase current = $598.026\angle-30.7°$ and Blue Phase current = $599.078\angle-150.5°$.
- Relay B then calculated its alpha values as show with notification 4 on Figure 6.34.
- Relay B Red Phase Alpha α = $0.99\angle91.1°$, White Phase Alpha α = $1\angle91.2°$ and Blue Phase Alpha α = $0.99\angle90.8°$ as show with notification 4 on Figure 6.34.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.34 it can be seen that:

- Relay A Red Phase current = 3875.692∠179.5°, White Phase current = 3882.488∠59.3° and Blue Phase current = 3880.706∠-60.5°.

- Relay B Red Phase current = 3296.267∠-89°, White Phase current = 3281.97∠150.9° and Blue Phase current = 3279.131∠31.1°.

- Relay C Red Phase current = 597.455∠-0.1°, White Phase current = 598.204∠-120° and Blue Phase current = 597.761∠120°.

- Relay C then calculated its alpha values as show with notification 6 on Figure 6.34.

- Relay C Red Phase Alpha α = 8.41∠139.8°, White Phase Alpha α = 8.39∠139.8° and Blue Phase Alpha α = 8.39∠139.7° as show with notification 6 on Figure 6.34.

6.6.10 Case study 10 – outfeed check logic

In line with the differential protection infeed/outfeed additional check logic in Figure 6.5, the results from Figure 6.35 and Figure 6.36 show that;

- The infeed and outfeed logic was tested on the same test module as shown with notification 1 on Figure 6.35.

- This external fault was simulated for 10 seconds as shown with notification 3 on Figure 6.35.

- For infeed logic test, 6.5∠0°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay A, 5.5∠89°A on red phase with balanced angles and equal magnitudes for on all phases was injected on relay B (notification 2 on Figure 6.35.) and 5∠180°A (= 1 x $I_{nominal}$) on red phase with balanced angles and equal magnitudes for on all phases was injected on relay C as shown with notification 2 on Figure 6.36.

- The angle between the biggest current (6.5∠0°A) and second biggest current (5.5∠91°A) is greater than 90° for 10 second.

- Restraint elements R87LA, R87LB and R87LC for relay A and B (notification 4 and 5 on Figure 6.35.) picked-up for 10.17ms as shown with notification 5 on Figure 6.35. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.

- Operate elements 87LOPA, 87LOPB and 87LOPC on (notification 4 and 5 on Figure 6.35.) picked-up 10 seconds later the phase angle between the biggest and second biggest was dropped below 90° subsequent to 10 seconds external fault as shown with notification 5 on Figure 6.35. This is the indication that the alpha plane differential protection characteristic additional outfeed logic operates as required for this test case.
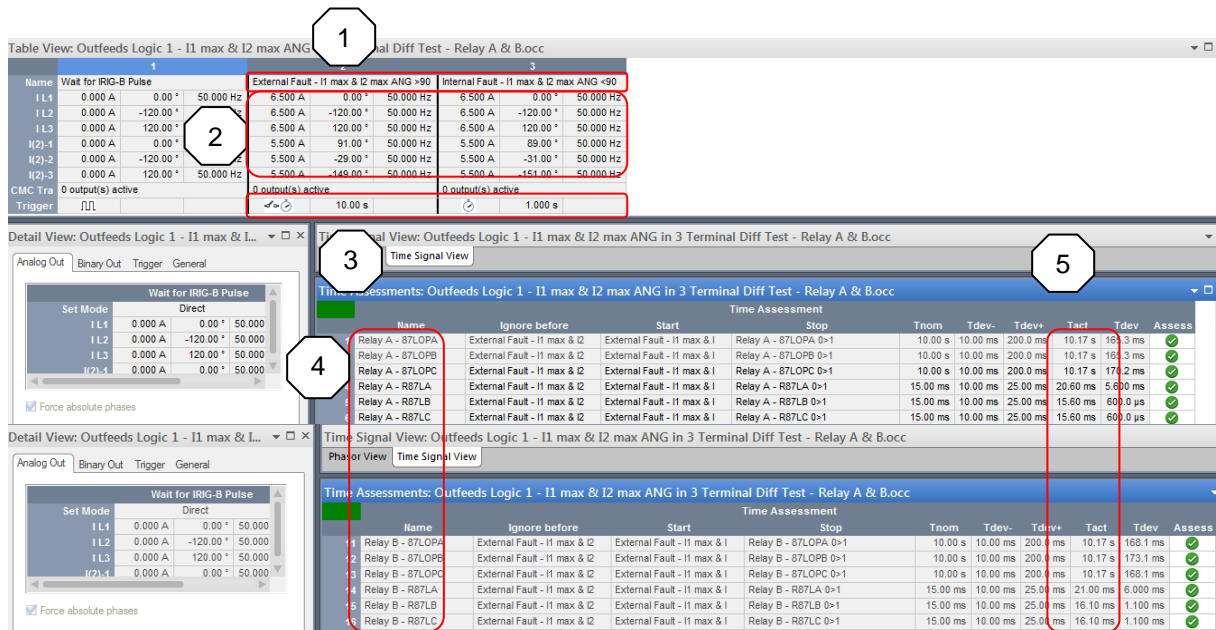
Figure 6.35: Injected analogue values and test results for relay A and B outfeed check logic
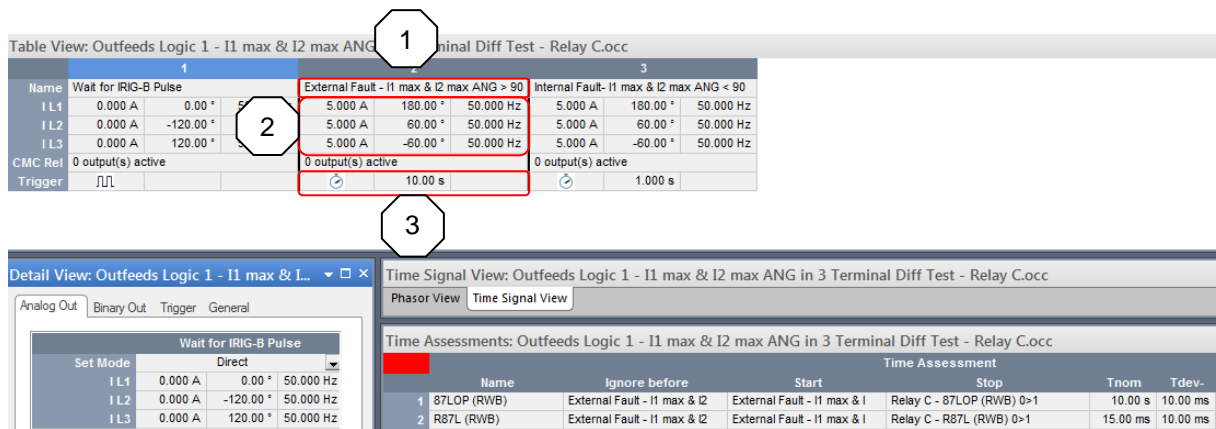

Figure 6.36: Injected analogue values and test results for relay C infeed logic

Figure 6.37 shows the measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channel X and Y.

```
MET

SEL-311L A                    Date: 11/08/2014      Time: 11:17:12.373
311L STUDY                  ①

Local          A          B          C         3I0        3I2         I1
I MAG (A Pri)  3884.501   3884.402   3882.294   10.823     11.190    3883.729
I ANG (DEG)      -0.10    -120.10     120.10   -136.90     -23.30       0.00
Channel X       A          B          C         3I0        3I2         I1
I MAG (A Pri)  3283.883   3291.310   3280.070   14.589      9.548    3285.087
I ANG (DEG)      89.10     -30.80    -150.80     -1.30    -133.70      89.20
Channel Y       A          B          C         3I0        3I2         I1
I MAG (A Pri)   597.526    597.478    597.065    1.336      1.545     597.356
I ANG (DEG)    -179.70      60.30     -59.60     39.80     175.60    -179.60
Vector Sum      A          B          C         3I0        3I2         I1
I MAG (A Pri)  4675.148   4677.051   4676.370   10.327     11.413    4675.465
I ANG (DEG)      44.30     -75.40     164.50    -41.60     -79.10      44.40
Alpha Plane     A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS  ②      0.850      0.850      0.850      0.000      0.000      0.850
ANG (DEG)       99.50      99.60      99.40      0.00       0.00      99.50


=>>MET

SEL-311L B                  ③ Date: 11/08/2014      Time: 11:47:45.209
311L STUDY

Local          A          B          C         3I0        3I2         I1
I MAG (A Pri)  3292.645   3288.979   3287.963    5.784      4.546    3289.862
I ANG (DEG)      -0.10    -120.00     119.90    -25.50      -6.40       0.00
Channel X       A          B          C         3I0        3I2         I1
I MAG (A Pri)   598.580    597.404    597.480    3.710      3.117     597.819
I ANG (DEG)      91.10     -28.50    -148.60     27.90      33.80      91.30
Channel Y       A          B          C         3I0        3I2         I1
I MAG (A Pri)  3887.397   3881.167   3877.385    2.840     14.952    3881.982
I ANG (DEG)     -89.00     150.90      31.00    -89.40     -53.50     -89.10
Vector Sum      A          B          C         3I0        3I2         I1
I MAG (A Pri)  4699.411   4676.747   4687.725    9.253     19.309    4683.803
I ANG (DEG)     -44.50    -164.50      75.40    -22.70     -34.00     -44.50
Alpha Plane     A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS  ④      0.990      0.990      0.990      0.000      0.000      0.990
ANG (DEG)       88.90      89.10      89.00      0.00       0.00      89.00


=>>MET

SEL-311L C                  ⑤ Date: 11/08/2014      Time: 03:02:13.963
311L STUDY

Local          A          B          C         3I0        3I2         I1
I MAG (A Pri)   597.779    598.022    598.064    1.612      1.151     597.954
I ANG (DEG)      -0.10    -120.00     120.00   -115.70     -87.90       0.00
Channel X       A          B          C         3I0        3I2         I1
I MAG (A Pri)  3887.571   3888.475   3872.975   23.733     18.909    3883.004
I ANG (DEG)     179.70      59.80     -60.20    103.20    -170.90     179.80
Channel Y       A          B          C         3I0        3I2         I1
I MAG (A Pri)  3297.810   3289.904   3282.137    4.012     19.571    3289.947
I ANG (DEG)     -91.30     148.60      28.70   -130.90     -56.70     -91.30
Vector Sum      A          B          C         3I0        3I2         I1
I MAG (A Pri)  4694.586   4697.469   4680.833   20.568     21.981    4689.625
I ANG (DEG)    -135.70     104.10     -15.60    115.00    -111.00    -135.70
Alpha Plane     A          B          C       ZERO-SEQ   NEG-SEQ    POS-SEQ
RADIUS  ⑥      8.600      8.610      8.570      0.000      0.000      8.590
ANG (DEG)      140.30     140.50     140.40      0.00       0.00     140.40
```

Figure 6.37: Measured primary currents and calculated alpha values for relay A, B and C

Relay A measured its local current and received measured currents by relay B and C via communication channel X and Y respectively.

Observed from relay A and shown with notification 1 on Figure 6.37 it can be seen that:

- The measured currents are displayed in primary values corresponding to the injected secondary currents.
- Relay A Red Phase current = 3384.501∠-0.1°A, White Phase current = 3384.402∠-120.1°A and Blue Phase current = 3882.294∠120.1°.
- Relay B Red Phase current = 3283.883∠89.1°A, White Phase current = 3291.31∠-30.8°A and Blue Phase current = 3280.07∠-150.8°A.
- Relay C Red Phase current = 597.526∠-179.7°A, White Phase current = 597.478∠60.3°A and Blue Phase current = 597.065∠-59.6°A.
- Relay A then calculated its alpha values as show with notification 2 on Figure 6.37.
- Relay A Red Phase Alpha α = 0.85∠99.5°, White Phase Alpha α = 0.85∠99.6° and Blue Phase Alpha α = 0.85∠99.4° as show with notification 2 on Figure 6.37.

Relay B measured its local current and received measured currents by relay A and C via communication channel Y and X respectively.

Observed from relay B and shown with notification 3 on Figure 6.37 it can be seen that:

- Relay A Red Phase current = 4604699.411∠-44.5°A, White Phase current = 4676.747∠-164.5°A and Blue Phase current = 4687.725∠75.4°A.
- Relay B Red Phase current = 3292.645∠-0.1°A, White Phase current = 3288.979∠-120°A and Blue Phase current = 3287.963∠119.9°
- Relay C Red Phase current = 598.58∠91.1°A, White Phase current = 597.404∠-28.5°A and Blue Phase current = 597.48∠-148.6°A.
- Relay B then calculated its alpha values as show with notification 4 on Figure 6.37.
- Relay B Red Phase Alpha α = 0.99∠88.9°, White Phase Alpha α = 0.99∠89.1° and Blue Phase Alpha α = 0.99∠89° as show with notification 4 on Figure 6.37.

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively.

Observed from relay C and shown with notification 5 on Figure 6.37 it can be seen that:

- Relay A Red Phase current = 3887.571∠179.7°A, White Phase current = 3888.475∠59.8°A and Blue Phase current = 3872.975∠-60.2°A.
- Relay B Red Phase current = 3297.81∠-91.3°A, White Phase current = 3289.904∠148.6°A and Blue Phase current = 3282.137∠28.7°A.
- Relay C Red Phase current = 597.779∠-0.1°A, White Phase current = 598.022∠-120°A and Blue Phase current = 598.064∠120°A.
- Relay C then calculated its alpha values as show with notification 6 on Figure 6.37.
- Relay C Red Phase Alpha α = 8.6∠140.3°, White Phase Alpha α = 8.61∠140.4° and Blue Phase Alpha α = 8.577∠140.4° as show with notification 6 on Figure 6.37.

Figure 6.38 shows the overview of Omicron control centre test results for relay A and B
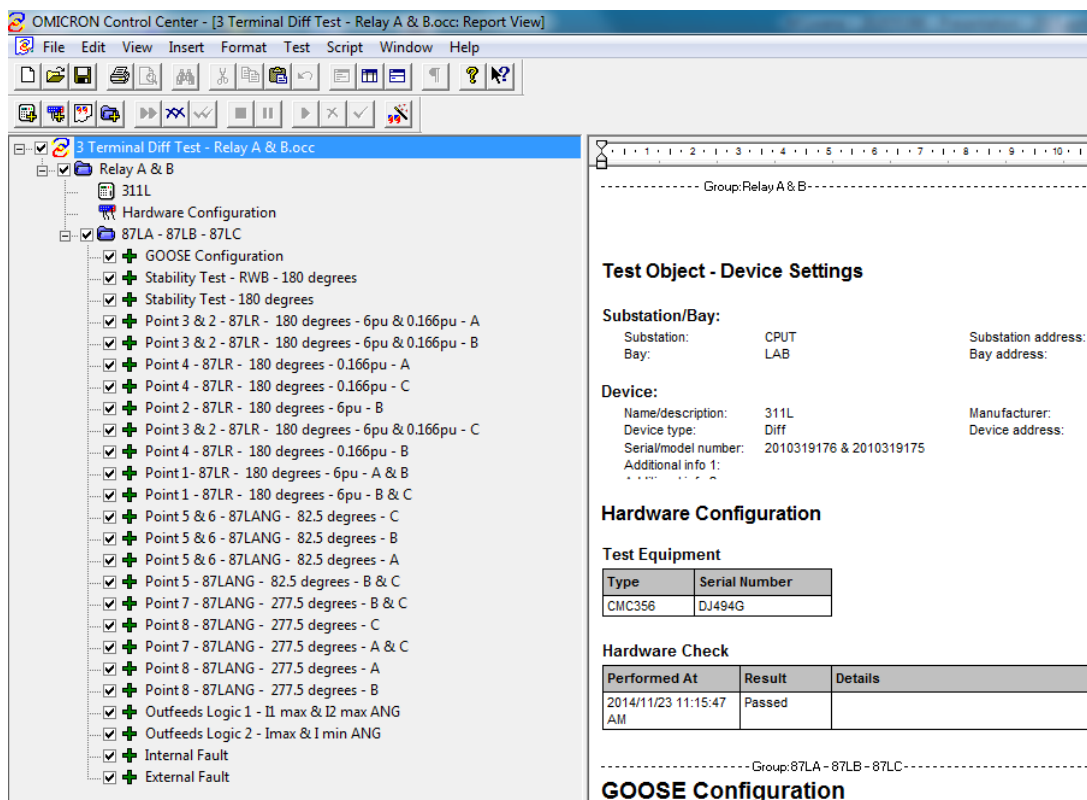

Figure 6.38: Omicron control centre test results for relay A and B

6.7   Discussion of test results

The test results are analysed in each case study. The analysis show that in all case studies the newly developed logical nodes, the alpha plane characteristic, and additional check logic are functioning as required. The method used to test these

functions defines the new method of test 3 terminal alpha plane differential protection using standard based numerical relays. The new method has significant advantages over the primitive method. As opposed to the primitive method, the new method offers the following advantages.

- No hardwiring is required which eliminates a room for human error and save time
- Relays are tested simultaneously, this shorten the outage period and the relays are tested in more realistic environment that they would be exposed in a real network unlike testing 2 relays at a time in the method

6.8   Conclusion

This chapter described the principle of alpha plane differential protection characteristic. The principle is presented in its simplest form in two terminal differential protection application which is basically the ratio of remote to local current. According to the literature, the SEL-311L relay applies the alpha plane concept of two-terminal application to three-terminal lines by combining (vectorily adding) currents from two of the terminals to produce the remote current. It was also discovered that there is an additional check logic that the SEL-311L relay applies in case of infeed and outfeed. This additional check logic is discussed in 6.2 of this chapter. This logic is not in the relay manual but exists in the relays, which also formed basis of this research.

Once the additional logic was discovered, the test method for 3 terminal alpha plane differential protection was developed and this method is defined by different case studies as presented in 6.6. The three terminal alpha plane differential protection characteristic and the additional check logic are tested in conjunction with the newly developed logical nodes. Ten case studies on this method are described in 6.6. The results on each case study are discussed an analysed. In summary, the newly developed logical nodes, three terminal alpha plane characteristic, and additional check logic and the developed test method are all proved to be functioning as required. Chapter 7 discusses the deliverables, findings and recommendation of the research.

CHAPTER SEVEN

THESIS DELIVERABLES, CONCLUSION AND RECOMMENDATION

7.1   Introduction

Any power system is prone to 'faults', (also called short-circuits), which occur mostly as a result of insulation failure and sometimes due to external causes. When a fault occurs, the normal functioning of the system gets disturbed. The high current resulting from a fault can stress the electrical conductors and connected equipment thermally and electro-dynamically. Arcs at the fault point can cause dangerous or even fatal burn injuries to operating and maintenance workers in the vicinity. Faults involving one phase and ground give rise to high 'touch' and 'step' voltages posing danger of electrocution to personnel working nearby. It is therefore necessary to detect and clear any fault quickly.

The differential protection principle is considered superior with respect to selectivity, sensitivity, and speed of operation as compared with other forms of protection for power system protection. The alpha plane differential relaying system as one form of differential protection provides sensitive protection for transmission lines, security and dependability for external faults. The relaying system is tolerant of unequal communication channel delays.

This thesis focusses on evaluating and analysing methods and algorithms of existing IEDs implementing alpha plane characteristic to develop a complete test method for three terminal differential alpha plane characteristic using OMICRON test universe software essentially defining security, dependability and sensitivity of the alpha plane characteristic.

This thesis first discusses and analyses the alpha plane differential protection characteristic and the primitive test methods for three terminal application. Upon analysis, the additional check logics which are not in the relay manual were discovered and the new test method the three terminal alpha plane differential protection characteristic and additional check logic was developed which included development of new logical nodes.

The deliverables and results and key finding of this research are summarised in 7.2. Applications are presented in 7.3 as well as possible future research on multi terminal line protection using alpha plane differential protection characteristic in 7.4

7.2 Deliverables

Testing of power system protection has evolved from primitive test methods using hard wires. These methods are time consuming and result in unnecessary prolonged outages. These methods have been discussed and improved by implementing IEC 61850 standard. The deliverables are as follows:

7.2.1 Literature review

Literature review was conducted on multi-terminal line protection particularly unit protection with more emphasis on differential protection. A number of papers on unit protection are discussed, compared and analysed.

Main papers in line with the research project are analysed and general remarks are given in the interest of this research and conclusion thereof.

7.2.2 Theoretical aspects of multi terminal lines

Theoretical aspects of multi terminal line protection are discussed in chapter 3 of this thesis particularly emphasising on the effects of infeed and outfeed.

7.2.3 Logical nodes development

Chapter 4 of this thesis provides a brief description of applicable parts of IEC-61850 standard in developing new logical nodes. Step by step process engineering in developing new logical nodes is also discussed which is important aspect in evaluation of existing test methods for 3 terminal differential protection and development of new test method.

7.2.4 Relay settings parameters

Relay parameter settings applied to all 3 relays are performed in chapter 5. Settings adjustments when using relays with different nominal currents for two terminal line protection are calculated. Different communication channel settings applicable to 3 terminal line protection as well as Ethernet interface settings for test purposes using IEC6180 are also determined and implemented.

7.2.5 Development of a test bed

Figure 7.1 the test bed with two OMICRON devices synchronized via IRIGB, connected to an Ethernet switch and protection relays which are also inter-connected with fibre optic cables for differential protection communication purpose.

One PC is used to control both test sets and communicates with all three relays.

Figure 7.1: Test bed

7.2.6 Development of method for testing

10 case studies to test 3 terminal alpha plane differential protection characteristic and additional infeed/outfed check logic are presented in chapter 6. The case studies define the new method using standard based numerical relays.

7.2.7 Testing of new logical nodes

The developed logical nodes, three terminal differential protection alpha plane characteristic, additional infeed/outfeed check logic and the developed test method are tested simultaneously, and the results are discussed in chapter 6. Chapter 6 also discusses the principle of alpha plane differential protection characteristic.

The three terminal alpha plane differential protection characteristic and the additional check logic are tested in conjunction with the newly developed logical nodes. Ten case studies on this method are discussed in 6.3 of this chapter. The results on each case study are discussed an analysed.

7.2.8 Software development

The process of developing the new test method involved a number of software. These software are tabulated in Table 7.1 with their respective applications.

Table 7.1: Software development

Environment	Application
XML Marker	Used to edit the IED Capability Configuration (ICD) files to develop new logical nodes
AcSELerator Achitect	Used to export the ICD files for editing with XML Marker software, import edited ICD files, to create Configured IED Description (CID) files, transfer CID file to the relays, export CID files for OMICRON device configuration
AcSELerator Quickset	Used to set relay parameters and transfer the setting files to the respective relays
Test Universe	Used to create test file and control the OMICRON devices

7.3 Industrial application

The test method developed in this research vindicates benefits of IEC 61850 standard over hard wired systems. Prolonged outage times due to test set preparation using hard wires will be drastically reduced. Hidden information that was not in relay manuals was discovered through this research and will be of much benefit to technicians and engineers. There are many SEL 311L relays that are in use in parts of the power systems around the world. SEL 311L is the solitary relay that uses alpha plane differential protection characteristic with additional infeed/outfeed check logic. This research work will assist technicians and engineers around the world in testing the SEL 311L relays essentially defining security, dependability and sensitivity of the alpha plane characteristic.

7.4 Other applications

The research work will be used in future for providing training students technicians and engineers. The research work also creates research opportunity in this line. Vendors may also use this work to develop test methods for their product, update relay manuals and include missing logical nodes.

7.5 Future work

This project only focussed on protection of three terminal lines using SEL 311L relays as it is designed to be used on maximum of three terminal lines. For future research it

would be interesting to investigate implications of using SEL 311L relays on more than three terminal lines. This will be essentially investigating the behaviour of the alpha plane characteristic and possible modification of the characteristic to be applied on more than three terminal lines.

This research has proved that multiple OMICRON test devices can be controlled simultaneously using one computer. Since the research was done in lab environment with all relays, OMICRON test devices and the computer connected in one Ethernet switch, it would be also interesting to investigate the effects of controlling multiple devices located at different substations in different networks or Wide Area Network (WAN), as it is the case in real power system protection testing.

7.6   Publication

M. Lwana, R. Tzoneva, C Kriger (2016) Development of a new test method for 3 terminal alpha plane differential protection characteristic using standard based numerical relays. Sent to Electrical Engineering and Technology (JEET), December 2016.

REFERENCES

ABB Document 1MRK 505 186-UEN 2007, "Application manual, Line differential protection IED RED 670", Product version: 1.1, ABB Power Technologies AB, Västerås, Sweden, Issued: March 2007.

ABB Document 1MRK 506 081-UEN 2001, "Technical reference manual, Line differential and distance protection Terminal REL 561", Product version: 2.3, ABB Automation Products AB, Västerås, Sweden, Issued: 2001.

Aggarwal R. K. and A.T Johns 1985, "High Speed Differential Protection of Teed Circuits Using Wide-band Communication Techniques", Proceedings of the Third International Conference on Developments in Power System Protection, LEE Publication No. 249, April 1985. pp. 60-64.

Aggarwal R.K. and A.T. Johns 1989, "New Approach to Teed Feeder Protection using Composite Current and Voltage Signal Comparison" Proceedings of the Fourth International Conference on Developments in Power System Protection. IEE Publication No. 302, April 1989. pp. 125-9.

Alstom 2011, "Network Protection and Automation Guide", Paris la Defense, France.

Areva 2002, "Network Protection and Automation Guide", First Edition July 2002, Paris la Defense, France.

B. Kasztenny, G. Benmouyal, H. J. Altuve, and N. Fischer 2011, "Tutorial on Operating Characteristics of Microprocessor-Based Multi terminal Line Current Differential Relays," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011. pp 30.

B. Kasztenny, N. Fischer, K. Fodero, and A. Zvarych 2011, "Communications and Data Synchronization for Line Current Differential Schemes," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011.

BA-Fakhri., and I. Elagtal 2001, "A Unique Current Differential Based Algorithm for Multi-terminal Lines", 15-19 July 2001 IEEE /PES T&D Conf, Vancouver-Canada.

Calero, F. and Elmore, W. 1992 "Current Differential and Phase Comparison Relaying Schemes," 19th Annual Western Protective Relay Conference, Spokane, Washington, USA, October 1992.

Chen Deshu, Ma Tianhao, Liu Pei 1996, ''Problems in Realization of Microcomputer Based Differential Current Protection by Sampling Values", Electric Power Automation Equipment, April 1996, pp 3-8.

Christoph Ruland, Namhi Kang, Jochen Sassmannshausen 2016, "Rejuvenation of the IEC 61850 Protocol Stack for MMS", IEEE Journal, 978-1-5090-4075-9/16.

Dale Finney, Normann Fischer, and Bogdan Kasztenny 2012, "Testing Considerations for Line Current Differential Schemes".

Debra Carroll, Hohn Dorfner, Tony Lee, Ken Fodero, Chris Huntley, 2002 "Resolving Digital Line Current Differential Relay Security and Dependability Problems: A Case History", Tacoma Power, Schweitzer Engineering Laboratories, Inc, and GE Lentronics.

Demetrios A. Tziouvaras, Hector Altuve, Gabriel Benmouyal 2002, "Jeff Roberts. Line Differential Protection with an Enhanced Characteristic", Schweitzer Engineering Laboratories, Inc.

G. Benmouyal 2005, "The Trajectories of Line Current Differential Faults in the Alpha Plane," proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

G. Benmouyal 2005, "The Trajectories of Line Current Differential Faults in the Alpha Plane," proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

G. Houlei, J. Shifang, and H. Jiali 1998, "Development of GPS synchronised digital current differential protection," in Proc. Int. Conf. Power System Technology, Apr. 1998, pp. 1177–1182.

Gabriel Benmouyal and Joe B. Mooney 2006, "Advanced Sequence Elements for Line Current Differential Protection", Schweitzer Engineering Laboratories.

Gabriel Benmouyal and Tony Lee 2004, "Securing Sequence-Current Differential Elements. Schweitzer Engineering Laboratories, Inc.

Gabriel Benmouyal 2005, "The Trajectories of Line Current Differential Faults in the Alpha Plane", Schweitzer Engineering Laboratories, Inc.

Gao Houlei 1997, "Study of new digital phase segregated current differential protection", Ph.D Dissertation, Tianjin University , China, July 1997, pp 31,32,40-45.

Gao Houlei, He Jiali Wang Gang, et al 1994, "Digital current differential protection using GPS", Proceedings of The CSU-EPSA , Vol.6, No.4, 1994, pp. 63-67.

Gurevich Vladimir 2005, "Microprocessor Protection relays: New Prospects of New Problems", Israel Electric Corp, Central Electric Laboratory.

Gurevich Vladimir 2006, "Non-conformance in Electromechanical Output Relays of Microprocessor-Based Protection Devices under Actual Operating Conditions", Israel Electric Corp, Central Electric Laboratory.

H. Ito, 1. Shuto, H. Ayakawa, P. Beaumont and K. Okuno 2001, " Development of an Improved Multifunctional Transmission Line Protection", Developments in Power System Protection", Conference Publication No. 419 IEE, 2001.

H. L. Gao, S. F. Jiang, J. L. He 1999, "Study on New Type of Current Differential Protection for Transmission Lines", Proceedings of the CSEE, 1999(19), 08, pp. 49-53.

H. Miller, J. Burger, N. Fischer, and B. Kasztenny 2010, "Modern Line Current Differential Protection Solutions," proceedings of the 63rd Annual Conference for Protective Relay Engineers, College Station, TX, March 2010.

H. Y. Li, E. P. Southern, P. A. Crossley, S. Potts, S. D. A. Pickering, B. R. J. Caunce, and G. C. Weller 1997, "A new type of differential feeder protection relay using global positioning system for data synchronization," IEEE Trans. Power Del., vol. 12, no. 3, pp. 1090–1099, Jul. 1997.

H.G. Wang, X.Z. Dong, Z.Q. Bo, B.R.J. Caunce, A. Klimek 2006, "An Operation Criterion for Line Current Differential Relay with Higher Sensitivity", Power Engineering Society General Meeting, IEEE, 2006.

Hachidai Ito, Gareth P. Baber, Itsuo Shuto, and Hideaki Sugiura 2006, "Technology and Experience of Fully Numerical Differential Protection Communication over Metallic Pilot-Wire", IEEE journal. 1-4244-0288-3/06/$20.00.

Houlei Gao, Jiali He, Shifang , Jiang 2002, "GPS synchronized digital current differential protection for transmission lines", Electric Power System Research, 62, 2002 pp.29-36.

Hu Yufeng, Chen Deshu, Yin Xianggen, Zhangzhe. Chen Yanxia 2002, "The theory and application of differential protection based on instantaneous values", Transmission and Distribution Conference and Exhibition 2002, Asia Pacific, IEEE/PES. pp:130~135,2002.

I. H. G. Brunello, I. Voloh, and J. Fitch 2004, "Current differential relaying-coping with communications channel asymmetry," in Proc. 8th IEE Int. Conf. Developments in Power System Protection, Apr. 2004, vol. 2, pp. 821–824.

I. Hall, P. G. Beaumont, G. P. Baber, and I. Shuto 2003, "New line current differential relay using GPS synchronization," presented at the IEEE Bologna Power Tech Conf., Bologna, Italy, Jun. 2003.

Ian Hall, Phil G. Beaumont, Gareth P. Baber, Istsuo Shuto, Masamichi Saga, Koichi Okuno, Hachidai Ito 2003, "New Line Current Differential relay using GPS Synchronization", IEEE journal. 0-7803-7967-5/03/$17.00.

IEC 615850-7-2 2003, "Basic Communication Structure for Substation and Feeder Equipment - Abstract Communication Service Interface (ACSI)".

IEC61850-8-1 2004"Communication Networks and System in Substations - part 8-1 : specific communication service mapping (SCSM) – Mapping to MMS", 2004.

IEC61850-90-1 2010, "Communication networks and systems in substations - Part 90-1: Use of IEC 61850 for the Communication Between Substations".

IEEE 2015, "IEEE Guide for Application of Digital Line Current Differential Relays Using Digital Communication". New York, USA.

IEEE Power System Relaying Committee Report 1995, "A Survey of Optical Channels for Protective Relaying: Practices and Experience," IEEE Transactions on Power Delivery, Vol. 10, No 2, April 1995, pp. 647458.

IEEE Transactions on Power Delivery "Line Protection Design Trends in the USA and Canada," IEEE Power System Relaying Committee Report, Vol. 3, No 4, October 1988, pp. 1530-1535.

IEEE Working group 1979, "Protection Aspects of Multi-Terminal Lines"-, IEEE Special Publication 79 THO056-2-PWR, 1979.

J Roberts, D A Tziouvaras, G Benmouyal, and H Altuve 2001, "The Effect of Multiprinciple Line Protection on Dependability and Security", 54th Annual Conference for Protective Relay Engineers, Texas A&M University, College Station, Texas, USA, April 2001.

J. Burger, H. Miller, N. Fischer, and B. Kasztenny 2009, "Modern Line Current Differential Protection Solutions," proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

J. P. Wang, V. ferry, W. Thomas 2010, "Effects of sensor technology on differential protection", 10th IET International Conference on Developments in Power System Protection, Manchester, UK, 2010.

J. S. Daniel,R K Aggrwal, and A T Johns 1993, "Three terminal line protection based on superimposed component impendance", IEE Prceedings-C, Vol. 140, No. 6, November 1993, pp 447-454.

J. V. H Sanderson and B.AL-Fakhri 1985, "improved performance of modern differential protection for Teed feeders-simulation studies", Proceedings of the Third International conference on Developments in Power System Protection, IEE Publication No. 249,Apri 1985, pp.70-73.

J.C. Yang, X.G. Yin, D.S. Chen 2003, "The Study of Sampling Value Differential Protection" Transmission and Distribution Conference and Exhibition 2003, USA, IEEE/PES . pp:256~261,2003.

Jeff Roberts, Demetrios Tziouvaras, Gabriel Benmouyal and Hector J. Altuve, 2001, "The Effect of Multiprinciple Line Protection on Dependability and Security", Schweitzer Engineering Laboratories, Inc.

Jeff Roberts, Demetrios Tziouvaras, Gabriel Benmouyal and Hector J. Altuve 2003, "The Effect of Multiprinciple Line Protection on Dependability and Security", Schweitzer Engineering Laboratories, Inc.

John Benckenstein 2001, "System Reliability Improvements through Fibre Optic Systems", Technical Publication, FD45-VER01.

K. Fodero, C. Huntley, and D. Whitehead 2009, "Wide-Area Time Synchronization for Protection", proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

K. Lee, D. Finney, N. Fischer, and B. Kasztenny, "Testing Considerations for Line Current Differential Schemes," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011.

Khodadadi, M. & Shahrtash, S.M. 2013, "A New Noncommunication-Based Protection Scheme for Three-Terminal Transmission Lines Employing Mathematical Morphology-Based Filters", Power Delivery, IEEE Transactions on, 28(1):347-356.

Kobayashi J., et al 1990, "The State-of-the-art of Multi-Circuit and Multi-Terminal Overhead Transmission Line Protection Systems Associated with Telecommunication Systems", CIGRE 1990, Paper No. 34-201, Aug. 1990.

Kwong, W.S., et al 1985, "A microprocessor current differential relay for use with digital communication system", Proceedings of the Third International conference on Developments in Power System Protection, IEE Publication No. 249,Apri 1985, pp.65-69.

Li H. Y., Southern E. P., Crossley P. A., et al 1997, "A new type of differential feeder protection relay using the Global Positioning System for data synchronization", IEEE Trans. on Power Delivery, Vol.12, No.3,July 1997 pp. 1090-1099.

Li H.Y., Southern E.P., Crossley P.A., Potts S, Pickering S.D.A., Caunce B.R.J., Weller G.C 1996, "A New Type Of Differential Feeder Protection Relay Using the Global Positioning System for Data Synchronisation", IEEE PES Summer Meeting July 96, Denver. Colorado.

Li Q B, Liu P 2002, "Application of Fiber Differential Protection and Sensitivity improvement", Electric Power Automation Equipment, Vol. 22, No. 4, pp. 21-24, April 2002.

M. G. Adamiak and W. Premerlani 1998, "A new approach to current differential protection for transmission lines," presented at the Protective Relaying Committee Meeting, Electric Council of New England, Portsmouth, NH, Oct. 1998.

M. Garcia-Gracia, W. Osal and M.P. Comech 2007 "Line protection based on the differential equation algorithm using mutual coupling", Electric Power Systems Research, Volume 77, Issues 5-6, April 2007, Pages 566-573.

M. Hank, B. John, F.Normann, K. Bogdan 2010, "Modern line current differential protection solutions", 63rd Annual Conference for Protective Relay Engineers, College Station, TX, US, 2010.

M. M. Eirsa and 0. P. Malik 2000, "investigation of impedance based protection technique for EHV 3-terminal double circuits lines", IEE Proc.-Gener, Trans, Dislrib.. , Val. 147, No. 6, November 2000, pp. 317.321.

M. Zhang, X. Dong, Z. Q. Bo, B. R. J. Caunce, and A. Klimek 2007, "A new current differential protection scheme for two terminal transmission lines," in Proc. Power Engineering Society General Meeting, Jun. 2007, pp. 1–6.

M.G. Adamiak, G.E. Alexander 1998 "A New Approach to Current Differential Protection for Transmission Lines", GE Power management, Malvern PA.

M.H. Wen, R.S. Li 2002, "Analysis of Zero Sequence Current Differential Protection in Phase Segregated Current Differential Protection for Transmission Lines", RELAY, Vol.30, No.12, pp.42-44, 2002.

M.S. Sachdev, Xianping Liu, and T.S. Sidhu 1993, "A differential algorithm for protecting parallel-teed transmission lines", CCECE/CCGEI '93 IEEE pp. 790-793.

Michael J. Thompson 2010, "Percentage Restrained Differential, Percentage of What?",Schweitzer Engineering Laboratories, Inc.

N. Villamagna P. A. Crossley, 11. Y. Li 2002, "PS Synchronized Current Differential Protection with Adaptive Bias Operating Characteristic", in Proc. International Symposium Modern Electric Power System MEPS'O2, Wroclaw, Poland.

P. K. Gangadharan, T. S. Sidhu, and A. Klimek 2007, "Influence of current transformer saturation on line current differential protection algorithms," Inst. Eng. Technol. Proc. Gen. Transm. Distrib., vol. 1, no. 2, pp. 270–277, Mar. 2007.

P. Meinhardt 2006, "Improved Possibilities for Testing of Line Differential Protection," proceedings of the Omicron International Protection Testing Symposium (IPTS), Vorarberg, Austria, September 2006.

P.A. Crossley, H.Y. Li, A.D. Parker 1998, "Design and Evaluation of a Circulating Current Differential Relay Test System", IEEE Trans. on Power Delivery, Vol. 13, No. 2, pp: 427~963, April 1998.

R. K. Aggarwal and A. T. Johns 1990, "Digital Differential Relaying Scheme for Teed Circuits Based on Voltage and Current Signal Comparison". IEE Proceeding, Vol. 137, P1. C. No. 6, November 1990, pp. 414-423.

R.K Aggarwal and A.T.Johns 1986, "The development of a new high speed 3-terminal line protection scheme", IEEE Trans. Power Delivery, Vol. PWRD-1, No.1 Jan. 1986 pp.125-133.

RK Aggarwal, and A-T. Johns 1986, "The developments of a new high speed 3-terminal line protection scheme," IEEE Trans. Power Delivery, vol. 1, no. 1, January 1986, pp. 125-134.

Rohan Perera, and Bogdan Kasztenny 2014, "Application Considerations When Protecting Lines With Tapped and In-Line Transformers" IEEE Journal on, 978-1-4799-4739-3/14.

S. C. Sun and R. E. Ray 1983, "A current differential relay system using fibre optics communications," IEEE Trans. Power App. Syst., vol. PAS-102, no. 2, pp. 410–419, Feb. 1983.

S. Holst, I. Brncic, D. Shearer, R. Mangelred, K. Koreman 2007, "Problems and Solutions for AC Transmission Line Protection under Extreme Conditions caused by VeryLong HVDC Cables", Study Committee B5 Colloquium, Madrid, Spain, October 2007.

S. S. Dambhare, S. A. Soman, and M. C. Chandorkar 2009, "Adaptive current differential protection schemes for Transmission-line protection", IEEE Transactions on Power Delivery, vol. 24, no. 4, pp. 1832-1841, Oct 2009.

S. Sheng, K. K. Li, W. L. Chan, X. J. Zeng, and D. Xianzhong 2005, "Agent based wide area current differential protection system," in Proc. Industry Applications Conf., Oct. 2005, pp. 453–458.

S. Ward and T. Erwin 2006, "Current Differential Line Protection Setting Considerations", RFL Electronics Inc, System Protection and Control Task Force of the NERC Planning Committee September 13 2006. The Complexity of Protecting Three-Terminal Transmission Lines.

S. Ward 2007, "Current Differential Line Protection Setting Considerations. RFL Electronics Inc. USA.

S. Ward, T. Dahlin, B. Ince 2004, "Pilot protection communication channel requirements", 57th Annual Conference for Protective Relay Engineers, Texas A and M University, 2004.

Sanderson J. V. H. and B. AI-Fakhri 1985, " Improved Performance of Modern Differential Protection for Teed Feeders- Simulation Studies", Proceedings of the Third international Conference on Developments in Power System Protection, IEE Publication No. 249, April 1985. pp. 70-74.

Schweitzer, E.O.. Larson, R.R and Flechsig, A.J. 1977 "An Efficient lnrush Current Detection Algorithm for Digital computer Relaying, Protection of Transformers", IEEE PES Summer Meeting, Mexico City, July 1977, pp:77 510.1.

SUONAN Jia-le, ZHANG Yi-ning 2006, "Study of current differential protection using time-domain capacitive current compensating algorithm on pie-model", Proceedings of the CSEE. 2006. 26 (5) , 12-18.

Sykes, J.A. and Momson, LF 1976, "A Proposed Method of Harmonic Restraint Differential Protection of Transformers by Digital Computer", IEEE Trans. On Power Apparatus and Systems, PAS-91, pp 1266-1273 Malik, O.P, Dash, P.K. and liope. G.S.. "Digital Protection of a Power Transformer". IEEE PES Winter Meeting, New York, Jan. 1976, pp A76 191-7.

T. Lobos 1991, "Digital line differential protection using symmetrical components", Electric Power System Research, vol. 22, 1991, pp. 85- 89.

Thorp J.S. et al 1988, "Some Applications of Phasor Measurements to Adaptive Protection." IEEE Trans. on Power Systems. Vol. 3, No. 2, May 1988, pp. 791-8.

Villamagna, N, Crossley P. A., Li H. Y. 2003, "Design of a symmetrical component based current differential protection scheme", IEEE Power Tech Conference Proceedings, Vol.4 2003, pp.23-26.

W.S.Kwong, M.J.Cloyton 1985, "A Microprocessor- Based Current Differential Relay for Use with Digital Communication System", 3rd International Conference on Developments in Power System Protection, IEE Conference Publication 249, April 1985, pp. 65-69.

Wen M H, Li R S 2002, "Analysis of Zero Sequence Current Differential Protection in Phase Segregated Current Differential Protection for Transmission Lines", RELAY, Vol. 30, No. 12, pp. 42-44, Dec. 2002.

Wheatly J. M. 1989, "A microprocessor based current differential protection", Proceedings of the Fourth International conference on Developments in Power System protection, IEE Publication No.302, April 1989, pp.116-120.

www.selinc.com

Wu Y K, Yuan B J 1996, "Split-phase Current Differential Protection Using Fault Components", RELAY, No.3 (Sum 95), pp. 4-9, Aug. 1996.

Y. Z. Ge 1980, "Analysis and study of operating criteria of differential relays", Journal of Xi'an Jiaotong University, 1980(14), 02, pp. 93-108.

Yiqing Liu, Houlei Gao et al 2011, "A Design Scheme of Line Current Differential Protection Based on IEC61850", 2011.

Yu B T, Zhang J, Ren S Y 2004, "Scheme of Adaptive Current Longitudinal Differential Protection for Transmission Line, RELAY, Vol.32, No, 4, pp.44-47, Feb. 2004.

Z. Gajic, I. Brncic T. Einarsson, B. Ludqvist 2007, "Practical Experience from Multi terminal Line Differential Protection Installations", International Conference on Relay Protection and Substation Automation of Modern EHV Power Systems, Moscow – Cheboksary, Russia, September 2007.

Z. Y. Xu, Z. Q. Du, L. Ran, Y. K. Wu, Q. X. Yang, and J. L. He 2007, "A current differential relay for a 1000-kV UHV transmission line," IEEE Trans. Power Del., vol. 22, no. 3, pp. 1392–1399, Jul. 2007.

Z. Y. Zhang, H. J. Liu 2010, "A New Synchronization Method of Optical Fibre Line differential Protection for Digital Substation", Automation of Electric Power Systems, 2010(34), 22, pp. 90–92.

Zheng Yuping, Wu Tonghua and Ding Yan 2004, "Applied criterion of current differential protection based on BERGERON model", Automation of Electric Power Systems. 2004, 28 (23) :50- 55.

APPENDIX A

IED CONFIGURATION SOFTWARE TOOLS

A.1   Introduction

Modern protection relays are sophisticated and required different software tools to configure and interrogate. In this Appendix, a detailed application description of the protection software tools is done. The software tool packages used for the IED configuration and development of new logical nodes for the project are described. These software tools can be used on products or relays from different vendors.

A.2   IED configuration using AcSELerator Architect

The AcSELerator Architect software allows engineers to create and edit projects. Projects are containers for Intelligent Electronic Devices (IEDs). All IEC 61850 configuration and SEL IED settings are saved in the project for later retrieval, editing, and transfer of configuration to IEDs. Figure A.1 shows typical AcSELerator Architect project.
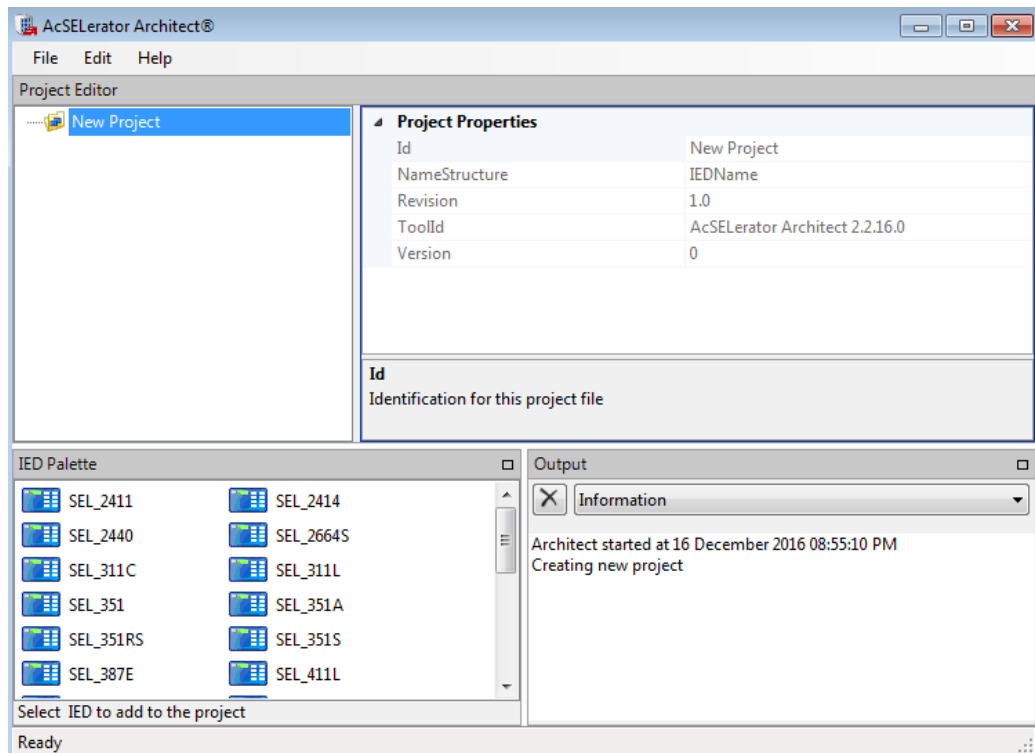
Figure A.1: AcSELerator Architect project

Upon opening AcSELerator Architect or upon selecting a project name, Architect displays a window similar to Figure A.2, from which you can see identification and version information for your project and the tools you used to create the project.

158

Figure A.2: IED properties

When right-clicking on project name within the Project Editor context menu similar to the Figure A.3 is obtained. From this menu, renaming of project or addition of another IED can be chosen.
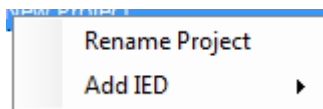

Figure A.3: Renaming of project or addition of IED

Upon selecting an IED to add to the Project Editor, Architect displays a dialog box such as in Figure A.4, from which a particular IED and the substation subnet in which it can be found can be identified.
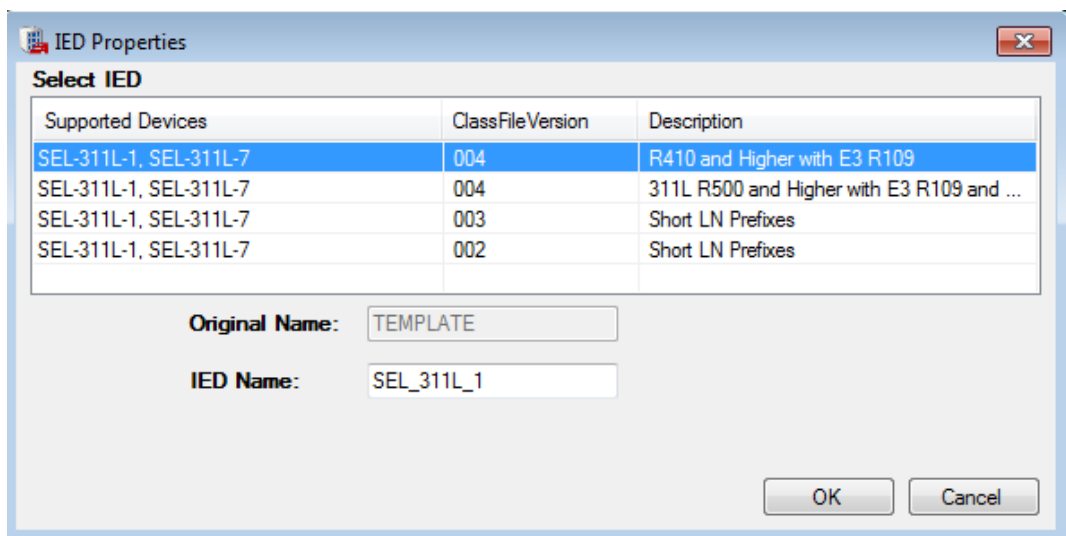

Figure A.4: Identification of IED

After adding a new IED, Architect displays an icon representing the new IED in the Project Editor as shown in Figure A.5.
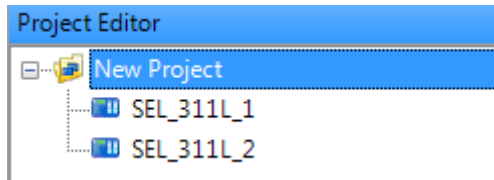
Figure A.5: Omicron control centre test results for relay A and B

Upon right-clicking an SEL IED name, a context menu such as in Figure A.6 is obtained.
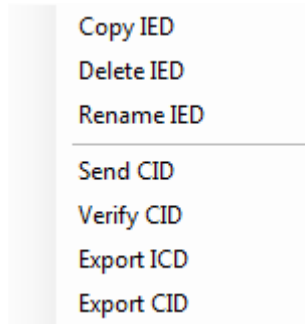
Figure A.6: SEL IED context menu

The options of this menu are used to remove an IED from the project, rename an IED, send a CID file or export ICD and CID files. Upon right-clicking a non-SEL IED name, a context menu as shown on Figure A.7 is obtained.

Figure A.7: Non SEL IED context menu

The options in this menu are used to remove an IED from the project or export CID files. After adding a new IED, Architect displays the IED Properties window with the following tabs:

- Properties
- GOOSE Receive
- GOOSE Transmit
- Reports and
- Datasets

A.2.1 Properties

Upon selecting an IED in the Project Editor view and selecting properties from any of the available windows in this view, the program displays the contents as shown in Figure A.8.

Figure A.8: **IED properties**

IED Properties form is use to establish addressing and communications information for an IED. Within this dialog box are the following:

- Subnet - This field is the IEC 61850 subnet definition (not to be confused with the network layer subnet associated to TCP). This field is used to group IEDs into logical groups for peer-to-peer messaging. According to the IEC 61850 standard, all devices within an individual subnet field are associated peers for GOOSE communication that should ignore GOOSE communication peer-to-peer messaging on different subnets.

- UTC Offset - This field determines the offset between your local PC time and Coordinated Universal Time.

- IP Address - This field contains an IED IP address as defined in an imported SCL file. IED IP address cannot be configured from this field. For an SEL IED not part of an imported SCL file, the device driver definition within AcSELerator QuickSet must be used to establish the appropriate setting for the IED IP address from within QuickSet.

- Subnet Mask - This field contains an IED subnet as defined in an imported SCL file. IED subnet mask cannot be configure from this field. For an SEL IED not part of an imported SCL file, the device driver definition within AcSELerator QuickSet must be used establish the appropriate setting for the subnet mask from within QuickSet.

- Gateway: This field contains an IED gateway as defined in an imported SCL file. IED gateway cannot be configured from this field. For an SEL IED not part of an imported SCL file, the device driver definition within AcSELerator

QuickSet must be used to establish the appropriate setting for the IED gateway from within QuickSet.

A.2.2 GOOSE Receive

Upon selecting an IED in the Project Editor view and selecting GOOSE Receive from any of the available windows in this view, the program displays the GOOSE receive contents as shown in Figure A.9.
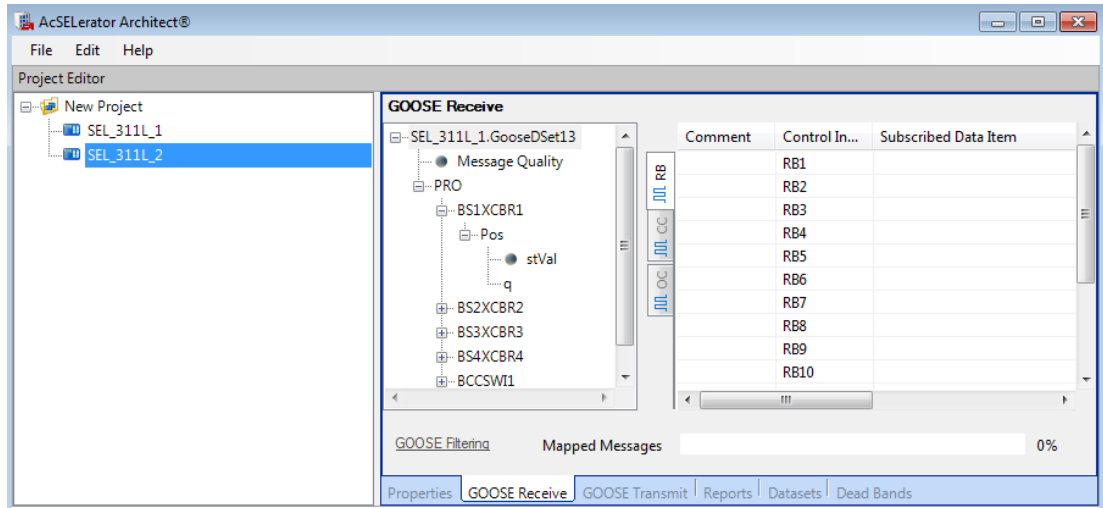

Figure A.9: GOOSE receive contents

To configure an SEL IED to subscribe to GOOSE receive messages, data in the tree is navigated and dragging the data to a control input. The actions are repeated for all received data

The GOOSE message (s) an IED will receive and the logic variable (s) to which the messages are mapped is determined. The example of the result is shown in Figure A.10.
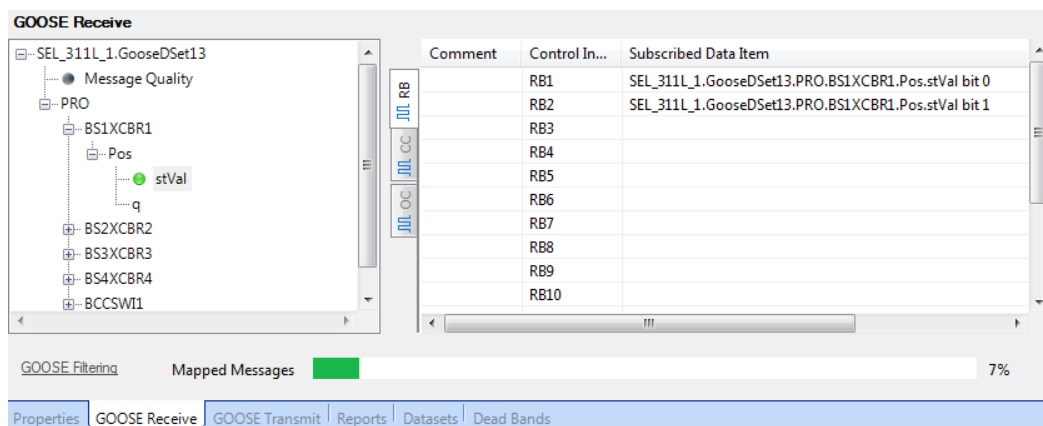

Figure A.10: GOOSE receive data

A.2.3 Message Quality/Validity

If a value that has an associated quality bit (q) is selected, Architect automatically displays a Quality Type Definition dialog box from which the conditions for which block questionable data can be selected as shown in Figure A.11.
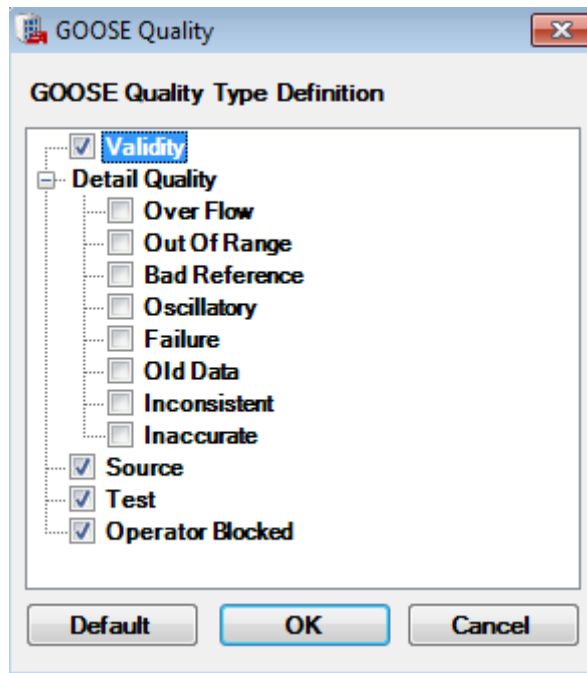
162

Figure A.11: Message quality/validity

A.2.4 GOOSE Transmit

Upon selecting an IED in the Project Editor view and selecting GOOSE Transmit from any of the available windows in this view, the program displays the following GOOSE transmit information as hown if Figure A.12
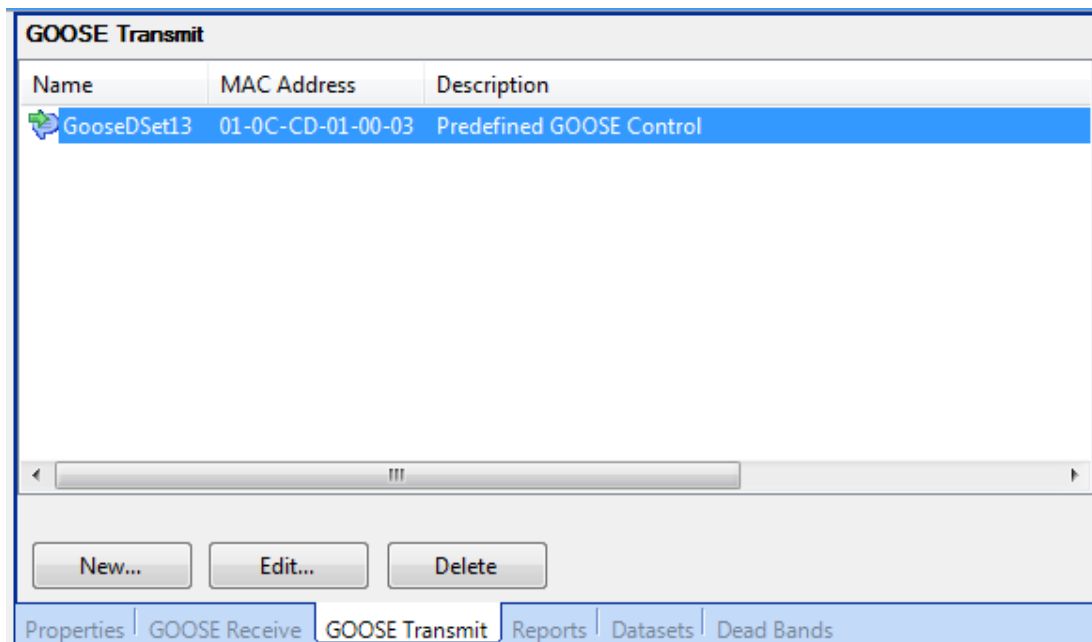

Figure A.12: GOOSE transmit information

To edit or create a GOOSE message for transmission from an SEL IED, either Edit or New can be selected, as appropriate, from the Goose Transmit dialog box.

Upon selecting either New or Edit, the program displays the following form. This form can be used to create or edit GOOSE messages. To edit the dataset that defines a GOOSE message, refer to the Datasets description as shown in Figure A.13.

Figure A.13: Dataset description

A.2.5 Reports

Upon selecting an IED in the Project Editor view and selecting Reports from any of the available windows in this view, the program displays the following listing of six buffered reports followed by six unbuffered reports as shown in Figure A14.

Figure A.14: Buffered reports and unbuffered reports

For each SEL IED, there are 12 associated reports (six buffered reports and six unbuffered reports). For each report, there can be just one client association. This means that only one client can be associated to the control block (BRCB or URCB) for each report at a given time. The number of reports (12) or the type of reports

164

(buffered or unbuffered) cannot change. However, through use of the Datasets tab, data within each report can be relocated to present different data combinations for each report beyond the predefined datasets contained within Architect.

Datasets

Upon selecting an IED in the Project Editor view and selecting Datasets from any of the available windows in this view, the program displays a listing such as the following of available datasets as shown in Figure A.15.
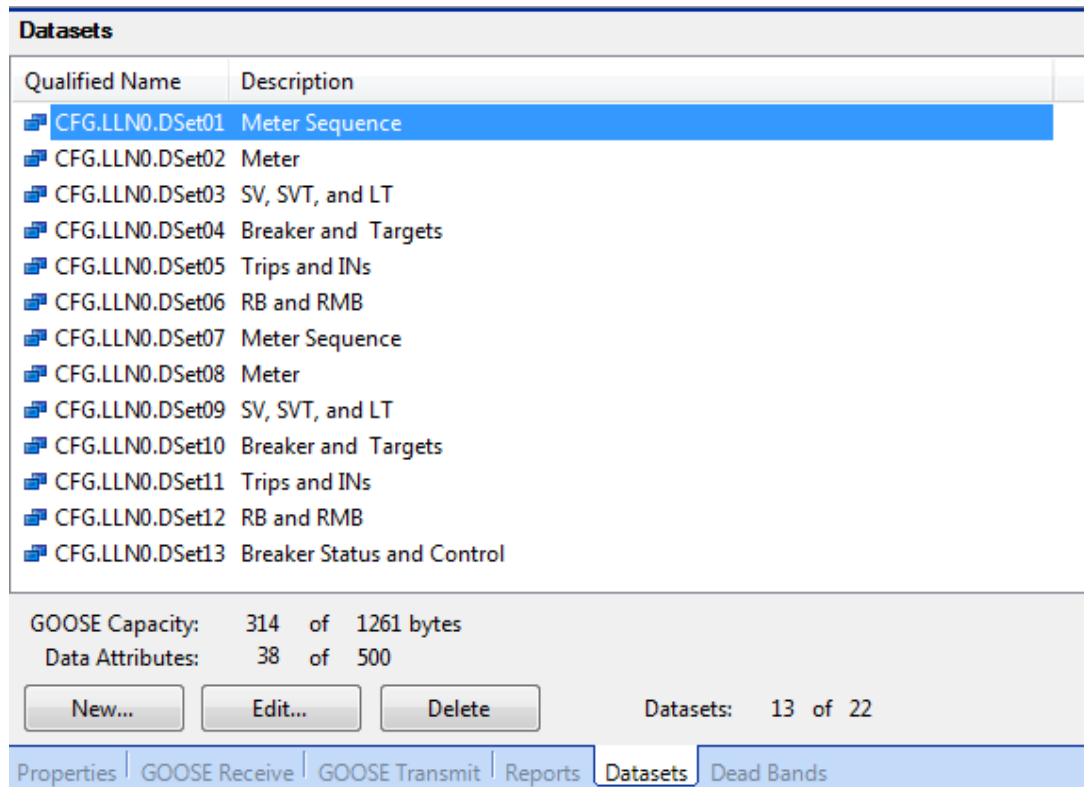

Figure A.15: Datasets list

To create or edit a dataset, New or the required dataset can be selected and then Edit can be selected from within the Datasets dialog box.

Within Architect, IEC 61850 datasets can be used for two different purposes:

GOOSE: Predefined datasets, edit datasets, and create new datasets can be used for outgoing GOOSE transmission.

Reports: Twelve predefined datasets (DSet01 to DSet12) correspond to the six buffered and six unbuffered reports that display upon selecting Reports. The number (12) or type of reports (buffered or unbuffered) can be changed. Changes to the listing that appears upon selecting Reports cannot be made. Upon selecting Datasets, however, the data a dataset contains and define what data an IEC 61850 client associates with a report can be altered.

A.2.6 Data Set Definition

Dataset definitions or additions to existing dataset definitions can be created by expanding the associated logical node definitions for each SEL IED and dragging the appropriate data objects and attributes into the dataset. Items from a dataset can be removed by right-clicking on the associated data attribute within the defined dataset and selecting 'Delete'. Typical dataset definition content is shown in Figure A.16.

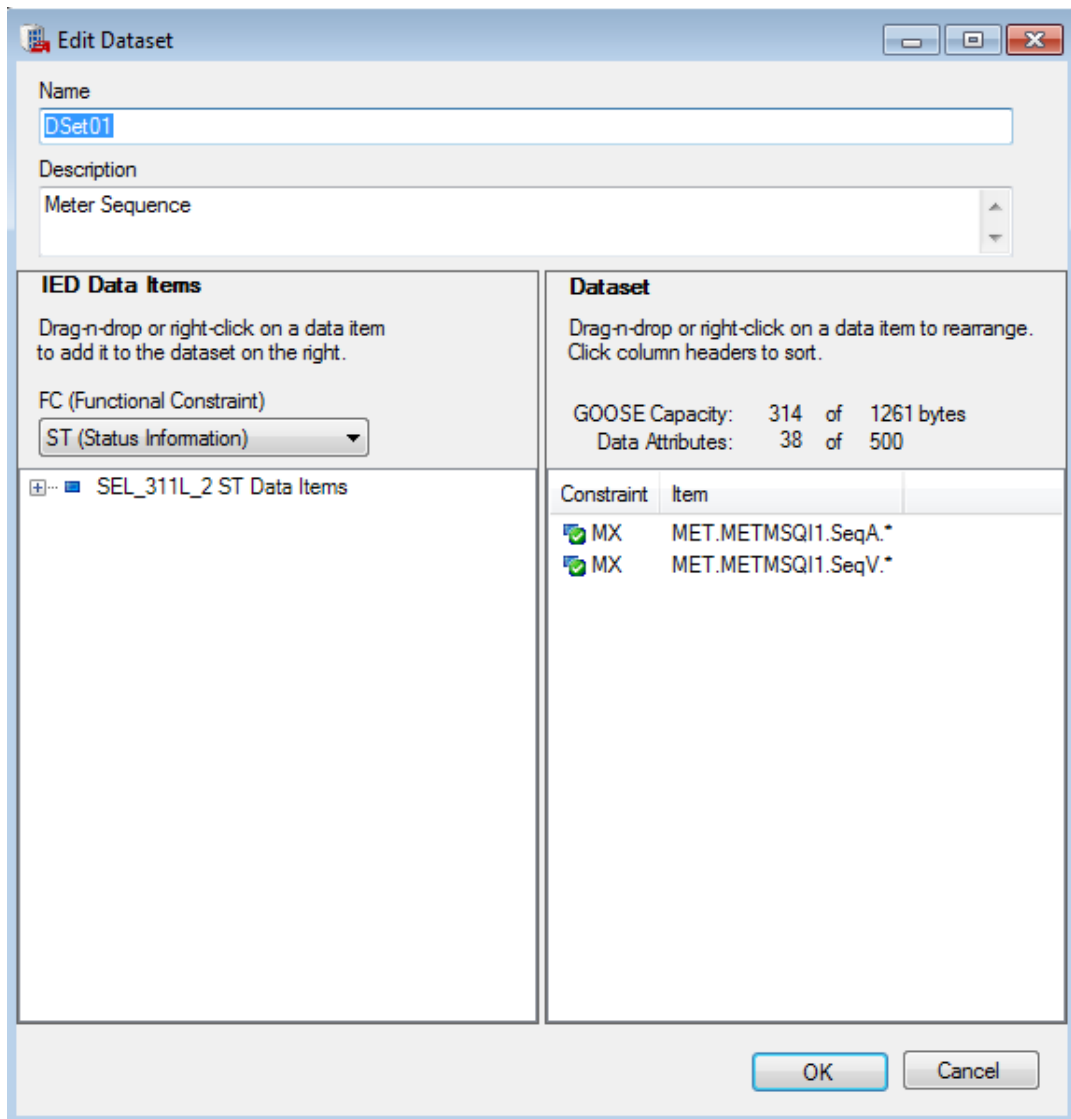**Figure A.16**: dataset definition

There are two capacity progress bars that represent the following information:

GOOSE Capacity: The percentage in this progress bar represents the amount of data defined in the dataset in relationship to the maximum allowable size for a GOOSE message. According to the IEC 61850 specification, the maximum size of a TCP frame defines the maximum size of a GOOSE message.

Report Capacity: The capacity percentage in this progress bar demonstrates the relationship of the dataset size in relation to the data buffering capabilities of the SEL IED.

A.3   XML language

An XML language was developed to present data that can be easily understood by humans and computers. Climatological data can be represented as an XML document to simplify data exchange. XML was designed to describe data and to focus on what data represents. XML was created to structure, store and to send information. XML does not define what is needed to be done with data; it is just pure information wrapped in XML tags and someone must write software to send, receive, process or display it. XML is free and extensible but XML tags are not predefined. Users must "invent" their own tags. XML allows the author to define their own tags and also their own document structure. The tags in the example above (like <Date> and <ff>) are not currently defined in any XML standard. The main benefit of XML is that XML is a cross-platform, software and hardware independent tool for transmitting information. XML was not designed to display data.

A.3.1 Exchange with XML
With XML, data can be exchanged between incompatible systems. In the real world, computer systems and databases contain data in incompatible formats. One of the most time consuming challenges for developers has been to exchange data between such systems over the Internet. Converting the data to XML can greatly reduce this complexity and create data that can be read by many different types of applications.

A.3.2 Storing Data in XML
XML can also be used to store data in files or in databases. Relational or native XML databases can be used to store XML. To store XML documents in relational databases you need applications to convert data from tables into XML and back. Generic applications can be used to process data in XML.

A.3.3 Processing Data in XML
Freely distributed applications are available to parse XML documents. International standards for XML Document Object Model (DOM) and document parsers allow for applications from different vendors and therefore simplify user applications.

A.3.4 XML document conversion

Documents in XML can be converted to any text document by using standard applications. A special language for transforming XML documents (XSLT) is available.

A.3.5 XML can be used to create new Languages

Through defining an XML document structure, you can create your own language.

Several of these languages are now available with the better known being:

- Geographic Makeup Language (GML);
- Metadata language (ISO 1915) and WMO profile; and
- Meteorological XML (MeteoXml).

A.3.6 XML syntax

The syntax rules of XML are very simple. The rules are very easy to learn, and very easy to use. XML document use a self-describing syntax. Figure A.17 shows the example of XML syntax.

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<station_metadata>
    <station_id>07149</station_id>
    <name>Paris-Orly</ name>
    <h>90</h>
    <lat>48.43</lat>
    <lon>2.23</lon>
</station_metadata>
```

Figure A.17: **XML syntax example**

The first line in the document, the XML declaration defines the XML version and the character encoding used in the document. In this case the document conforms to the 1.0 specification of XML and uses the ISO-8859-1 (Latin-1/West European) character set. The next line describes the root element of the document, i.e. providing information that "this document is a station_metadata". The next 5 lines describe 5 child elements of the root (station_id, name, h, lat, lon) and finally the last line defines the end of the root element.

It can be detected from this example that the XML document contains metadata for a station.

All XML documents must have opening and closing tags with the same name that are case sensitive. All XML elements must be properly nested. All XML documents must have a root tag. All other elements must be within this root element. All elements can

have sub elements (child elements). Sub elements must be correctly nested within their parent element as shown in Figure A.18.

Figure A.18: XML root, child and subchild elements

A.3.7 XML attributes

XML elements can have attributes in the start tag that provide additional information about elements. Attributes must be present in name/value pairs. Where name is attribute name and value is value of this attribute. In the example shown in Figure A.19, element remark has attribute "lang". The "lang" attribute provides additional information about the remark element, i.e. the language used. Attribute values must always be quoted.

The syntax for writing comments in XML is <!-- This is a comment -->

Figure A.19: XML attributes

A.3.8 Element naming

XML elements must follow these naming rules:

- Names can contain letters, numbers, and other characters;
- Names must not start with a number or punctuation character;
- Names must not start with the letters xml (or XML or Xml ..); and
- Names cannot contain spaces.

Non-English letters like éòá are perfectly legal for XML element names, but problems may occur if the software vendor doesn't support them. The ":" should not be used in element names because it is reserved to be used for something called namespaces.

A.3.9 XML document extension

XML documents can be easily extended to carry more information. Looking again at the earlier 'Observation' example, this can be extended with the addition of Td, i.e. dew point as shown in Figure A.20.

```
<?xml version="1.0" encoding="utf-8"?>
<Observation>
    <Station>27612</Station>
    <Date>2005-01-18T15:00</Date>
    <dd>200</dd>
    <ff>2</ff>
    <TTT>-5.2</TTT>
    <Td>-6.1</Td>
    <PPPP>1016.4</PPPP>
    <RRR/>
</Observation>
```

Figure A.20: XML document extension

A.3.10 XML document encoding

An XML document can contain not only be English characters but also, for example, Norwegian or French characters at the same time. To let the XML parser understand these characters, XML documents should be saved as Unicode and identify corresponding encoding as show in Figure A.21.

```
<?xml version="1.0" encoding="utf-16"?>
```

Figure A.21: XML document encoding

It is possible to use encoding for specific language. For instance, encoding "windows-1251" support Russian Cyrillic characters.

A.3.11 XML DTD

A DTD defines the legal elements of an XML document. The purpose of a DTD is to define the legal building blocks of an XML document. It defines the document structure with a list of legal elements. An example of DTD that corresponds to the observation XML document is shown in Figure A.22.

```
<?xml version="1.0" encoding="UTF-8"?>
<!ELEMENT Observation  (Station, Date, dd?, ff?, TTT?, Td?, PPPP?, RRR?)>
<!ELEMENT Station (#PCDATA)>
<!ELEMENT Date (#PCDATA)>
<!ELEMENT dd (#PCDATA)>
<!ELEMENT ff (#PCDATA)>
<!ELEMENT TTT (#PCDATA)>
<!ELEMENT Td (#PCDATA)>
<!ELEMENT PPPP (#PCDATA)>
<!ELEMENT RRR (#PCDATA)>
```

Figure A.22: **XML DTD**

This DTD document defines all tags that can be included in a document. Station and Date tags are permanent but others are optional.

A.3.12 XML schema

XML Schema is an XML based alternative to DTD. W3C supports an alternative to DTD called XML Schema.

A.3.13 XML document editors

XML is a text based markup language and XML files can be created and edited using a simple text editor like Notepad. However, when start working with XML, it is better to edit XML documents using a professional XML editor. Notepad can be used for quick editing of simple HTML, CSS, and XML files. But, Notepad does not know that XML is being written, so it will not be able to assist. In using a simple text editor, it is more likely to create many errors, and as the XML documents grow larger control could be lost. To be able to write XML documents for all new development projects, an intelligent editor is need to help write error free XML documents. Appropriate XML editors will also validate text against a DTD or a schema, and force to stick to a valid XML structure.

A good XML editor should be able to:

- Add closing tags to opening tags automatically;
- Force to write valid XML;
- Verify XML against a DTD;
- Verify XML against a Schema; and
- Colour code XML syntax.

XMLSPY is a very popular XML editor and these are some of the features:

- Easy to use;
- Syntax colouring;
- Automatic tag completion;

- Automatic well-formed check;

- Easy switching between text view and grid view;

- Built in DTD and / or Schema validation;

- Built in graphical XML Schema designer;

- Powerful conversion utilities;

- Database import and export;

- Built in templates for most XML document types;

- Built in XPath analyzer; and

- Powerful project management.

An XML document is a very powerful facility to define a flexible data exchange format that is very important for climate data, where we often do not have predefined formats and have a very wide list of parameters.