INVESTIGATING THE CAPABILITIES OF SEL 787 TRANSFORMER PROTECTION RELAY USING LOW LEVEL SIMULATORS.

Thesis submitted to the School of Engineering and Information Technology, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering

Tendai Raymond Dube

Supervisor: Assoc. Prof. Graeme Cole
Co-supervisor: Dr. Gregory Creebin

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STATEMENT OF ORIGINALITY

This thesis is my own original work. To the best of my knowledge, I hereby certify that the work in this thesis contains no material previously written by another person or submitted for the award of any other degree in any university. All literature and information sources derived from unpublished and published work of others has been acknowledged and indicated in this thesis.

09 /01/2016

SIGNED DATE

Abstract

Protection relays play an integral part in electrical power systems. They monitor and detect abnormal system conditions and initiate the operation of protective devices like circuit breakers to take corrective action and restore the power system to its normal state. Over the years, the technology has evolved from the old electromechanical-based relays to the new microprocessor-based relays also known as intelligent electronic devices, such as the SEL 787 transformer protection relay. Correct operation of these devices is critical as malfunction or incorrect operation might lead to severe damage to protected equipment and costly power outages. In commissioning, maintenance and training fields, the correct operation and accuracy verification is determined through carrying out fault simulations on the relay using different types of test equipment or simulators. This thesis investigates the capabilities of SEL 787 relay by using low level fault simulators and setting the foundation for the development of a National Instrument CompactDaq and LabVIEW fault simulator.

The thesis comprises the following three main parts:

Part 1: SEL 787 Transformer protection relay

In this thesis, research has been carried out on the design and application of the SEL 787 relay in transformer protection. The hardware components and the software platform used by the relay has been analysed. Investigation of the software tools to facilitate efficient simulations and hence explore the functionality of the relay has been conducted.

Part 2: Fault simulators / Test equipment

Focuses on the different types of fault simulators in particular low level simulators like the SEL RTS system. Simulations where carried out on the SEL 787 relay using the SEL RTS system. The simulation results were analysed using standards and manufacturer specifications.

Part 3: LabVIEW CompactDaq Simulator

Involves the proposed design of a low level simulator using the CompactDaq modules and LabVIEW software. Analysis of the CompactDaq modules was conducted. Tests were successfully carried out using the CompactDaq system via NI Max test panel on the SEL 787 protection relay.

Acknowledgements

I would like to express my sincere gratitude to my project supervisor, Associate Professor Graeme Cole, for his support and guidance throughout my studies at Murdoch University.

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List of Abbreviations

AC - Alternating current

DC Direct current

CT -Current transformer

CVT-Capacitor Voltage Transformers

EMF-Electromotive force

I_M – Magnetization Current

I_{NOM}-Nominal Current

BIL –Basic Insulation Level

HMI- Human machine interface

PROM, Programmable read only memory

ms, Millisecond

REF-Restricted Earth fault

RTD –Resistance temperature device

SEL –Schweitzer Engineering Laboratories

SER –Sequential Event Report

VT-Voltage transformer

Chapter 1 Project Introduction

The three phase power transformer is the most critical link in power system networks. The transformer links generation and transmission by stepping up generated voltages to transmission levels. The transmission voltages are in turn stepped down to distribution voltage levels [1]. Protection of three phase transformers from fault currents is done by complex protection systems. One of the key elements of these systems is the protection relay. Protection relays have the ability to detect fault currents and initiate the operation of a circuit breaker which interrupts or disconnects the fault current hence protecting the transformer. Protection relays have developed over the years from the old electromechanical relays to numeric relays and now the microprocessor-based relays. The accuracy in metering, monitoring and operation of the protection relays is of utmost importance in preventing or minimizing damage to faulty equipment [3].

1.1 Background

To determine the accuracy and the functionality of the relays in commissioning, maintenance and education purposes, various brands of simulators have been developed . The most popular brands simulators used in industry are Megger, Omicron and Doble. There are two main types of fault simulators: High level simulators shown in Figure 3, and low level simulators like the Schweitzer Engineering Laboratories Relay Testing System (SEL RTS) system shown in Figure 5. The main difference between the two is the low level simulators bypass the analog input transformers and lower analog voltage inputs and currents are used in the simulation process [8]. Previous ENG 454 and thesis students at Murdoch University have used the Labvolt system, a high level simulator for fault simulation, to demonstrate the functionality of the SEL relays. Other students had begun the development of a National Instrument CompactDaq system fault simulation system with limited success [13]. Following on from some of those previous students' recommendations, this project will endeavour to continue on with the development of the system by using a different approach that is described in detail in Chapter 10 of this thesis [13].

1.2 Objectives

The aim of the project is to gain an in-depth understanding of the capability and functionality of the SEL 787 transformer protection relay available at Murdoch

University through carrying out tests and simulations on the relay using the low level simulator SEL RTS test system.

Documentation of the research and findings from this report will aid present and future Industrial Computer Systems students at Murdoch University to have a better understanding of the transformer protection relay.

A further aim is to advance the understanding of the use of low level simulators in testing protection relays. Low level simulators, as shown in Figure 5, facilitate fault simulation in protection by bypassing the protection relay input current and voltage transformers, hence eliminating the use of large amplifiers.

This project aims to contribute to an ongoing goal of eventually developing a CompactDaq and LabVIEW protection relay simulator. This will assist engineering students at Murdoch University and others in understanding the capabilities of the SEL protection relays as the simulator will provide a faster and more efficient way of carrying out fault simulations. The relay's capabilities in protection, monitoring and metering are thus explored.

Chapter 2 Protection Scheme

With the advancement in technology, protection relay systems have become more complex. The design of the systems and the core components has evolved to provide more effective and efficient systems. This chapter looks at the aims and requirements of a protection system together with the main components.

2.1 Purpose

A protection scheme is a system of plant and equipment responsible for detecting abnormal conditions in electrical power systems and initiate the operation of switchgear to isolate the faulted equipment in the shortest time possible. This reduces damage on the faulted equipment and stops the effects of the fault from affecting other functioning parts of the power system [2]. There are two main types of protection schemes, unit and non-unit protection schemes. Unit schemes of protection operate only for faults within a clearly demarcated zone. There is no time coordination required with other protection systems in the power system. On the other hand, non-unit protection schemes have to be coordinated with other protection systems in the overall power system. Figure 1 shows the core components of a typical protection scheme [2].

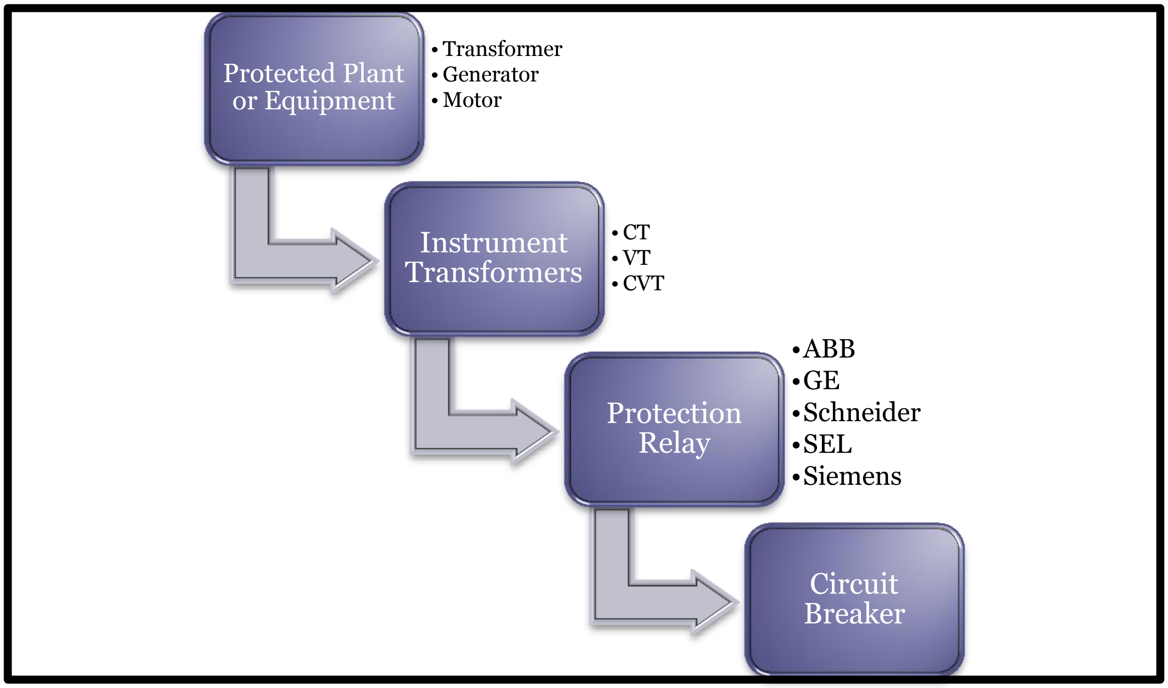

Figure 1 Protection scheme components

The main components of a protection scheme are described below:

- Current transformers (CT): these reduce the high values of fault currents which result under fault conditions to suitable values for protection relay operation. Thus, the main purpose of the current transformer in protection systems is to provide currents to the control and protection circuits which are proportional to the power system currents [4].

- Voltage transformers (VT): these step down the system voltage to lower scaled values to be used in control and protection circuits.

- Capacitor voltage transformers (CVT) have a capacitance voltage divider which steps down extra high voltages to low voltages [4].
- Protection relay: the device, which is activated by appropriate system parameters, for example, current and voltage. The relay indicates an abnormal condition in the power system and initiates the operation of a protection device, for example, a circuit breaker. There are several manufactures of these devices including Siemen and SEL, as indicated in Figure 1 above [2].
- Circuit breakers: these close and open the electrical circuit under both normal and fault conditions. The circuit breaker operation under fault conditions is usually initiated by the protection relay operation [6].

2.2 Attributes of a good protection scheme

Protection systems in most cases do not prevent damage to the faulted equipment during a fault but rather minimise the damage and the effects of the fault on the entire electric circuit. The following are the attributes of a good protection system:

- Reliability: the protection scheme has to be dependable and operate when required as per design specifications. Incorrect operation of the protection scheme may lead to a disastrous situation with damage to plant and equipment. Reliability of the protection system can be affected by the following factors: incorrect design, incorrect installation and deterioration of the protection equipment over time [2].

- Speedy isolation: to minimise damage to faulted equipment and prevent system instability, the protection system has to isolate the fault as quickly as possible. Isolation of the disturbance in the shortest amount of time ensures continuity of power supply in the functioning parts of the power system. [2]
- Sensitivity: this refers to the minimum amount of system quantities (for example, current) required to activate the protection system when an abnormal condition arises in the power system. A protection system with a very low operating current is said to be very sensitive. [2]
- Stability: this mainly refers to unit schemes of protection which are only required to operate for faults occurring within a clearly demarcated region and not operate for faults outside the protected zone. [2]
- Selectivity: this is also referred to as discrimination and refers to the protection system operating only for the faulty part of the electrical network, isolating it and leaving the healthy parts of the circuit with supply. [2]
- Economical: it is imperative to have appropriate levels of protection for plant and equipment at an appropriate cost. The degree of protection of a piece of equipment has to be weighed against the cost of the equipment and the cost of loss of power supply to the network. The degree of protection usually increases with the value of equipment being protected as the repair or replacement cost of the equipment are high. [2]

2.3 Protection Relays

2.3.1 Electromechanical

These relays are made of mechanical, electrical and magnetic components and the majority are of the moveable coil type. The principle of operation of these relays is based on the establishment of torque, produced by the interaction of magnetic flux, which is of a magnitude proportional to the value of current and voltage being measured. These types of protection relays are very reliable and robust, however, they are less accurate compared to solid state relays and deteriorate over time due to mechanical moving parts getting worn. [7]

2.3.2 Solid State

Over the years, the development of semiconductors and associated electronic advances has led to the design of numeric or solid state protection relays. These relays are more accurate, consume less power, occupy less place on installation, and are more resistant to vibrations and shock compared to the electromechanical relays. The downside to the solid state relays is that they require an independent power supply and are more affected by humidity and temperature. [21]

2.3.3 Microprocessor-based Relays

The growing intricacy in modern power networks has necessitated the development of microprocessor-based relays with sophisticated characteristics. These protection relays, also called intelligent electronic devices, have high-performance microprocessors which have the capabilities of performing all the protection functions done by solid state relays with greater speed and efficiency [7]. Figure 2 shows the typical general arrangement of microprocessor-based relays.

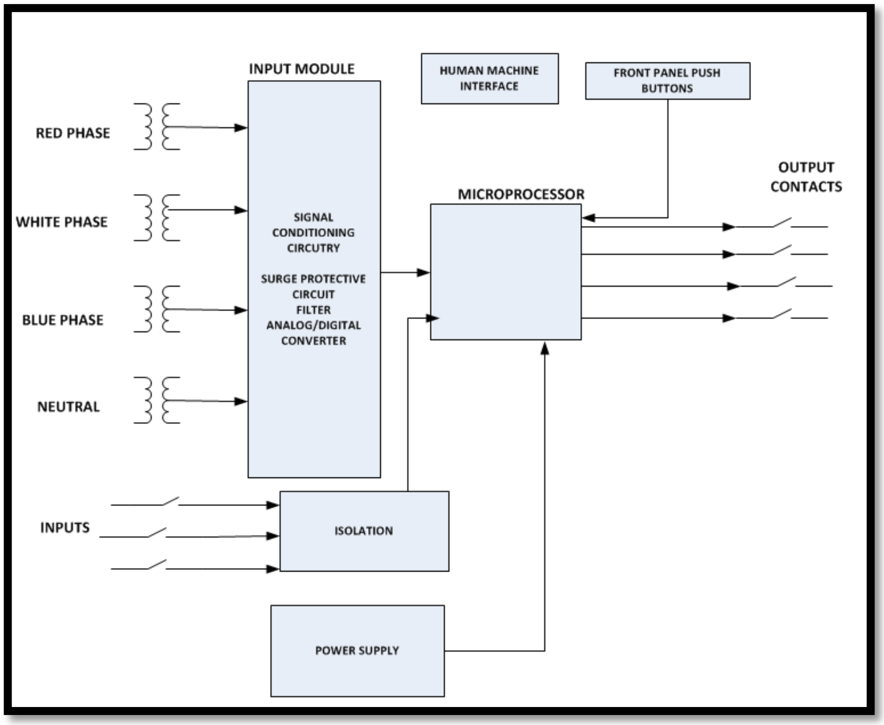

Figure 2 General arrangement of a microprocessor relay

The main components of a microprocessor-based relay are as follows:

- Input module: this consists of analog filters, signal conditioner and analog to digital converters. Signals from the power system are captured and sent to the microprocessor via this module [7].
- Microprocessor: the main purpose of this is to process the protection relay algorithms. It consists of two memory components: random access memory responsible for storing information during the processing of protection algorithms; and read only memory which stores data permanently [7].
- Output module: output signals from the microprocessor are conditioned and sent to the external elements which it controls [7].
- Communication module: consists of series and parallel ports which facilitate connection of protection relays with communication and control systems [7].

Chapter 3 Protection relay fault simulators

After manufacture, on installation and during maintenance, protection relays are tested for correct operation. This chapter provides an overview of the different types of test equipment used to verify the correct operation of these relays.

Protection relay test sets or simulators are the pieces of equipment used to measure the accuracy and demonstrate the full functionality of the relays. The modern day microprocessor protection relays have multiple functions and require sophisticated test simulators with hardware and software to comprehensively analyze the operation of the relay through simulation of real life conditions. There are several types used in industrial applications, in commissioning the relays in new installations and maintenance testing in already established installations [4].The commonly used ones include the Doble F6150, Omicron CMC 365 and Megger MPRT. For educational purposes, the most popular simulator is the Labvolt system, shown in Figure 3, which is available at Murdoch University. The fault simulators can be categorized into two main groups; high level and low level fault simulators.

Figure 3 Labvolt high level simulator

3.1 High level simulators

These simulators have the capability of simulating different fault conditions through hardware and software and monitor the performance of the protection relay. The hardware components consist of analog outputs, binary outputs and binary inputs and communication interface for the associated software. The software is used to control the hardware, monitor and record the protection relay performance during the simulation. The simulation process mimics real life analog inputs to the relay from CTs and VTs and monitors the operation of the relay via relay indicators and output contacts of the relay’s changing state [4].

3.2 Low level simulators

The main purpose of these simulators is to supply the protection relay with voltage and current inputs that resemble fault conditions and monitor how the relay responds in these situations. The main difference between the two is that the low level simulators bypass the analog input transformers and lower analog voltage inputs and currents are used in the simulation process [8]. For example, the SEL RTS low level simulator provides low voltage AC signals to the protection relay microprocessor via the relay test interface on the analog input circuit board as shown in Figure 4. The simulators usually come with the associated software which is used to control, monitor and record the simulation results. For the SEL RTS simulator, the software is called SEL 5401. These simulators are less expensive than the high level simulators [8].

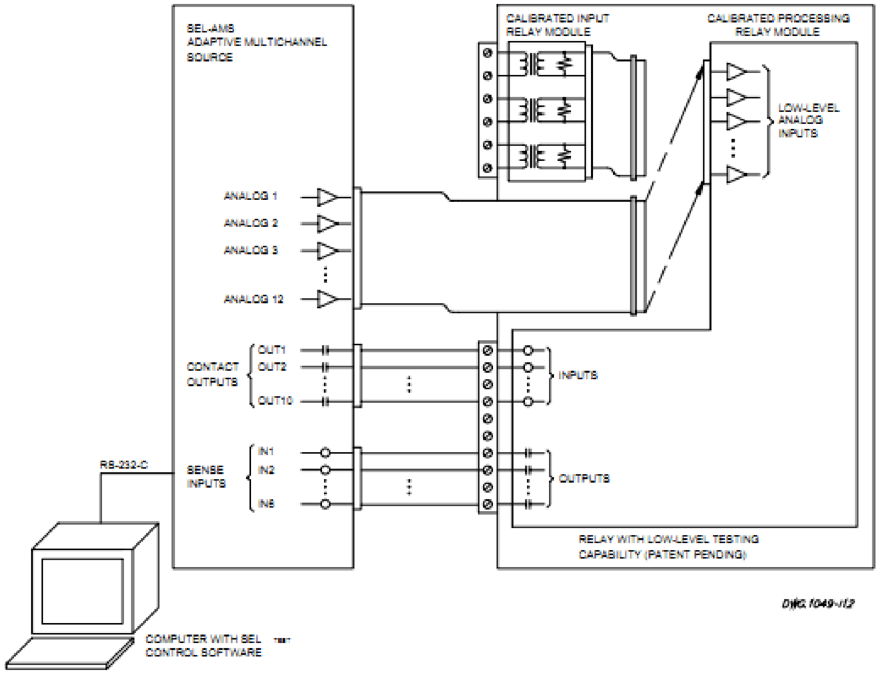

Figure 4 Low level protection relay simulator set up [8]

Figure 5 Low level protection relay simulator

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Chapter 4 Power Transformer

Invented towards the end of the nineteenth century the power transformer has become a vital link in today's transmission and distribution systems. This chapter reviews the theory of principle of operation and the different type of faults which can occur on transformers.

4.1 Power transformer construction

A power transformer is a static electrical device used to step up or step down voltage. It consists mainly of two windings: the primary and the secondary windings which are electrically isolated but magnetically linked through a magnetic core made of insulated laminations. The insulated laminations are usually made from silicon steel which increases the magnetic coupling due to its high magnetic permeability properties.

4.2 Principle of operation

A transformer operates on the principles of electromagnetic induction. When an alternating voltage is applied to the primary windings, self-induction occurs on the primary windings and the changing alternating current in the primary winding induces an EMF in the secondary winding, with the process called mutual induction. The silicon steel core serves to provide a very low reluctance path for the magnetic flux. The effect of the magnetic flux is to generate a mutually induced EMF in the secondary winding which is not supplied with the alternating voltage. This is illustrated in Figure 6 [6].

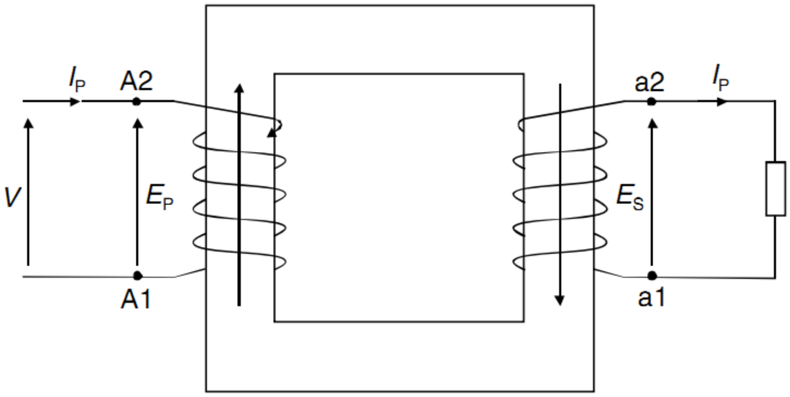


Figure 6 Transformer principle of operation [6]

4.2.1 Transformer magnetisation Characteristics

During normal operation, the transformer follows the typical magnetization curve shown in Figure 7.

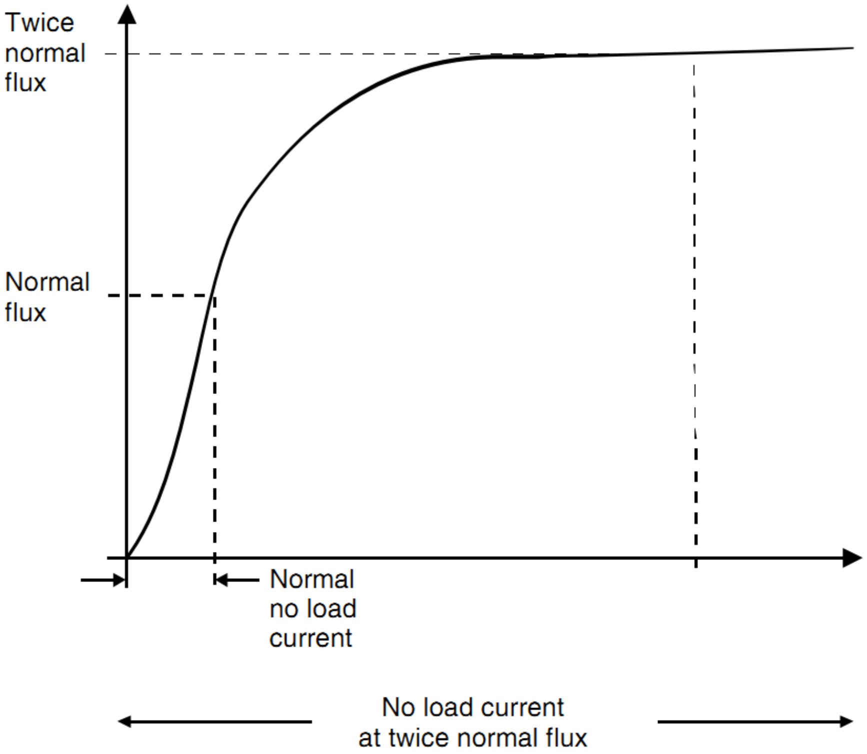


Figure 7 Transformer magnetisation curve [6]

Transformers are usually operated close to the knee point of the characteristic to get the best efficiency. Increasing the terminal voltage leads to the saturation of the core and excessive magnetization currents being drawn.

Figure 8 shows the relationship between the voltages V, magnetization current I_M and ф magnetic flux under steady state conditions [6].

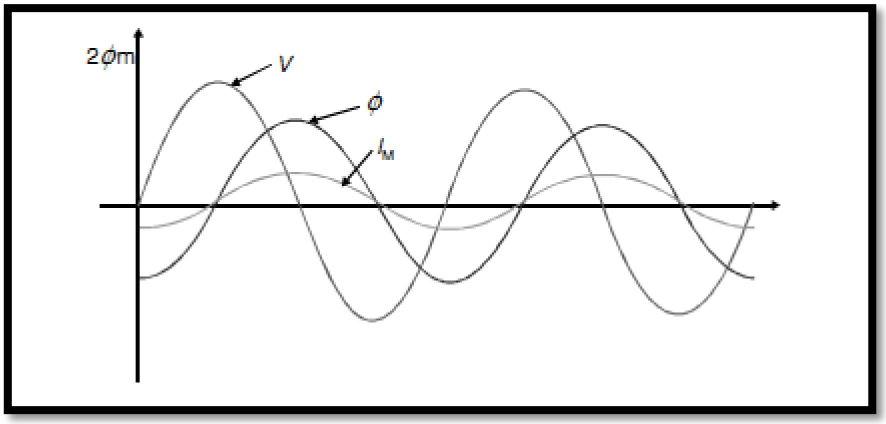


Figure 8 Transformer steady state operation [6]

On energization when the voltage is at zero, the magnetic flux demand is very high and can be twice the normal magnetic flux. This causes a very high magnetising current to flow, as illustrated in Figure 9. This high magnetising current (I_M) is also known as the transformer inrush current. The presence of residual flux or remanent flux can further increase the magnitude of this current on energization [6].

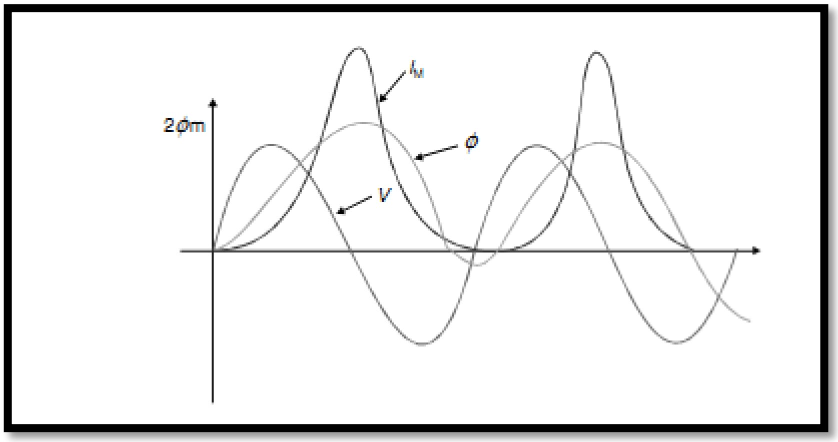


Figure 9 Transformer transient operation on energisation [6]

4.3 Power transformer faults

4.3.1 Phase-to-Phase faults:

These faults are rare on transformers and can be caused by both internal and external conditions. Insulation breakdown due to mechanical stress and overheating can cause phase to phase and phase to earth faults. External conditions which can lead to phase to phase faults include overloading, overvoltage and other power system faults. Internal conditions include ageing insulation and presence of contaminants in insulating medium [2].

4.3.2 Phase-to-Earth faults:

These faults occur when the transformer windings get into contact with earth or any other conductive material connected to earth. Insulation breakdown due to ageing, poor workmanship and overheating can cause these type of faults.

4.3.3 Core faults:

The magnetic or iron circuit of the transformer made of insulated laminated silicon steel has bolts which clamp the laminations together. The bolts are insulated from the laminations and if this insulation breaks down, high eddy currents may flow which cause overheating in the transformer. Power system over voltages may lead to high magnetization currents that produce flux from the highly saturated core, which is diverted to the clamping bolts. The bolts usually have low flux circulation but the high flux can result in very high temperatures emanating from the bolts. The high temperatures cause damage to the insulation leading to the short-circuiting of the core laminations [6].

4.3.4 Tank faults:

Oil filled transformers are housed in tanks containing insulating oil which completely covers the windings and the core. The main purpose of the oil is to cool the transformer; it also acts as an insulating medium. The loss of oil via leaks can lead to overheating of the transformer and insulation reduction. Overheating of the transformer causes break down of insulation in the winding and results in short circuit faults [2]

4.3.5 Inter-turn Faults:

Insulation between turns can break down due several factors which include overheating, mechanical stress from over voltages and ageing of the insulation which can be made worse by the presence of moisture in the transformer. Figure 10 shows an inter-turn fault on the secondary side of the transformer. The inter-turn short circuit will result in high currents in the short- circuited loop. The terminal currents will be low due to the high transformation ratio between the whole affected winding and the turns, which are short-circuited [6].

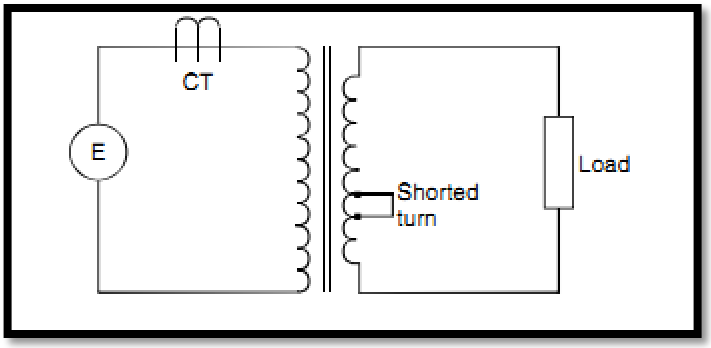


Figure 10 Transformer inter-turn fault [6]

Chapter 5 Schweitzer Engineering Laboratories, Inc.

Established in 1982, Schweitzer Engineering laboratories SEL is an organisation based in Washington, United States of America and specialises in the manufacture of power system protection relays. This chapter provides an overview of the SEL protection relay software package and some of its key features used throughout this project.

5.1 SEL Acselerator Quick set

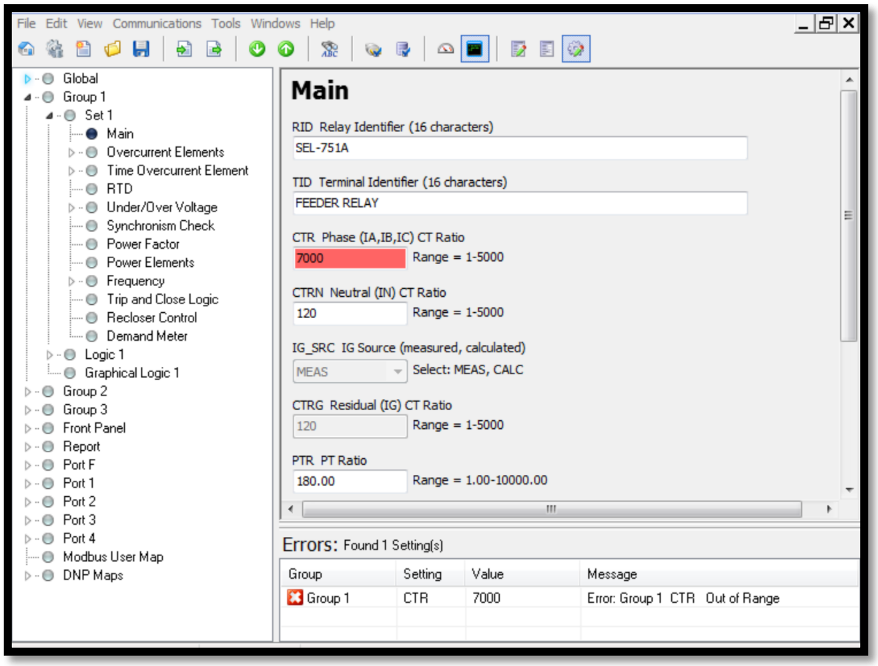
This software platform tool from SEL is used as the interface between the SEL protection devices and the user for communication, metering, control, protection and monitoring purposes. The following section will look at some of the important features of this software platform [9].

5.2 Settings

5.2.1 Settings Editor

The protection relay settings specific to the device are found in the settings editor. The settings can be edited according to the protection system requirements. The settings have a fixed range which when violated an error message comes up and setting box is highlighted in red as shown in Figure 11.

This feature also applies for logic based settings and equations, if an invalid word bit is entered in the setting box for the logic equation an error message comes up. These features are useful for identifying any setting errors in conducting simulations.



Main

RID Relay Identifier (16 characters)
SEL-751A

TID Terminal Identifier (16 characters)
FEEDER RELAY

CTR Phase (IA,IB,IC) CT Ratio
7000 Range = 1-5000

CTRN Neutral (IN) CT Ratio
120 Range = 1-5000

IG_SRC IG Source (measured, calculated)
MEAS Select: MEAS, CALC

CTRG Residual (IG) CT Ratio
120 Range = 1-5000

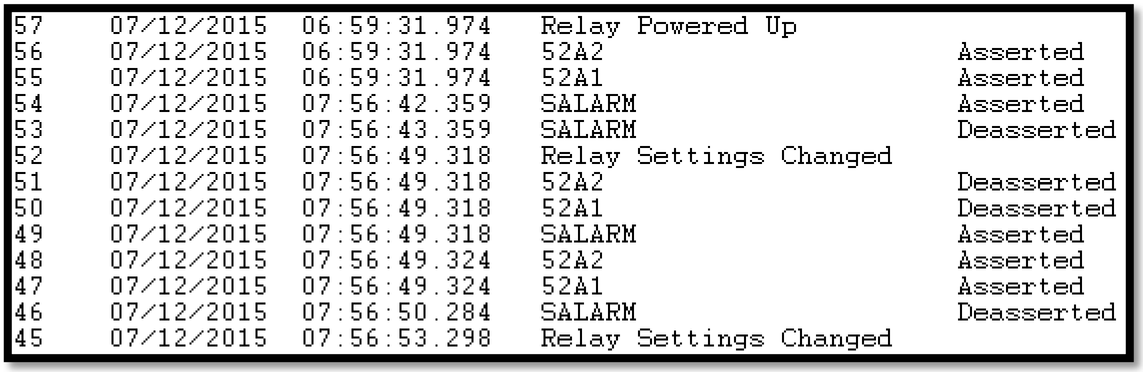
PTR PT Ratio
180.00 Range = 1.00-10000.00

Errors: Found 1 Setting(s)

Group	Setting	Value	Message
☒ Group 1	CTR	7000	Error: Group 1 CTR Out of Range

Figure 11 SEL relay setting editor page

Protection relay setting changes can be tracked or monitored via the terminal window by typing the sequential event record command (SER). This will give the date and time when changes to the settings were made as shown in Figure 12 taken during simulations on the SEL 787 relay [9].



```
57     07/12/2015  06:59:31.974   Relay Powered Up
56     07/12/2015  06:59:31.974   52A2                         Asserted
55     07/12/2015  06:59:31.974   52A1                         Asserted
54     07/12/2015  07:56:42.359   SALARM                       Asserted
53     07/12/2015  07:56:43.359   SALARM                       Deasserted
52     07/12/2015  07:56:49.318   Relay Settings Changed
51     07/12/2015  07:56:49.318   52A2                         Deasserted
50     07/12/2015  07:56:49.318   52A1                         Deasserted
49     07/12/2015  07:56:49.318   SALARM                       Asserted
48     07/12/2015  07:56:49.324   52A2                         Asserted
47     07/12/2015  07:56:49.324   52A1                         Asserted
46     07/12/2015  07:56:50.284   SALARM                       Deasserted
45     07/12/2015  07:56:53.298   Relay Settings Changed
```

Figure 12 SEL 787 terminal window showing setting change

5.2.2 Group setting

The software platform also allows for the flexibility to have more than one group setting for each device. These settings are configured in groups, as shown in Figure 13, which was taken from the SEL 787 protection relay at Murdoch University via Acselerator software. The user is able to configure different settings for different applications if required; for example, a power utility company might desire to have different protection settings for different seasons of the year [9].

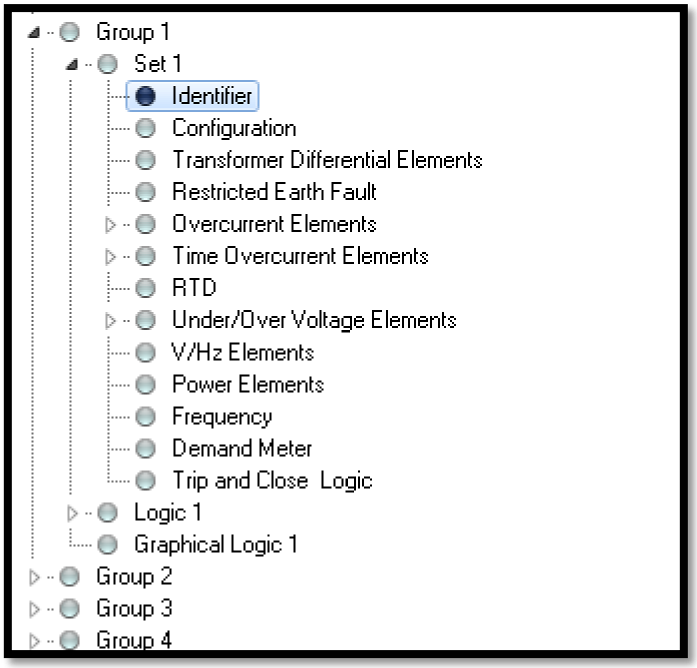
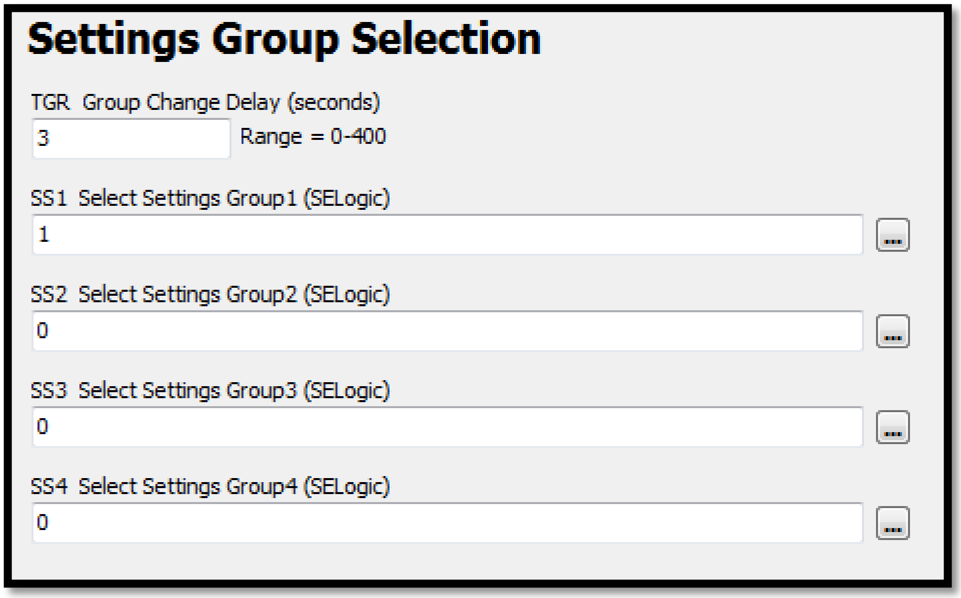


Figure 13 SEL787 Group settings

For testing purposes, having a different group of settings is convienient as changes can be made to these settings without affecting the original settings [9]. Selection of the final group settings to be used at a particular time can be done via the setting group selection tab shown below in Figure 14.



Settings Group Selection

TGR Group Change Delay (seconds)
3 Range = 0-400

SS1 Select Settings Group1 (SELogic)
1

SS2 Select Settings Group2 (SELogic)
0

SS3 Select Settings Group3 (SELogic)
0

SS4 Select Settings Group4 (SELogic)
0

Figure 14 SEL 787 group setting selection

5.2.3 Settings compare

This feature allows the user to compare settings between databases. During testing, the user may need to disenable some of the protection element settings to accommodate the verification or testing of required protection elements. This feature affords the user to compare the original settings and the modified settings verify the changes and update the settings as required. With the setting compare feature, comparison of settings between different setting groups can be done [9].

5.3 Terminal

The terminal window accessed on the tools tab is shown in Figure 15.

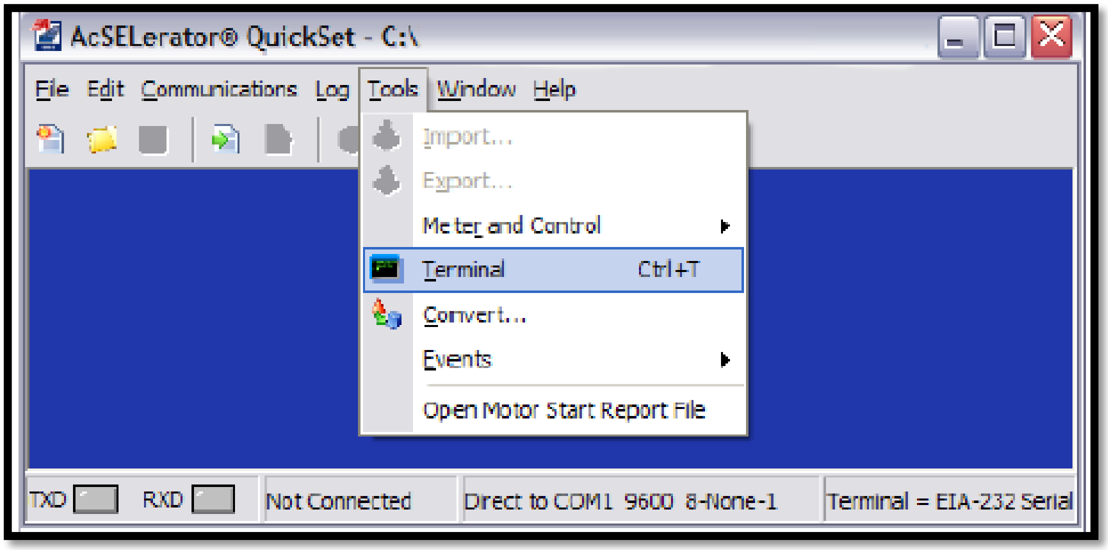


Figure 15 Acselerator Terminal tab [9]

The terminal or command window is an interface with the relay using ASCII. This window was used in the project for the following: relay verification, identification, communication verification, monitoring, protection element operation verification and event history analysis [9].

5.4 Human machine Interface HMI

This tool is useful for commissioning and testing and throughout the project duration it was used to observe metering and target data. Operation of protection elements can be viewed from this window. The control window of the HMI was used to reset metering data, clear event history and the sequential event report [9].

5.5 SEL Logic

The block diagram shown in Figure 16 shows the sequential interaction of the protection and programmable logic. SEL logic equations are used to logically integrate chosen protection relay elements for different control functions. Protection relay inputs are assigned via the logic equations to suit specific applications [9].

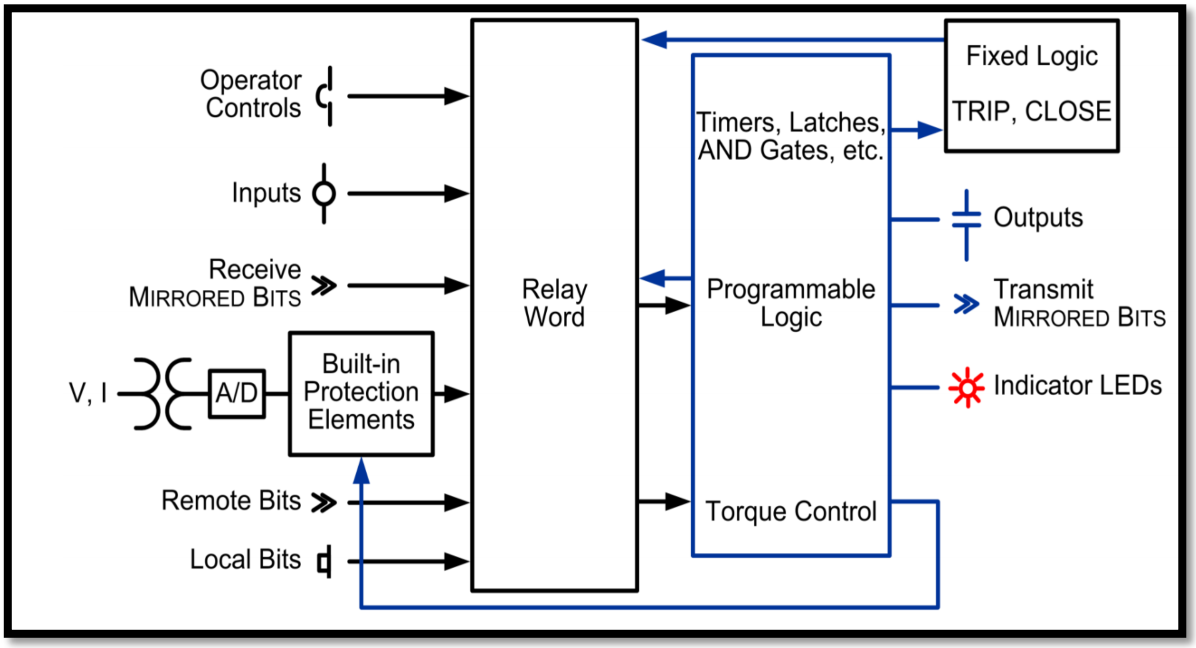
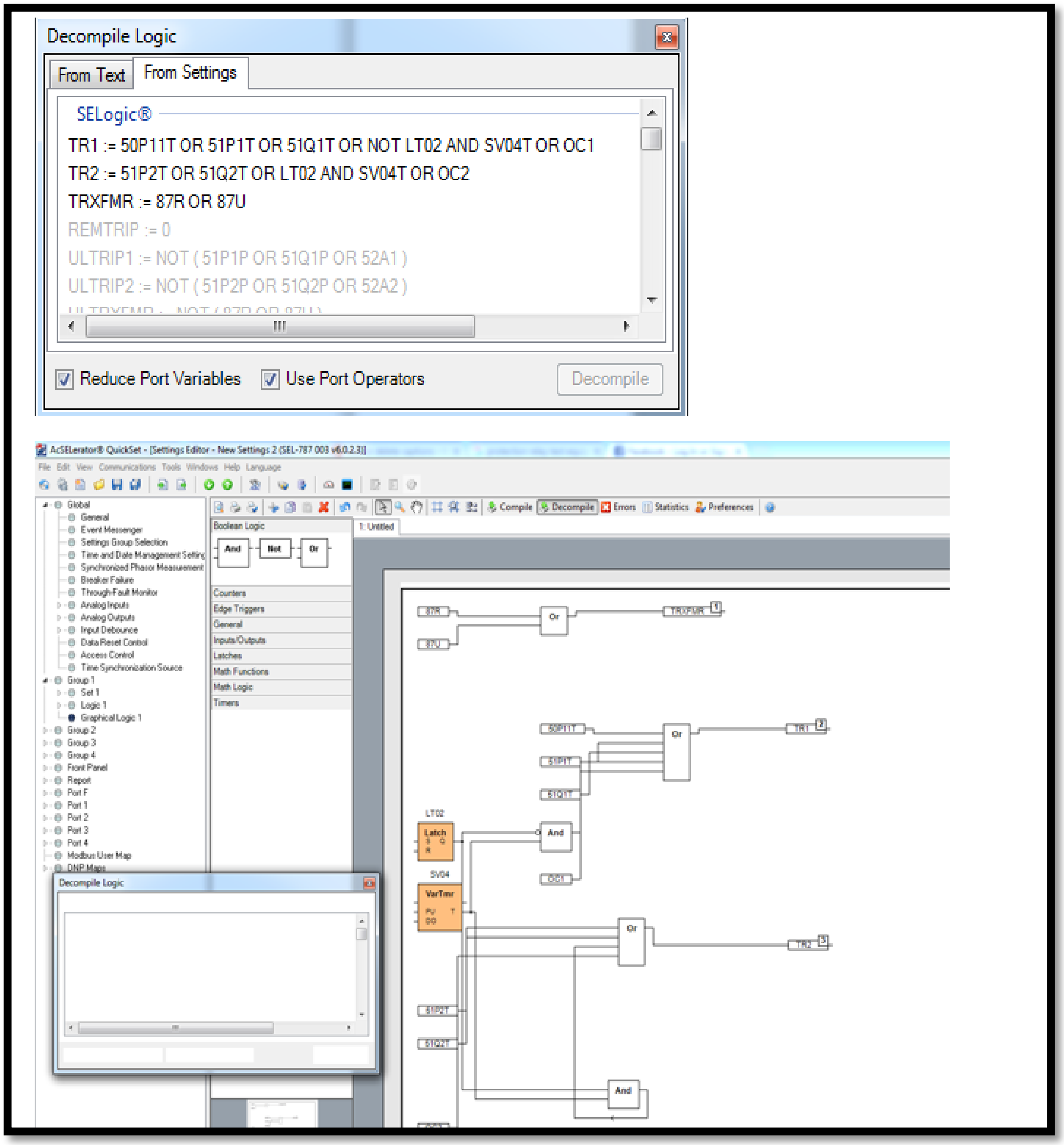


Figure 16 SEL protection relay logic structure overview [9]

Design of the application suited trip, open, close and reclose control logic circuits can be achieved in programming the logic equations. Using the logic has the benefit of eliminating the use of external timers and needing counters hard wired, hence saving time and money. Programming in SEL protection relay is done in two programming languages. The default language used is structured text.

This can be changed to function block language via decompiling, as shown in Figure 17, which was captured from the SEL 787 relay at Murdoch University.



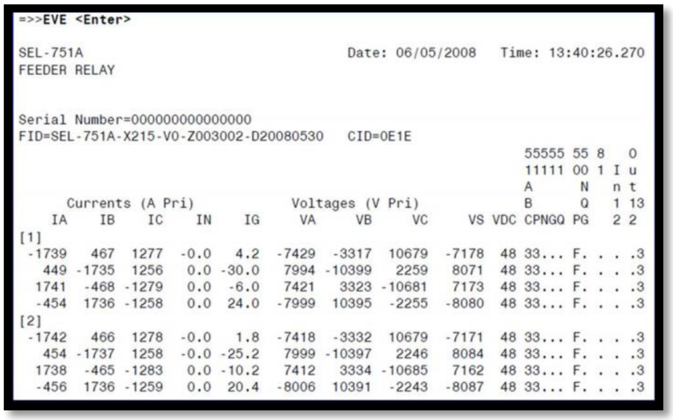
```
TR1 := 50P11T OR 51P1T OR 51Q1T OR NOT LT02 AND SV04T OR OC1
TR2 := 51P2T OR 51Q2T OR LT02 AND SV04T OR OC2
TRXFMR := 87R OR 87U
REMTRIP := 0
ULTRIP1 := NOT ( 51P1P OR 51Q1P OR 52A1 )
ULTRIP2 := NOT ( 51P2P OR 51Q2P OR 52A2 )
```

☑ Reduce Port Variables ☑ Use Port Operators

Figure 17 SEL programing language in structured text and decompiled to function block

5.6 Event analysis

Event reports and fault data can be viewed in the terminal window by typing the command EVE or via SEL Acselerator analytical assistant software 5601. In the terminal window the data is presented in text format as shown in Figure 18 [20]. The analytical tool on the other hand displays an analog oscillography which the user can customise.



```
=>>EVE <Enter>

SEL-751A                                      Date: 06/05/2008   Time: 13:40:26.270
FEEDER RELAY


Serial Number=000000000000000
FID=SEL-751A-X215-V0-Z003002-D20080530   CID=0E1E
                                                               55555 55 8   0
                                                               11111 00 1 I u
                                                               A      N   n t
      Currents (A Pri)              Voltages (V Pri)           B      Q   1 13
    IA    IB    IC    IN    IG     VA     VB     VC     VS VDC CPNGQ PG   2 2
[1]
 -1739   467  1277  -0.0   4.2  -7429  -3317  10679  -7178  48 33... F. . . .3
   449 -1735  1256   0.0 -30.0   7994 -10399   2259   8071  48 33... F. . . .3
  1741  -468 -1279   0.0  -6.0   7421   3323 -10681   7173  48 33... F. . . .3
  -454  1736 -1258   0.0  24.0  -7999  10395  -2255  -8080  48 33... F. . . .3
[2]
 -1742   466  1278  -0.0   1.8  -7418  -3332  10679  -7171  48 33... F. . . .3
   454 -1737  1258  -0.0 -25.2   7999 -10397   2246   8084  48 33... F. . . .3
  1738  -465 -1283   0.0 -10.2   7412   3334 -10685   7162  48 33... F. . . .3
  -456  1736 -1259   0.0  20.4  -8006  10391  -2243  -8087  48 33... F. . . .3
```

Figure 18 Terminal Event Report [20]

Figure 19 shows and oscillography for a fault simulation in three states prior the fault, during the fault and post fault. This was captured during fault simulation on the SEL 787 protection relay housed at Murdoch University. The event reports contain the following information date and time of the event, fault data in primary values, relay identifiers. These tools were used throughout the project to verify correct operation of the relay and analysis of fault simulation results.

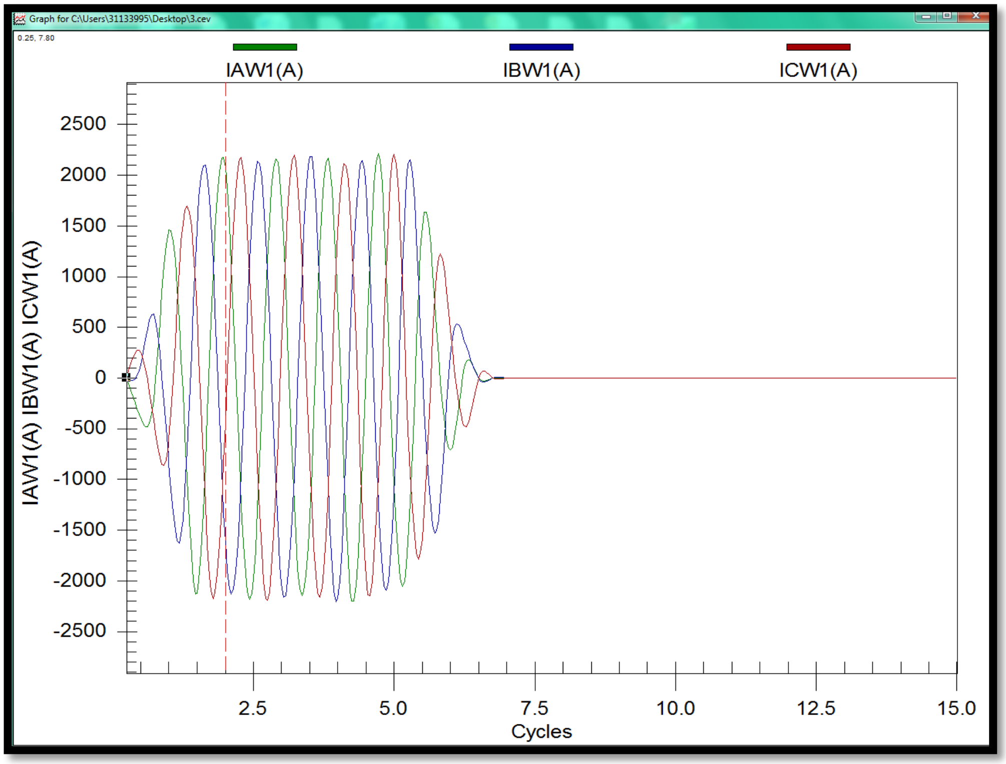
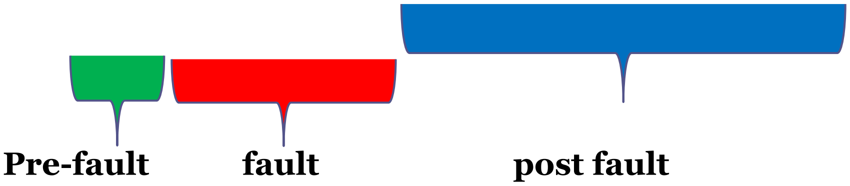


Figure 19 Event Oscillography



Chapter 6 SEL 787 Protection relay overview

Microprocessor based relays offer effective and efficient fault detection. This chapter looks at the architecture of the SEL 787 transformer and different types of wiring configuration to facilitate fault simulation.

6.1 Hardware

The SEL-787 protection belongs to a family of SEL transformer protection relays shown in Figure 20. The SEL transformer protection relays have a rugged design and are robust. Two-winding and multiple winding transformers can be protected by this series of relays depending on the application. Apart from the primary function of protecting the transformer under abnormal conditions the protection relays can be used for, transformer monitoring, metering and reporting [9].

Figure 20 SEL transformer protection series

6.1.1 I/O cards

The SEL 787 protection relay is a two-winding transformer protection relay. The SEL 787 relay full complement has a total of six rear –panel slots labelled A, B, C, D, E and Z as as shown in Figures 21 and 22. The protection relay specifications for all the individual slots are detailed in appendix C of this report.The specifications are critical to ensure correct operation of the relay and avoid damage to it .The nominal operating volatges of the relay and slot maximum voltage and current ratings are detailed in this section [9].

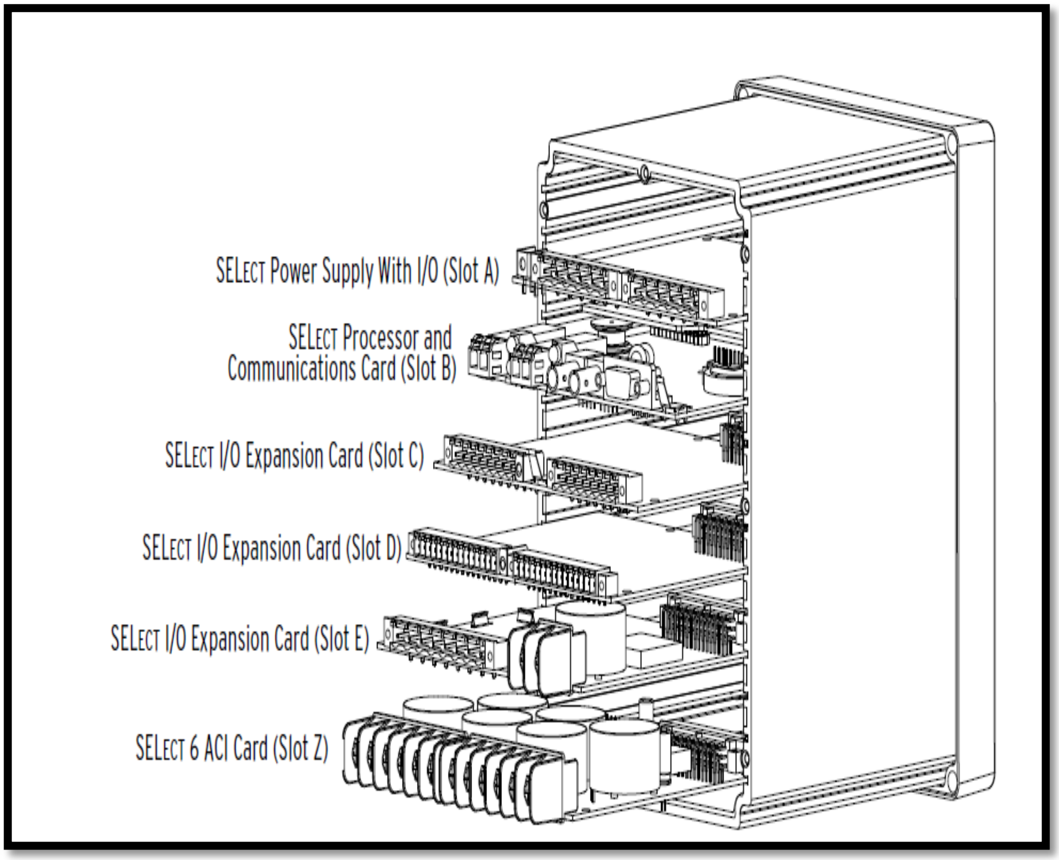


Figure 21 SEL 787 relay I/O cards [9]

Figure 22 shows typical rear view of the SEL 787 protection relay with all seven card slots. Slot A is the power supply and input and output card. The inputs and outputs can be configured to meet specific applications via the logic programming in Acselerator Quickset. Slot B in the main base communication card. The slot has fibre - optic, serial and Ethernet ports. An additional communication slot with input and output contacts can be accommodated in slot D. Slot E is the voltage input card and also accommodates for the neutral current analog input.

The final slot Z is the analog current transformer input slot with the SEL 787 protection relay having option for 1 amp or 5-amp input [9].

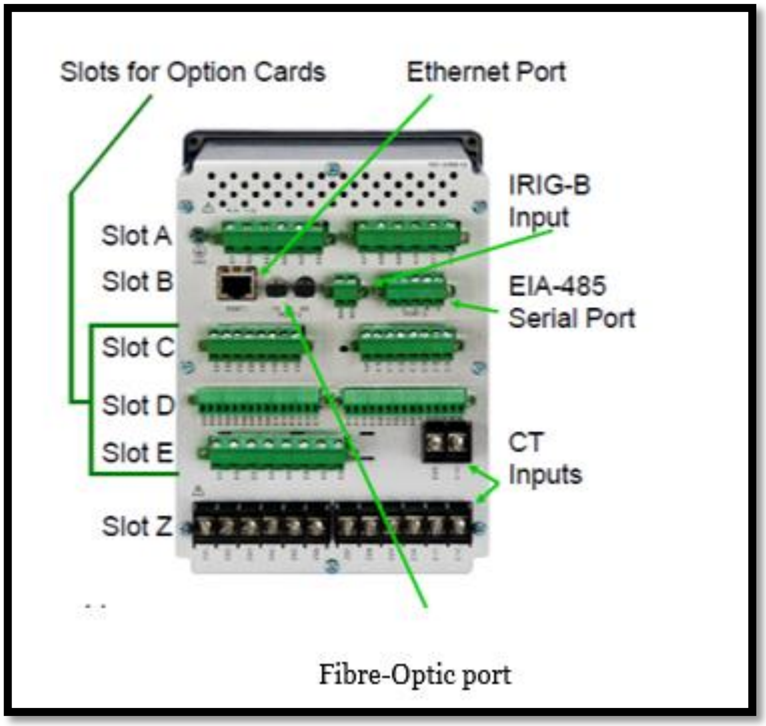
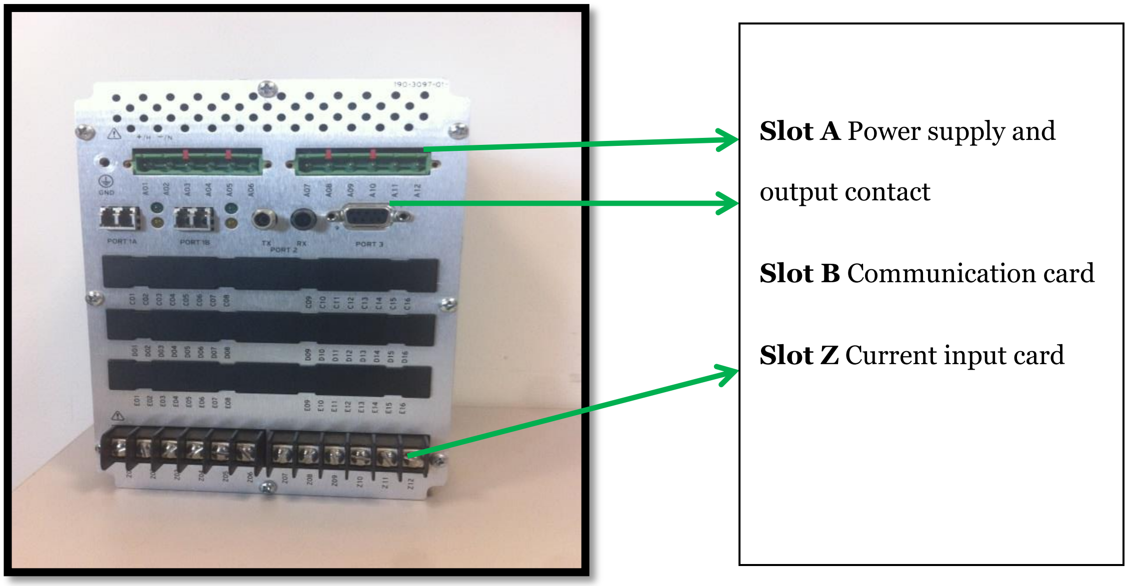


Figure 22 SEL 787 rear view slots [9]

Figure 23 shows the actual SEL 787 at Murdoch University which only has the base cards slots A, B and Z.



Slot A Power supply and output contact

Slot B Communication card

Slot Z Current input card

Figure 23 SEL 787 relay at Murdoch University rear view

The additional digital communication and voltage cards are not available on the SEL 787 transformer protection relay housed at Murdoch University. Investigations were only undertaken for the protection functions for the available hardware slots, that is, for the current based elements, such as overcurrent and differential protection. The following protection functions: restricted earth fault, volts/hertz and RTD-based protection element could not be investigated due no hardware slot cards being available. A relay nameplate depicting the available slot cards and the expansion card is shown in Figure 24 below.

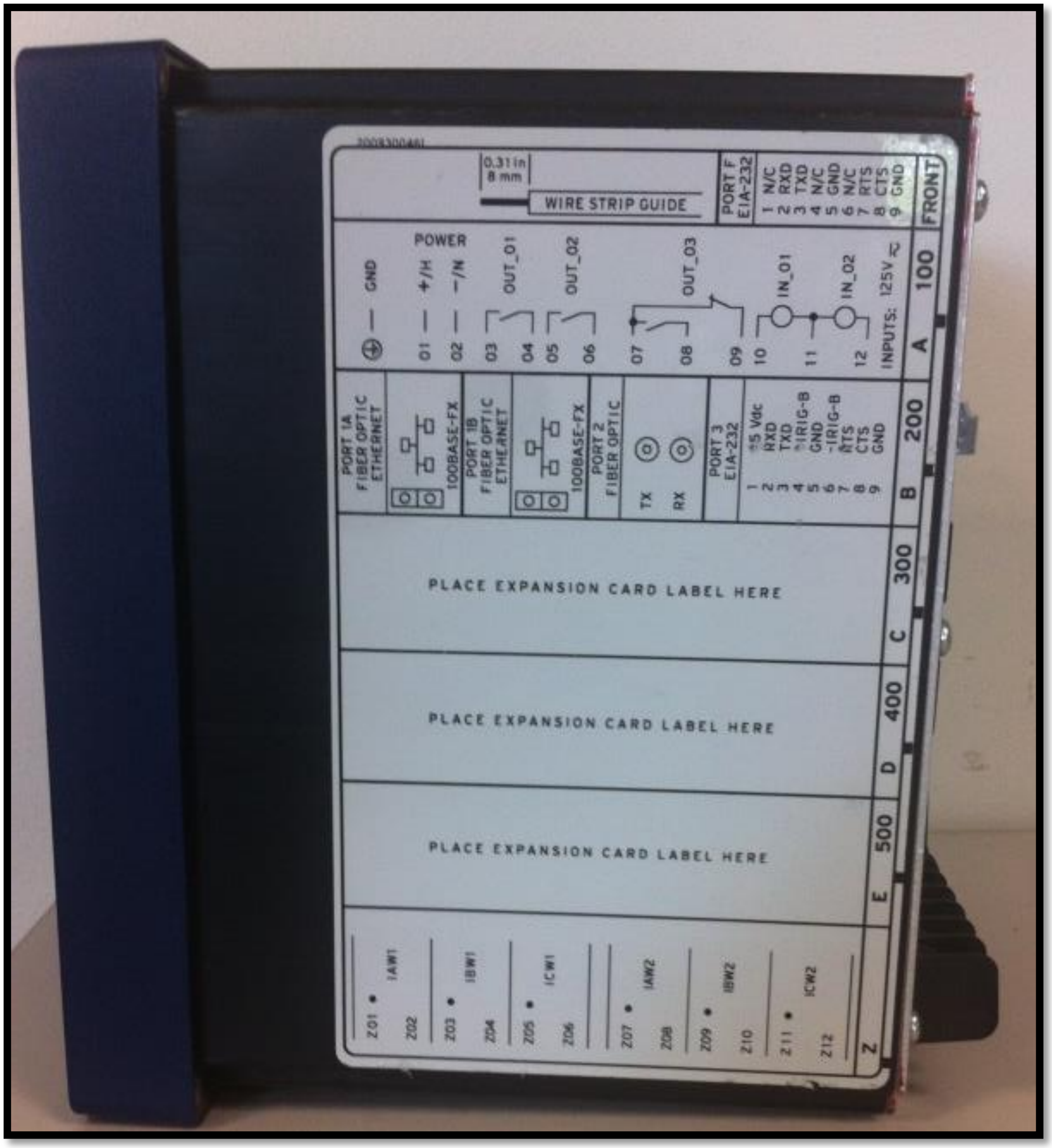


Figure 24 SEL 787 relay side view information template

6.1.2 Front panel

The SEL 787 protection relay has 16 trip target and status indication light emitting diodes (LEDs), as shown in Figure 25. These LEDs can be programmed for a specific application. Factory labels for each protection function can be replaced with custom made labels to suit the user's application, as shown in Figure 25 below. The front panel LCD display is used for displaying measured values and input and output status. Four pushbuttons that can be programmed for operator control are also located on the front panel.

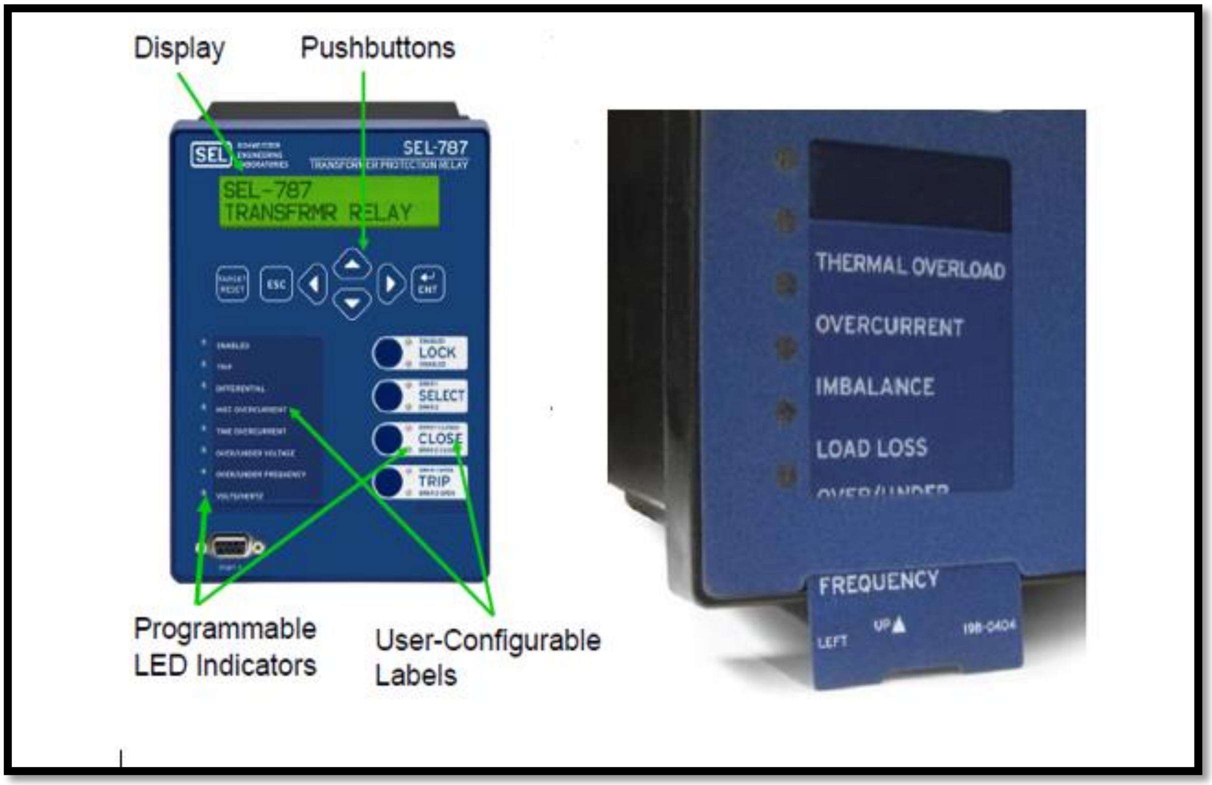


Figure 25 SEL 787 front panel [9]

6.1.3 Wiring configuration

For current based fault simulations both high and low level testing slot Z of the protection relay is used. For high level simulations the analog simulation currents are wired directly on the slot Z terminals.

Carrying out high level fault simulations on protection relays can be tedious and time consuming with regards to the wiring configuration as illustrated in Figure 26 which shows the wiring configuration done by previous students at Murdoch university to carry out fault simulations on the SEL 787 protection relay.

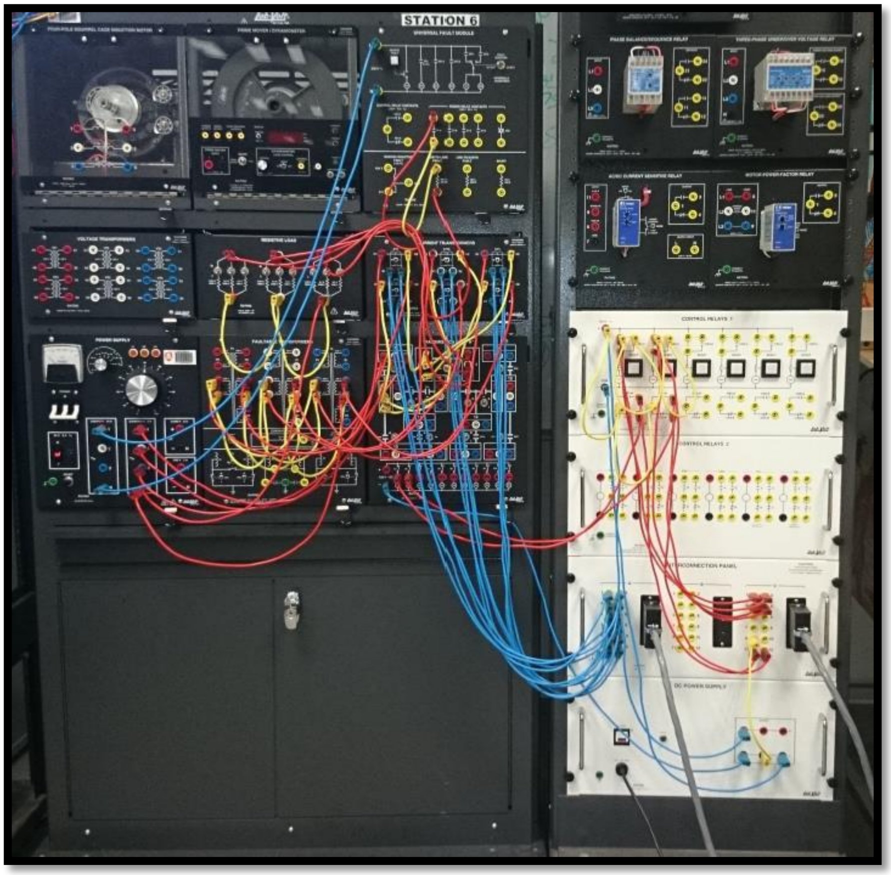


Figure 26 Labvolt relay fault simulation setup [13]

For low level fault simulation, the SEL 787 relay has to be configured to cater for this type of testing The current input card in slot Z, shown in Figure 27, was removed from the relay and set up for low level testing.

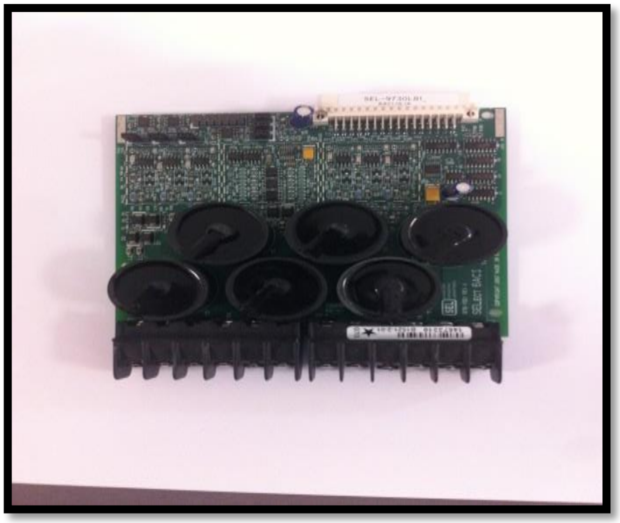
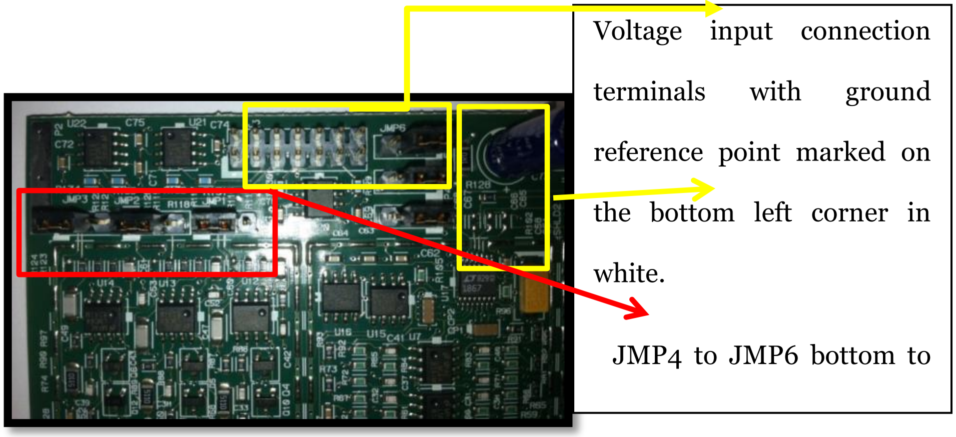


Figure 27 Analog current card

To facilitate for the low-level interface fault simulation Jumpers 1, 2, 3, and 6 on the analog current card had to be reconfigured as shown in Figure 28.

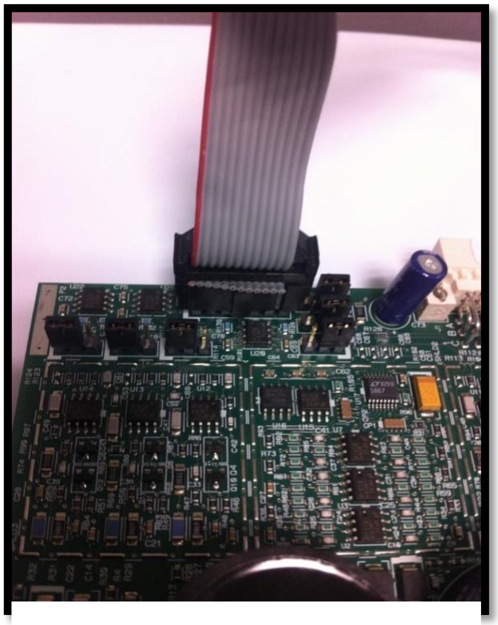


Voltage input connection terminals with ground reference point marked on the bottom left corner in white.

JMP4 to JMP6 bottom to

Figure 28 Slot Z Input circuit board

Caution in connecting the ribbon test cable to the circuit board was of great importance to prevent damage to the card. Figure 29 below shows the connection of the test cable on the circuit board.



The Ribbon cable co
AMS simulator. The
cable connected to t
white mark.

Figure 29 Test cable input connection

Chapter 7 Protection relay standards and testing

To correctly carry out simulations on protection relays is complex as fault conditions have to be simulated instead of normal operation conditions. This chapter provides an insight into the recommended approach to be taken when carrying out the testing and the related standards. The simulation approach taken to carrying out tests throughout this project is also covered in this chapter.

7.1 Protection relay standards

Correct operation of protection relays during fault conditions is critical in preventing and minimising damage to the protected plant and equipment and ensuring power system stability. Incorrect operation may lead to protected devices being damaged and undesirable power outage, hence testing of the relays to manufacturer specifications is critical [22]. For the SEL 787 protection relay, the manufacturer specifications with regards to relay element operation accuracy and metering accuracy are detailed in appendix C of this report. The IEC 60255 standard details the minimum requirements for the performance of protection relays under both steady state and dynamic conditions.

The different types of simulation methodologies for verifying the accuracy and performance characteristics of the relays are also specified in this standard [17].

IEEE Standard C37.2-2008 covers and specifies the different elements and abbreviations for protection relays. The protection relay functions or elements are referred to by device numbers specified in this standard and letters are often added to identify a certain application. Table 2 in appendix B of this report details the SEL 787 protection function acronyms and their description, all specified to ANSI and IEEE standards [18].

7.2 Relay Testing and fault simulations

The guide for power system protection testing, IEEE C37.233/D3 lays out the different methodologies and procedures to follow in testing protection relays. The guide specifies the different types of tests and the minimum requirements for the test equipment used in carrying out the simulations. These guidelines were used as the foundation in carrying out the fault simulations analysing and verifying the simulation results [18].

7.2.1 Types of tests

The guide lists the following tests; certification, performance, application, conformance, commissioning and maintenance are carried out during the life span of a protection relay. For this project conformance and performance tests or simulations were carried out to verify and explore the capability of the relay.

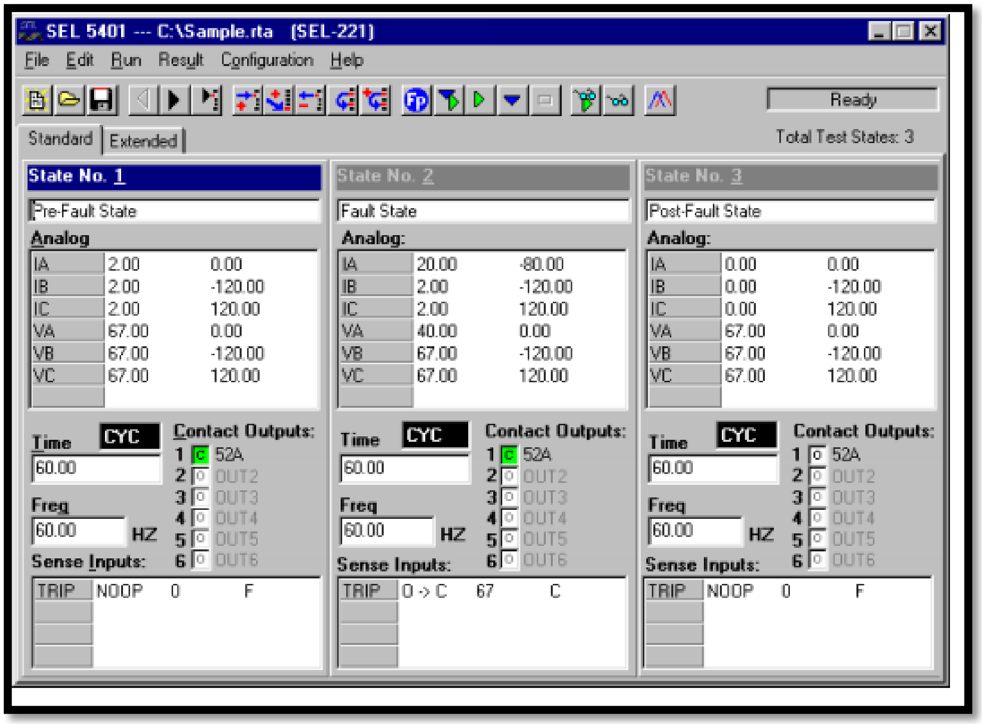
Conformance tests are done to verify the functionality of a protection element as expected. The characteristics of the protection element are verified against specifications. These tests are usually steady state test with the test signals not having transient and DC components. By contrast, performance tests focus on what is desired from the protection function under specific network conditions [18].

7.2.2 Test equipment

The IEE c37.233/D3 specifies some of the requirements for simulation equipment as having software to generate fault sequences. The associated vendor software to communicate with the protection device and the test equipment has the capability to record the fault and capture all information associated with the fault. In addition, the actual miscellaneous test equipment such as test leads and connector jumpers, are all rated to withstand the required simulation voltages and currents [18].

7.2.3 Fault data arrangement

Fault simulations or tests on the protection relays can be done as a single or three phase injection, depending on the specific requirements. The layout of the fault simulation can consist of different states and transitions. The states contain the simulation data, for example pre-fault, fault and the post-fault as shown in Figure 30 [8]. To move from one state to the next, different transitions can be used as desired by the user, for example, using a timer or user initiated digital input.



Total Test States: 3

State No. 1

Pre-Fault State

Analog

IA	2.00	0.00
IB	2.00	-120.00
IC	2.00	120.00
VA	67.00	0.00
VB	67.00	-120.00
VC	67.00	120.00

Time CYC 60.00

Freq 60.00 HZ

Contact Outputs:
1 C 52A
2 O OUT2
3 O OUT3
4 O OUT4
5 O OUT5
6 O OUT6

Sense Inputs:
TRIP NOOP 0 F

State No. 2

Fault State

Analog:

IA	20.00	-80.00
IB	2.00	-120.00
IC	2.00	120.00
VA	40.00	0.00
VB	67.00	-120.00
VC	67.00	120.00

Time CYC 60.00

Freq 60.00 HZ

Contact Outputs:
1 C 52A
2 O OUT2
3 O OUT3
4 O OUT4
5 O OUT5
6 O OUT6

Sense Inputs:
TRIP O -> C 67 C

State No. 3

Post-Fault State

Analog:

IA	0.00	0.00
IB	0.00	-120.00
IC	0.00	120.00
VA	67.00	0.00
VB	67.00	-120.00
VC	67.00	120.00

Time CYC 60.00

Freq 60.00 HZ

Contact Outputs:
1 O 52A
2 O OUT2
3 O OUT3
4 O OUT4
5 O OUT5
6 O OUT6

Sense Inputs:
TRIP NOOP 0 F

Figure 30 State sequence test template [8]

7.2.4 SEL-4000

The SEL-4000 system is a low level protection relay simulator and consists of the SEL AMS shown in Figure 7 and the accompanying software SEL-5401. [8]. This system was used for the greater part of the project to develop simulation templates and carry out the testing.

The SEL-AMS consists of twelve analog outputs for voltage and current outputs, and digital and analog inputs to capture measured times and for the simulation of circuit breaker status condition. The test system also consists of LEDs on the front panel for indication of input and output channels, auxiliary DC power supply and a serial communication port [8].

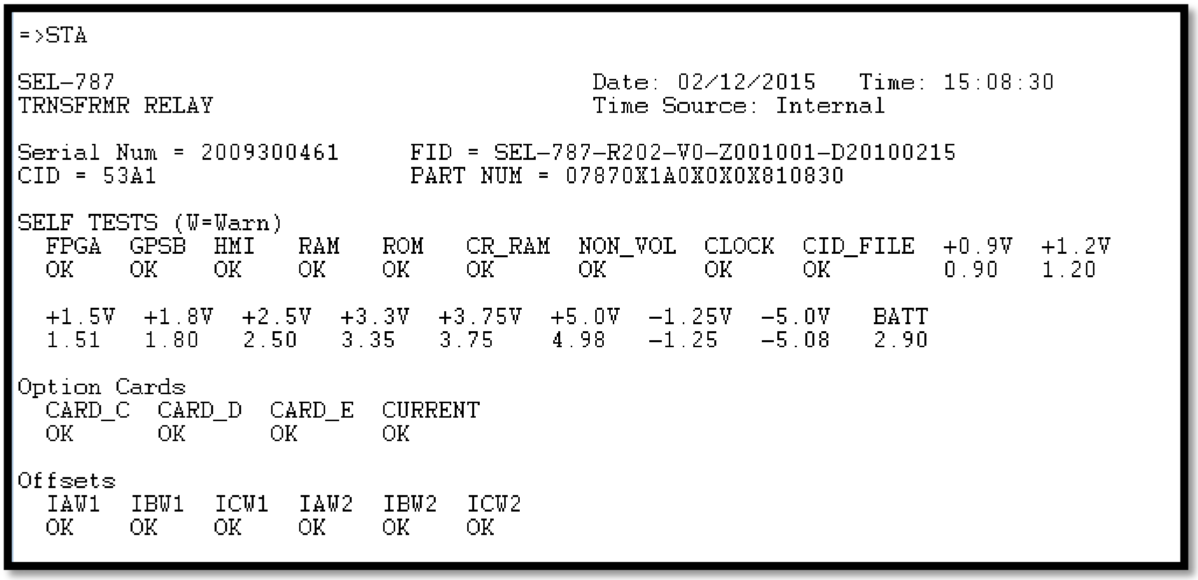
The SEL-5401 software employs the finite state machine simulation philosophy to enable simulation using different states as shown in Figure 30. Increment of fault data in small values in a process called test ramping can be achieved using this software to determine the minimum fault values which initiate operation of the relay. Simulation results can be viewed via the simulation window. Both single phase and three phase fault simulation was carried out [8].

7.2.5 Safety

In order to minimise the risk of injury and damage to equipment and devices, it is critical to identify the dangers or hazards associated with the specific task to be undertaken and also to take up actions to reduce or eliminate the hazards. For this project prior to carrying out the simulations, a job hazard analysis document was completed to identify the hazards and establish the appropriate controls to reduce or eliminate the hazard.

7.2.6 Self-test

Prior to carrying out the simulations the condition of the protection relay was assessed by carrying out a self-test and displaying the results in the terminal window. The command to display the self-test status is STA as shown in Figure 31.



```
=>STA

SEL-787                                  Date: 02/12/2015   Time: 15:08:30
TRNSFRMR RELAY                           Time Source: Internal

Serial Num = 2009300461     FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  PART NUM = 07870X1A0X0X0X810830

SELF TESTS (W=Warn)
  FPGA  GPSB  HMI   RAM   ROM   CR_RAM  NON_VOL  CLOCK  CID_FILE  +0.9V  +1.2V
  OK    OK    OK    OK    OK    OK      OK       OK     OK        0.90   1.20

  +1.5V  +1.8V  +2.5V  +3.3V  +3.75V  +5.0V  -1.25V  -5.0V   BATT
  1.51   1.80   2.50   3.35   3.75    4.98   -1.25   -5.08   2.90

Option Cards
  CARD_C  CARD_D  CARD_E  CURRENT
  OK      OK      OK      OK

Offsets
  IAW1  IBW1  ICW1  IAW2  IBW2  ICW2
  OK    OK    OK    OK    OK    OK
```

Figure 31 Relay self- test report

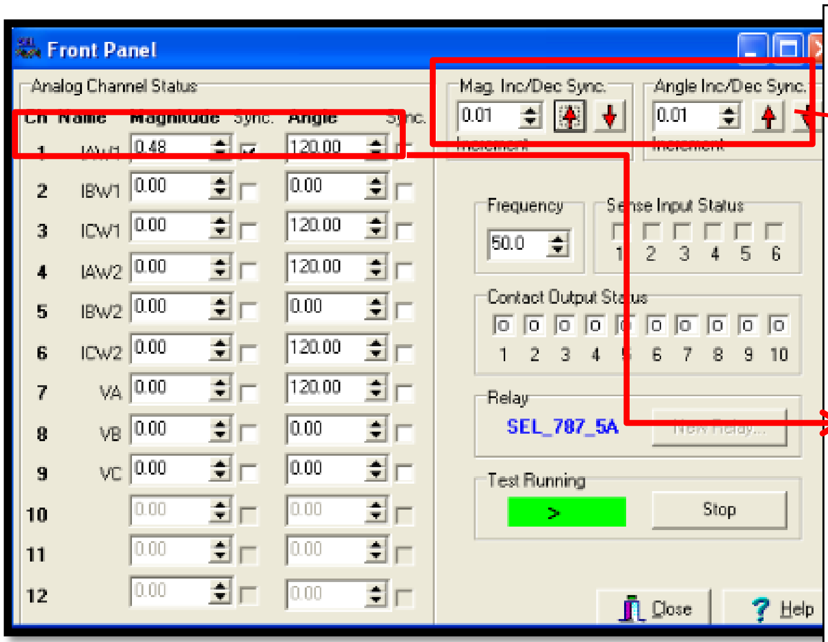
7.3 Simulation Methodology

The approach in carrying out the testing or fault simulations was divided into the following three categories:

1. **Device under test**: This section involved obtaining all the necessary information and specifications of the protection relay with regards to power supply, analog AC voltage and current input, frequency and communication parameters. A thorough understanding of the protection relay elements was required with regards to their operation characteristics, element setting, relay model current rating 1 Amp or 5 Amp, the accuracy limits of the secondary current in steady state and time delay accuracy limits.

2. **Low Level simulator:** After gathering all the information about the protection relay to be tested and determining the protection relay elements and the associated settings, the next step was to configure the simulator or test equipment to carry out the simulation. For this report, single phase and three phase fault simulations were carried out. Two main simulation techniques were employed during the testing process, state sequence and ramping. Ramping involved incrementing current or phase angle values at a desired rate, either manually by clicking on the red arrows shown in Figure 32 below, or automatically by defining the rate of increment. The state sequence method involved developing static tests with simulation data which is applied to the device under test. For a defined period of time, transition to the next state is

done. If required, as described earlier, there can be a pre-fault, fault and post-fault states.



Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	0.48	☑	120.00	☐
2	IBW1	0.00	☐	0.00	☐
3	ICW1	0.00	☐	120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync.: Increment 0.01

Angle Inc/Dec Sync.: Increment 0.01

Frequency: 50.0

Sense Input Status: 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

Contact Output Status: 1 0, 2 0, 3 0, 4 0, 5 0, 6 0, 7 0, 8 0, 9 0, 10 0

Relay: SEL_787_5A

This section of the test template is used for ramping the magnitude of the test parameter voltage, current, frequency and phase angle.

This magnitude of the test parameter in this case current will increase in steps specified in the increment section.

Figure 32 Ramp testing

<u>Result monitoring and Analysis:</u> The following tools were used to monitor operation and analysing the protection results. Protection relay front panel LEDs and human machine interface device view event report, sequential event report, terminal which are part of the Acselerator Quickset software. Protection relay operation was monitored using these tools and the results were compared and analysed against the manufacturer specifications.

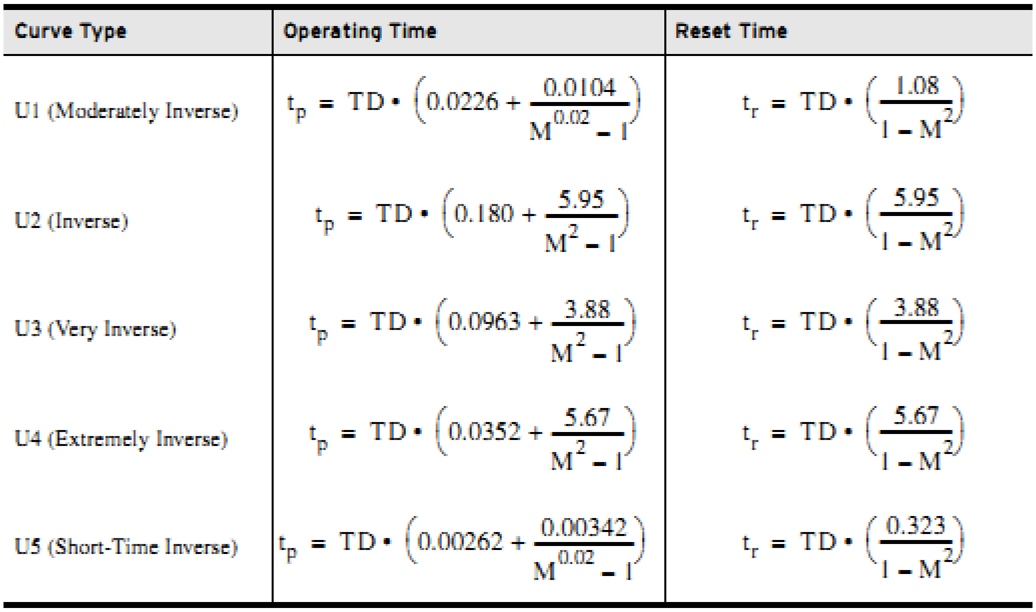
Chapter 8 SEL 787 Protection relay elements

The SEL 787 transformer protection relay consists of current and voltage based protection functions. This chapter covers in detail the operation and the work carried out to explore the functionality of these protection functions or elements.

8.1 Current based protection elements

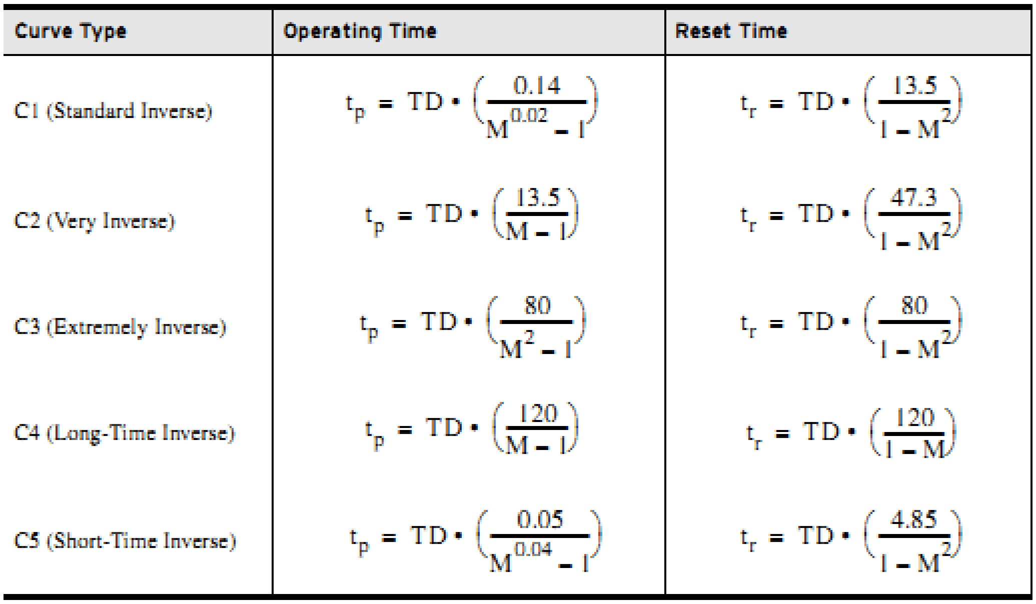
The SEL 787 transformer protection relay has the following instantaneous and timed based current elements: phase overcurrent, residual and negative phase sequence for both the primary winding and secondary winding of the transformer. The difference between the instantaneous and timed elements is that an intentional time delay is introduced on the timed elements for the purposes of achieving protection relay co-ordination. Protection relay coordination is a process that involves the appropriate selection of current and time settings of the relay operation to achieve discrimination in a power system network [9].

The current based elements for SEL 787 protection relay, that is residual, phase and negative sequence, have inverse time characteristics from five U.S and IEC characteristics. The equations for these characteristics are shown in Figure 33 below [9].



Curve Type	Operating Time	Reset Time
U1 (Moderately Inverse)	$t_p = TD \cdot \left(0.0226 + \frac{0.0104}{M^{0.02} - 1}\right)$	$t_r = TD \cdot \left(\frac{1.08}{1 - M^2}\right)$
U2 (Inverse)	$t_p = TD \cdot \left(0.180 + \frac{5.95}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{5.95}{1 - M^2}\right)$
U3 (Very Inverse)	$t_p = TD \cdot \left(0.0963 + \frac{3.88}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{3.88}{1 - M^2}\right)$
U4 (Extremely Inverse)	$t_p = TD \cdot \left(0.0352 + \frac{5.67}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{5.67}{1 - M^2}\right)$
U5 (Short-Time Inverse)	$t_p = TD \cdot \left(0.00262 + \frac{0.00342}{M^{0.02} - 1}\right)$	$t_r = TD \cdot \left(\frac{0.323}{1 - M^2}\right)$

Table 4.15 Equations Associated With IEC Curves



Curve Type	Operating Time	Reset Time
C1 (Standard Inverse)	$t_p = TD \cdot \left(\frac{0.14}{M^{0.02} - 1}\right)$	$t_r = TD \cdot \left(\frac{13.5}{1 - M^2}\right)$
C2 (Very Inverse)	$t_p = TD \cdot \left(\frac{13.5}{M - 1}\right)$	$t_r = TD \cdot \left(\frac{47.3}{1 - M^2}\right)$
C3 (Extremely Inverse)	$t_p = TD \cdot \left(\frac{80}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{80}{1 - M^2}\right)$
C4 (Long-Time Inverse)	$t_p = TD \cdot \left(\frac{120}{M - 1}\right)$	$t_r = TD \cdot \left(\frac{120}{1 - M}\right)$
C5 (Short-Time Inverse)	$t_p = TD \cdot \left(\frac{0.05}{M^{0.04} - 1}\right)$	$t_r = TD \cdot \left(\frac{4.85}{1 - M^2}\right)$

Figure 33 Inverse time current characteristic equations [9]

Achieving protection co-ordination between electromechanical relays and microprocessor-based relays can be challenging, as the electromechanical relays require a longer period of time to reset. The SEL 787 transformer protection relay overcomes the issue via the torque control switch, which is enabled by its associated logic equations as shown in Figure 34 [9].

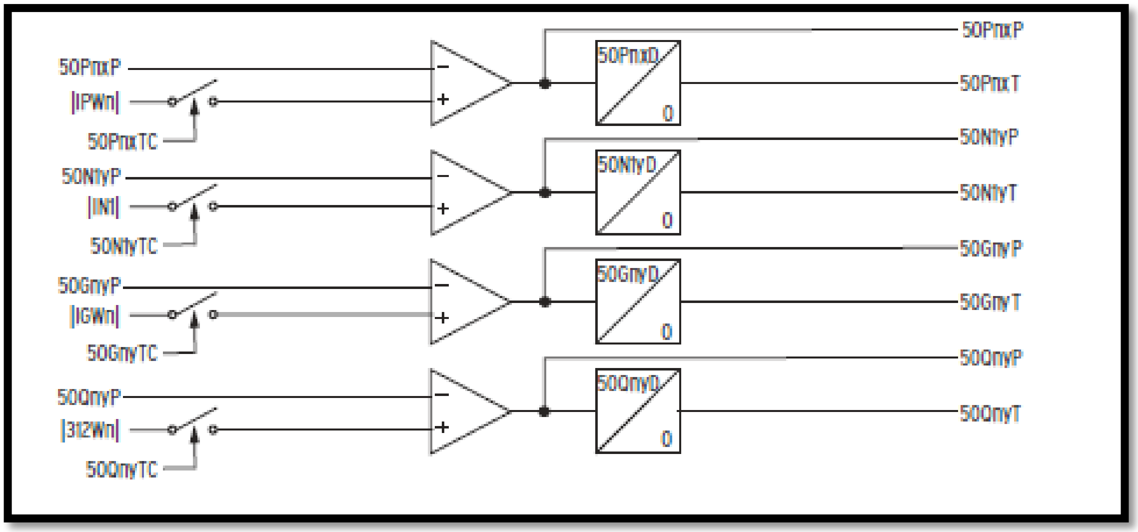


Figure 34 Torque control switch logic for overcurrent element [9]

Figure 35 shows an illustration of current protection elements of the SEL 787 protection relay: the raw input data from the field is calculated in the relay to determine if pre-set values have been exceeded for phase, residual and negative phase sequence elements.

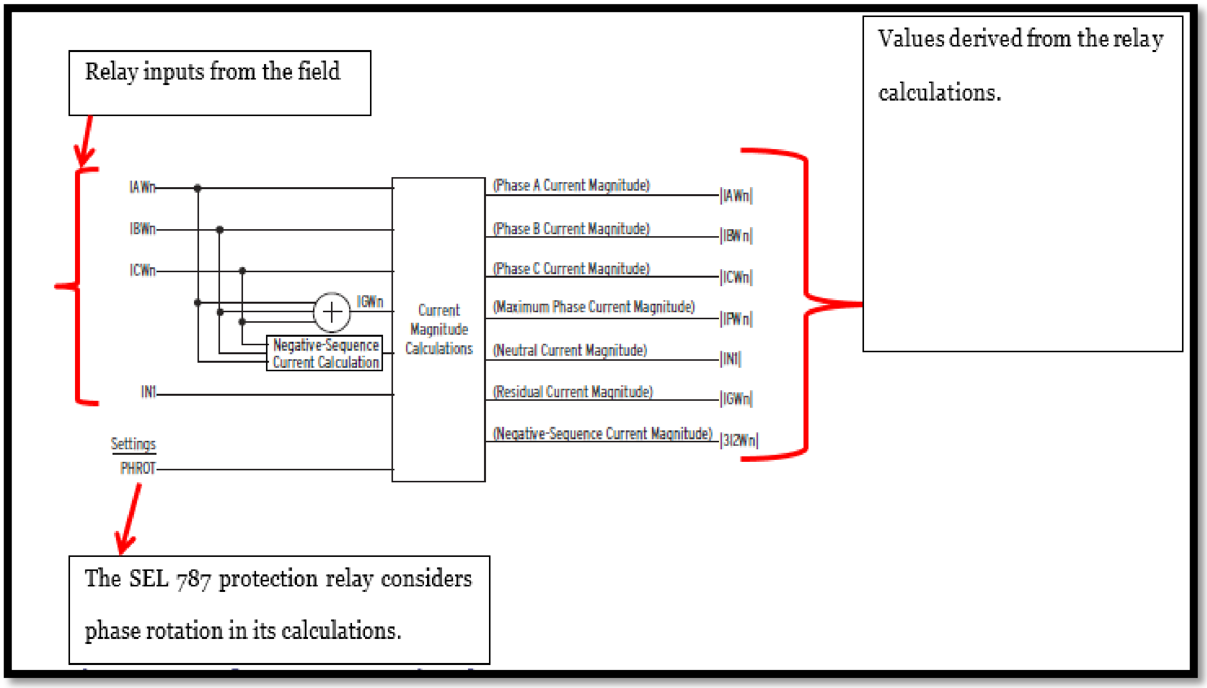
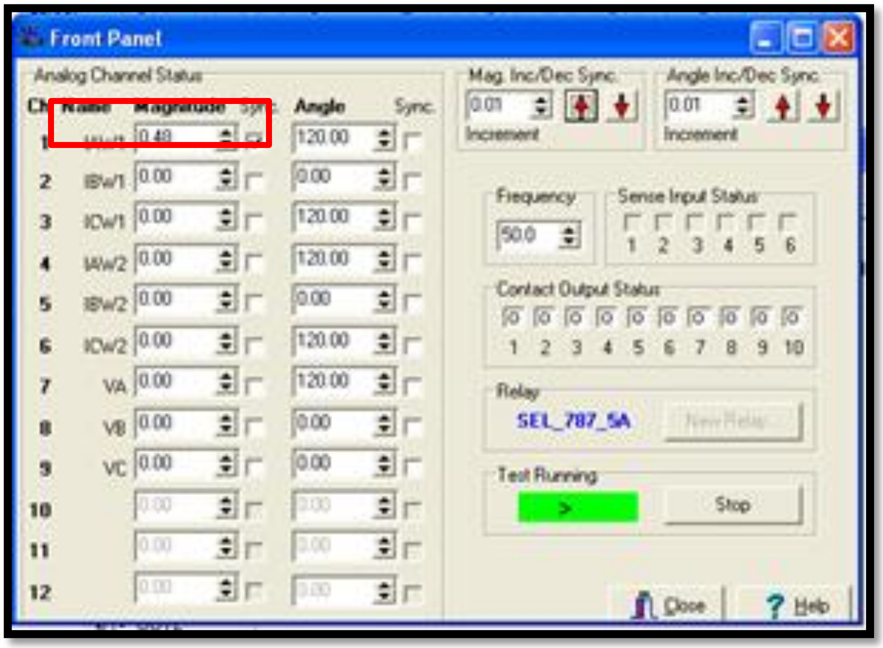


Figure 35 SEL 787 Current protection elements [9]

8.1.1 Phase overcurrent protection

This protection element, also denoted by its ANSI code of 50P11P for the instantaneous element, was initially tested without an intentional time delay and later tested with a time delay of 5 seconds. The ramping method was used to increase the currents in incremental steps of 0.01 to determine the minimum amount of current that causes operation of the relay. The minimum amount of current to operate the relay was 0.48 Amps as shown in Figure 36, which shows the front panel display for a single-phase fault simulation on the red phase. Both single phase and three phase simulations were carried out to investigate operation of this protection element.



Ch	Name	Magnitude	Sync	Angle	Sync
1	IAW1	0.48	☑	120.00	☐
2	IBW1	0.00	☐	0.00	☐
3	ICW1	0.00	☐	120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync Increment: 0.01

Angle Inc/Dec Sync Increment: 0.01

Frequency: 50.0

Sense Input Status	1	2	3	4	5	6
	☐	☐	☐	☐	☐	☐

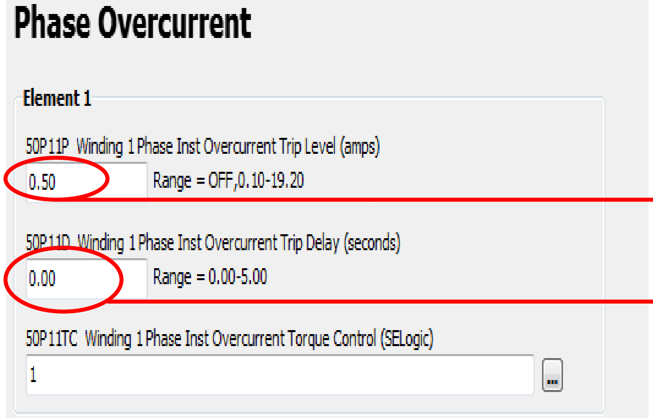
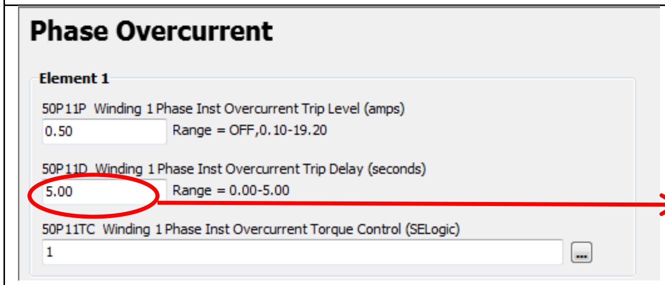
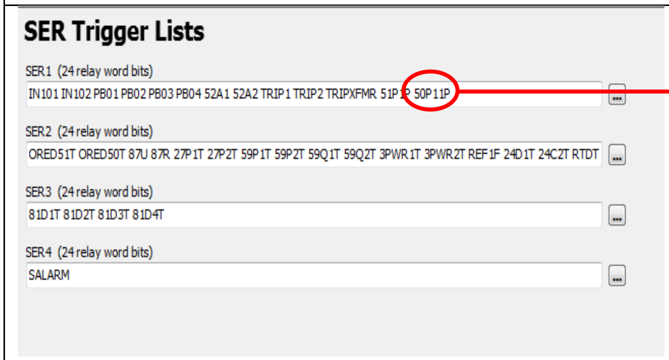
Contact Output Status	1	2	3	4	5	6	7	8	9	10
	0	0	0	0	0	0	0	0	0	0

Relay: SEL_787_5A

Figure 36 Fault simulation template

Table 1 shows an example of some settings and changes done prior to carrying out simulations. This was done to enable the investigation of the relay functions regarding how the relay responds to different fault simulations. As mentioned earlier in the simulation methodology for testing the device, this process was done for each and every protection element being investigated in this project.

Table 1 Phase overcurrent settings

<table>
<tr><th colspan="2">Phase overcurrent Test settings</th></tr>
<tr><td>Phase Overcurrent
Element 1
50P11P Winding 1 Phase Inst Overcurrent Trip Level (amps)
0.50 Range = OFF,0.10-19.20
50P11D Winding 1 Phase Inst Overcurrent Trip Delay (seconds)
0.00 Range = 0.00-5.00
50P11TC Winding 1 Phase Inst Overcurrent Torque Control (SELogic)
1</td><td>Current setting of 0.5 Amps instantaneous phase overcurrent.
Time delay for the instantaneous phase overcurrent set at 0 seconds.</td></tr>
<tr><th colspan="2">Phase overcurrent setting change</th></tr>
<tr><td>Phase Overcurrent
Element 1
50P11P Winding 1 Phase Inst Overcurrent Trip Level (amps)
0.50 Range = OFF,0.10-19.20
50P11D Winding 1 Phase Inst Overcurrent Trip Delay (seconds)
5.00 Range = 0.00-5.00
50P11TC Winding 1 Phase Inst Overcurrent Torque Control (SELogic)
1</td><td>Time delay setting change from the initial 0 seconds to 5 seconds.</td></tr>
<tr><th colspan="2">Sequential Event Report</th></tr>
<tr><td>SER Trigger Lists
SER1 (24 relay word bits)
IN101 IN102 PB01 PB02 PB03 PB04 52A1 52A2 TRIP1 TRIP2 TRIPXFMR 51P1P 50P11P
SER2 (24 relay word bits)
ORED51T ORED50T 87U 87R 27P1T 27P2T 59P1T 59P2T 59Q1T 59Q2T 3PWR1T 3PWR2T REF1F 24D1T 24C2T RTDT
SER3 (24 relay word bits)
81D1T 81D2T 81D3T 81D4T
SER4 (24 relay word bits)
SALARM</td><td>Adding the instantaneous phase over current word bit in the equation event report trigger lists so that operation of the protection element can be monitored in terminal via its word bit.</td></tr>
</table>

8.1.2 Negative phase sequence

This protection element is mainly used for protection of the power transformer when there are unbalanced loads and faults in the power system that can cause negative sequence currents in the transformer. The presence of negative phase sequence components is an indication of an abnormal condition in the power system. Figure 37 illustrates the process that a microprocessor relay goes through to filter the sequence components from the input phase quantities [11].

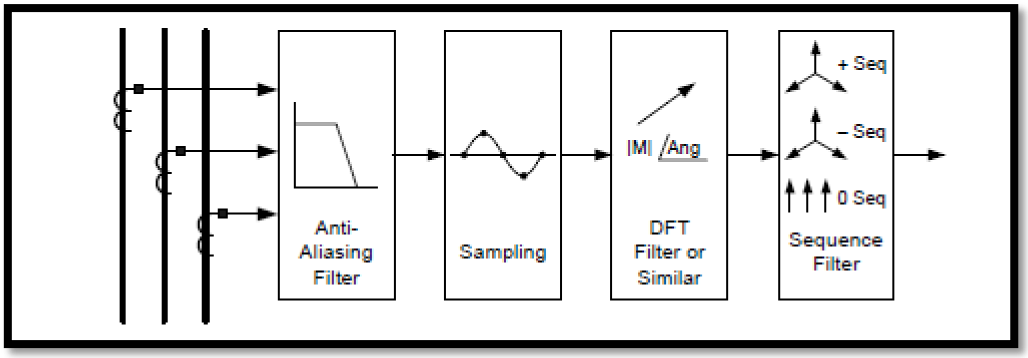


Figure 37 Obtaining Sequence quantities in Microprocessor-based relays [11]

This protection element does not respond to balanced load. Due to this fact, the negative sequence element can be set to be more sensitive and operate faster than the phase overcurrent for coordination purposes in power networks [12]. From Figure 37 the SEL 787 transformer relay calculates the negative sequence phase quantity and this value is multiplied by a factor of 3.

This value is compared to the element predetermined setting value as shown in Figure 39. If the setting value is exceeded, then an output signal is initiated [9].

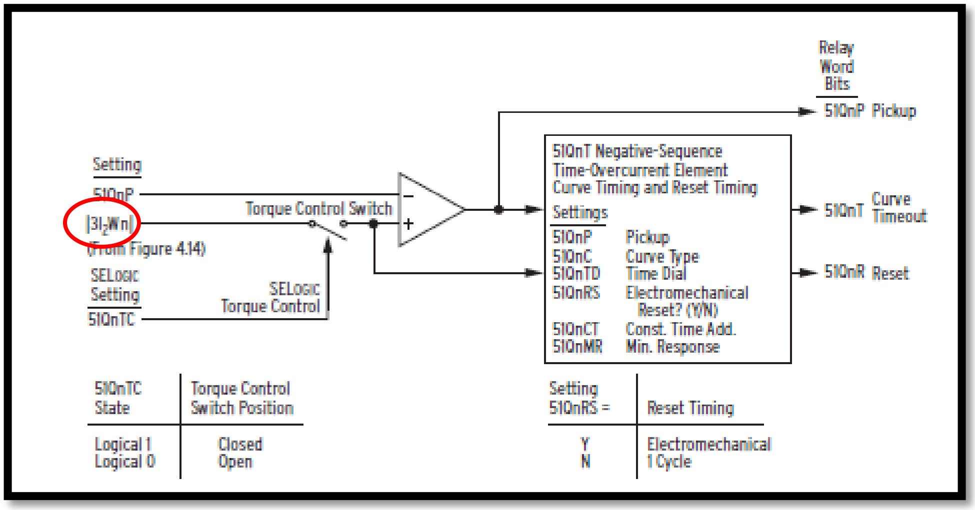
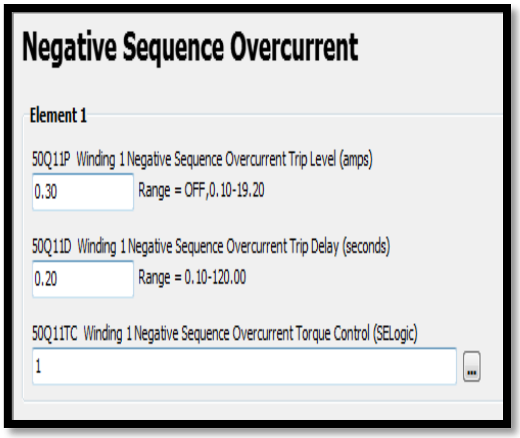


Figure 38 Negative Sequence 50Q [9]

A three phase fault simulation was carried out to investigate the operation of this element with the protection setting at 0.3 Amps as shown in Figure 39 below.



Negative Sequence Overcurrent

Element 1

50Q11P Winding 1 Negative Sequence Overcurrent Trip Level (amps)

0.30 Range = OFF,0.10-19.20

50Q11D Winding 1 Negative Sequence Overcurrent Trip Delay (seconds)

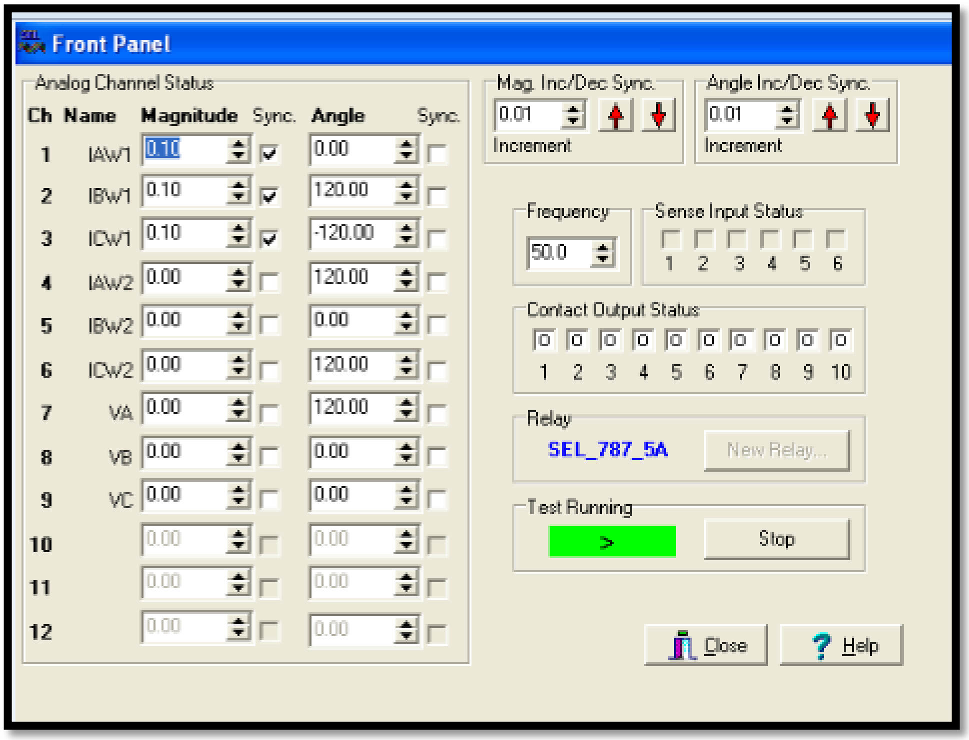
0.20 Range = 0.10-120.00

50Q11TC Winding 1 Negative Sequence Overcurrent Torque Control (SELogic)

1

Figure 39 Negative Sequence overcurrent settings editor

The relay operated as desired for input values of 0.1 Amps, as shown in Figure 40 illustrating the front panel display of the fault simulation currents. The results for the operation of this element are detailed in the results and analysis section of this report.



Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	0.10	☑	0.00	☐
2	IBW1	0.10	☑	120.00	☐
3	ICW1	0.10	☑	-120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync. Increment: 0.01

Angle Inc/Dec Sync. Increment: 0.01

Frequency: 50.0

Contact Output Status: 0 0 0 0 0 0 0 0 0 0

Relay: SEL_787_5A

Figure 40 Simulation template Negative Sequence Element

8.1.3 Residual overcurrent protection

This protection element is used against earth faults. The relay uses the vector sum of the currents from the phase current transformer. Under normal conditions the vector sum of the currents is zero. The residual component only exists under earth fault conditions and is not affected by balanced or unbalance load currents.

The residual quantity (IGWn) if present is compared to the setting value on the relay as shown in Figure 41 below, and an output is initiated if the value exceeds the predetermined setting [9].

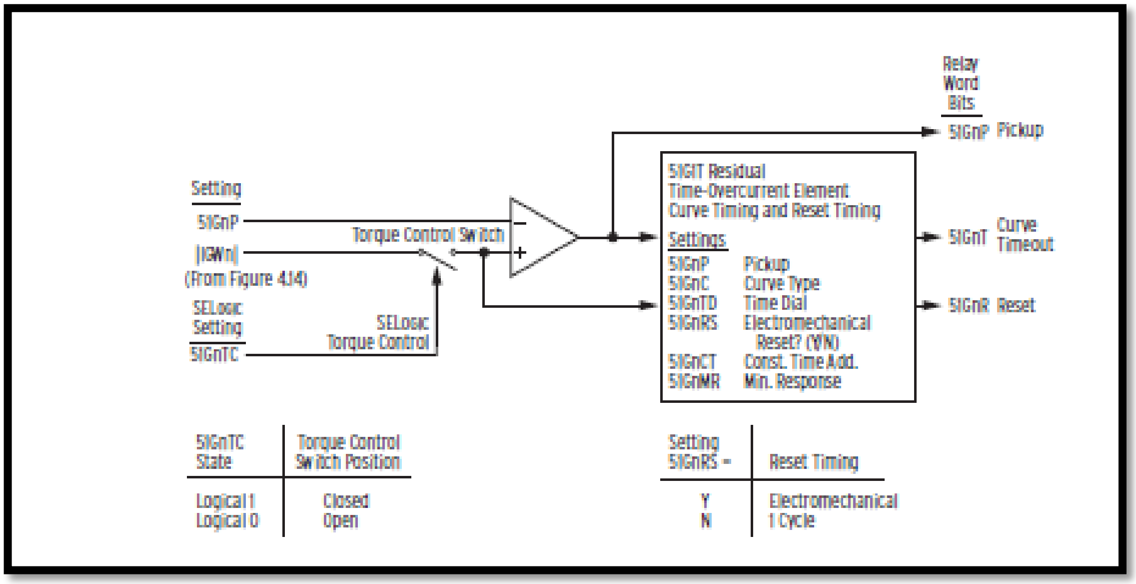
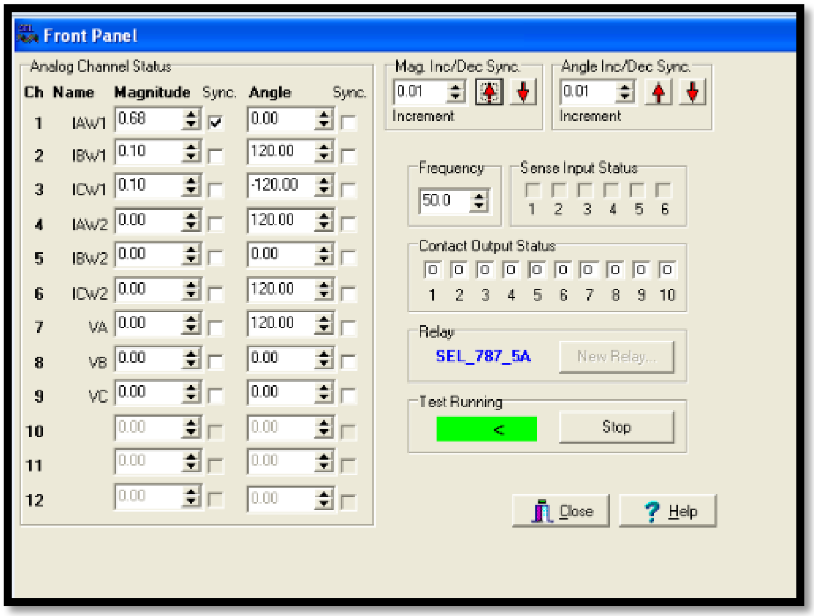


Figure 41 Residual element 50G [9]

To investigate the operation of this element, the ramping method was used. The fault current simulation value on the red phase was incremented while having the other two phases with the same value; and the relay operated when the value reached 0.68 Amps. Figure 42 shows the simulation template.



Analog Channel Status

Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	0.68	☑	0.00	☐
2	IBW1	0.10	☐	120.00	☐
3	ICW1	0.10	☐	-120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync.: 0.01 Increment

Angle Inc/Dec Sync.: 0.01 Increment

Frequency: 50.0

Sense Input Status

1	2	3	4	5	6
☐	☐	☐	☐	☐	☐

Contact Output Status

1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0

Relay: SEL_787_5A

Figure 42 Simulation template residual element

8.1.4 Breaker failure protection

The SEL 787 relay has breaker failure protection that provides an option to initiate tripping of back up or adjacent circuit breaker to operate when the main circuit breaker fails hence preventing power system instability [9]. Assertion of the associated trip relay word bits starts the circuit breaker failure timer. This occurs when a fault occurs and one of the protection elements operates for example residual overcurrent [9]. If the magnitude of the current remains above the pre-set value for the breaker failure delay setting the relay word bit for the breaker failure BFT will assert. Figure 43 shows the breaker failure logic.

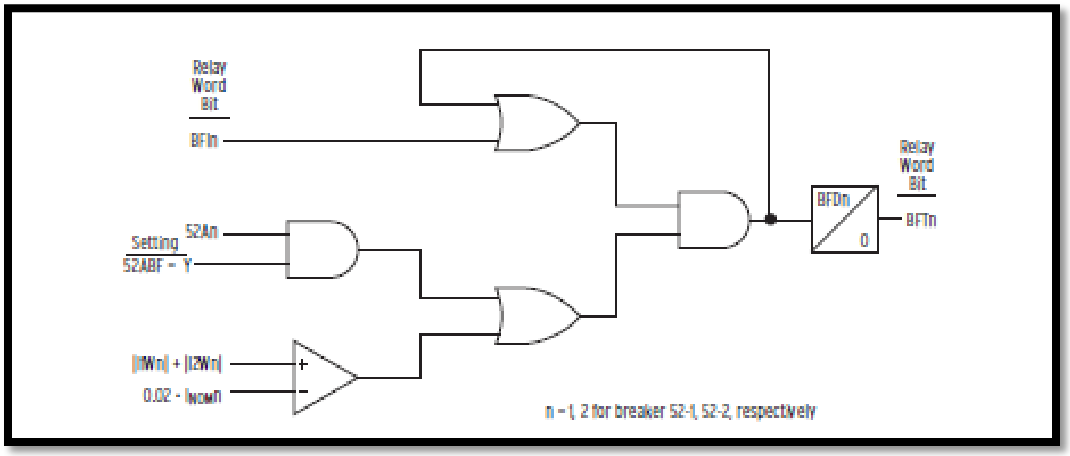
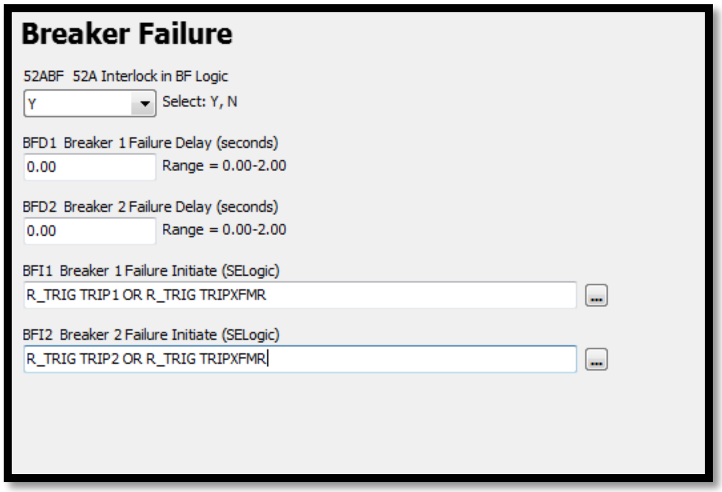


Figure 43 Breaker failure logic [9]

Investigation of this function was carried out in conjunction with the residual ground overcurrent element. The settings used for the failure are shown in Figure 44. To detect failure of the circuit breaker, auxiliary contact opening after a trip signal has been initiated input 50ABF was selected as YES. The results of the operation can be found in the results and analysis section of this report.



Breaker Failure

52ABF 52A Interlock in BF Logic
Y — Select: Y, N

BFD1 Breaker 1 Failure Delay (seconds)
0.00 — Range = 0.00-2.00

BFD2 Breaker 2 Failure Delay (seconds)
0.00 — Range = 0.00-2.00

BFI1 Breaker 1 Failure Initiate (SELogic)
R_TRIG TRIP1 OR R_TRIG TRIPXFMR

BFI2 Breaker 2 Failure Initiate (SELogic)
R_TRIG TRIP2 OR R_TRIG TRIPXFMR

Figure 44 SEL 787 Breaker failure settings editor

8.2 Differential protection

8.2.1 Principle of operation

Transformer differential operation is based on Kirchhoff's first current law which states that the sum of currents flowing towards a junction or node is equal to the sum of currents flowing from that same junction [3]. The differential protection compares the currents entering and leaving the protected area, in this case the transformer, and operates only if the differential current between these two currents exceeds a pre-set value [5]. This type of protection falls under unit schemes of protection, which are only required to operate for faults within the protected area governed by the current transformer as shown in Figure 45 and is required to remain stable for out of zone faults.

This type of protection operates instantaneously for transformer faults and does not need to be co-ordinated with other protection systems in the power system network [9].

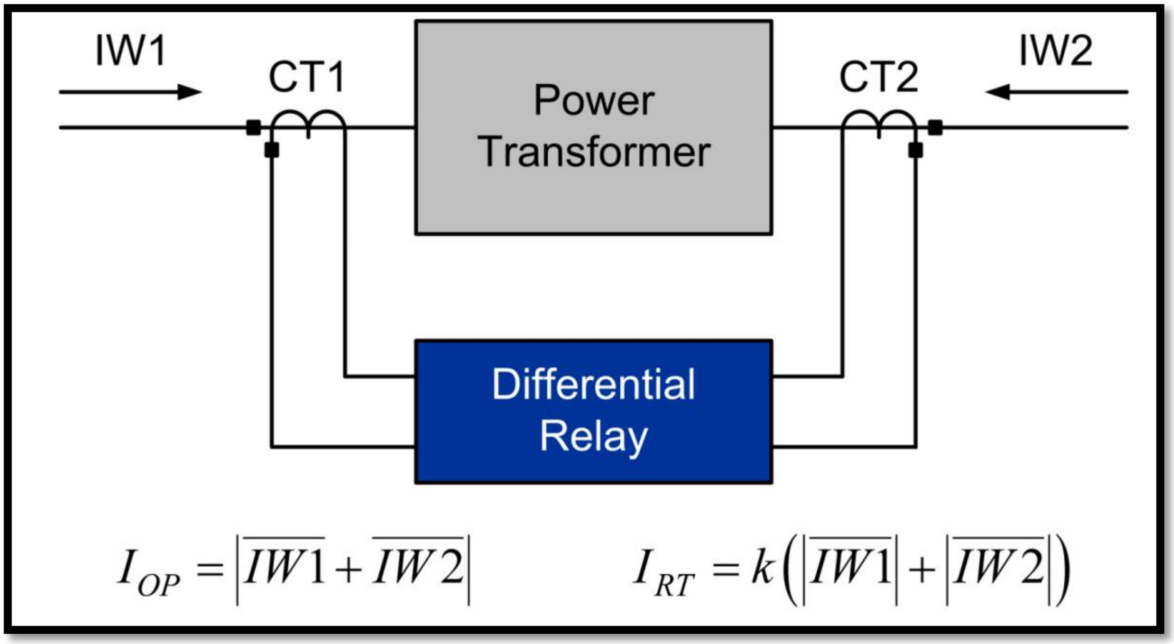


Figure 45 Transformer differential protection [9]

Operating Characteristic: The SEL 787 transformer protection relay uses a dual slope percentage differential characteristic as shown in Figure 46. This characteristic provides more sensitive and secure differential protection. The differential dual slope characteristic compensates for errors due to tap changing, CT ratios, CT mismatching and CT saturation. From Figure 46, the characteristic has two regions: the operate and the restrain. The differential element 87R employs the operate (I_{OP}) and restraint

(I_{RT}) quantities [9]. Figure 45 above shows the equations for the I_{OP} the operate quantity and I_{RT} the restraint quantity. These quantities are calculated by the relay from the differential current transformer input currents. Operation of the differential element takes place when I_{OP} quantity exceeds a predetermined value for the particular IRT value for example for transformer internal faults. The relay will not operate in the restraining region for example in cases of out of zone faults [9].

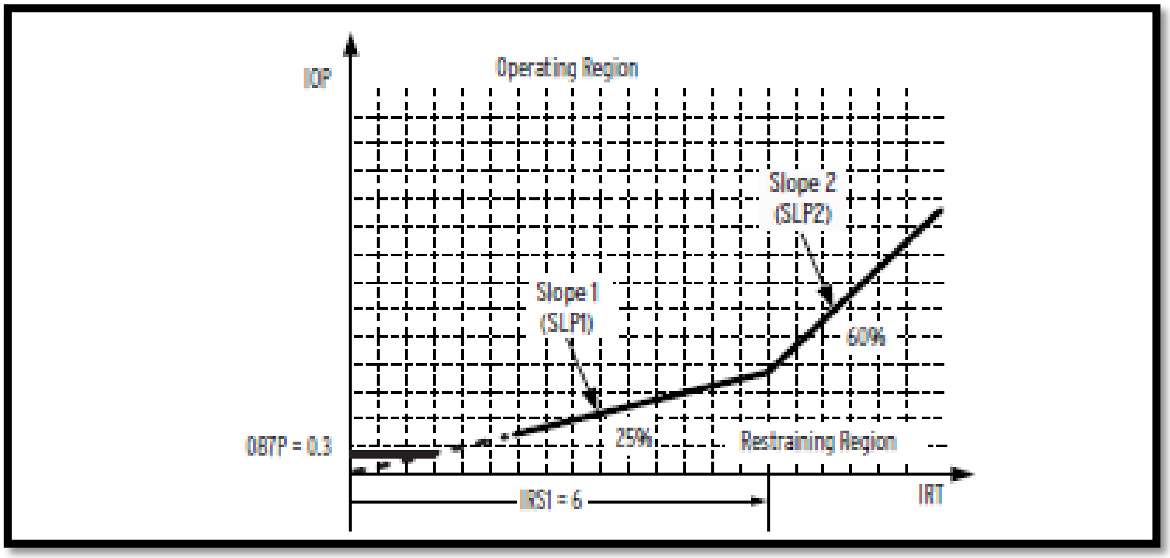


Figure 46 Operating Characteristic [9]

The following factors have to be taken into consideration in the application of differential protection for transformers:

Transformation ratio: The relationship between the primary winding and secondary winding nominal currents changes in inverse ratio to the associated voltages.

Compensation of this is done by using current transformers to achieve differential ratios in relation to the primary and secondary currents of the transformer. On the SEL 787 transformer protection relay the settings for current transformer ratio selection are found in the group setting configuration window that is shown in Figure 51 [7].

Tap Changer: The main function of tap changers both on load and off load is voltage regulation, which is maintaining a constant voltage on the secondary side of the transformer under varying load conditions. During its operation the tap changer changes the transformation ratio of transformer by changing the primary winding turns hence maintaining a constant secondary side voltage. The practicality of changing current transformation ratios for every tap change operation is impossible hence the differential protection relay has to compensate for the tap changer operation by modifying its sensitivity. This is done by providing an operating and biasing characteristic shown in figure 46 [7].

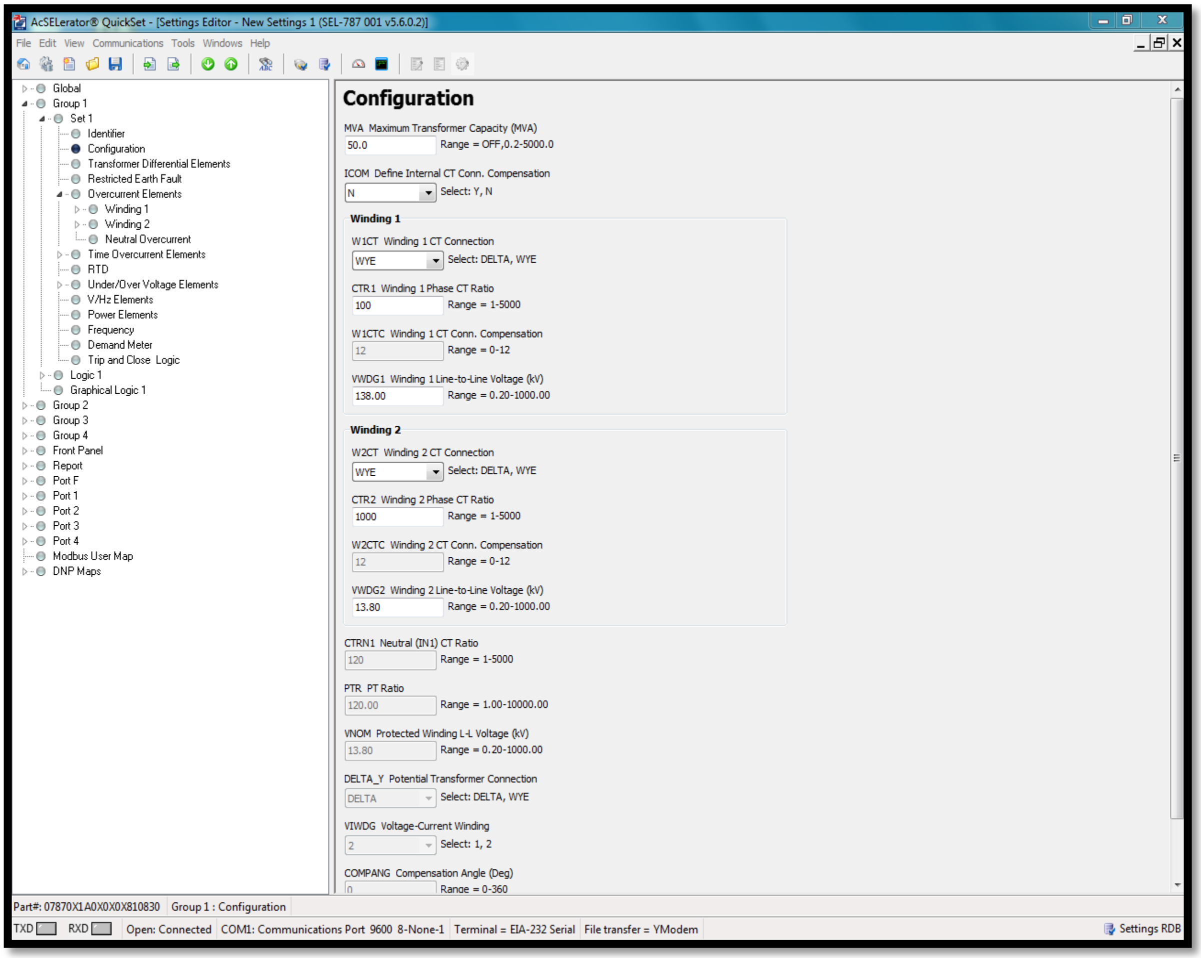
Transformer Winding Connections: There are several ways to make internal connections of the transformer windings. The different arrangements can be specified into groups called vector groups. The vector groups define the internal arrangements of the high voltage and low voltage windings of the transformer and the phase displacement between the windings with the high voltage being the reference. The phase shift causes a differential current as seen by the protection relay which causes its operation. The relay has to compensate for the phase displacement [7].

In the SEL 787 relay the ICOM setting allows the user to select if the input currents to the relay require phase shift compensation. The relay uses a list of compensation matrices to cater for the different vector group and phase displacement. For this project a transformer with a star primary winding and star secondary winding with a 0 degrees' phase displacement was used.

Magnetisation inrush current: This phenomenon, as described earlier, takes place during the energization of the transformer. The inrush current flows on the primary winding of the transformer but no equivalent current flows on the secondary winding of the transformer. This resembles an internal fault hence the need for the protection relay to compensate for this situation. The waveforms for the inrush current and transformer fault currents when compared differ greatly. The presence of the second and fourth harmonic currents in higher magnitudes in the inrush current provides a way to distinguish between a genuine fault current and inrush current. The magnetising inrush current can have peak values of six to eight times the full load current on energisation. The difference in the waveforms is used by the SEL 787 transformer protection relay to either block the operation of the relay or restrain its operation during energization [7].

8.2.2 Differential relay configuration

The transformer SEL 787 relay configuration settings shown below in figure 47 below specify the parameters of the transformer and the associated protection scheme devices that is current transformers and voltage transformers.



Configuration

MVA Maximum Transformer Capacity (MVA)
50.0 Range = OFF,0.2-5000.0

ICOM Define Internal CT Conn. Compensation
N Select: Y, N

Winding 1

W1CT Winding 1 CT Connection
WYE Select: DELTA, WYE

CTR1 Winding 1 Phase CT Ratio
100 Range = 1-5000

W1CTC Winding 1 CT Conn. Compensation
12 Range = 0-12

VWDG1 Winding 1 Line-to-Line Voltage (kV)
138.00 Range = 0.20-1000.00

Winding 2

W2CT Winding 2 CT Connection
WYE Select: DELTA, WYE

CTR2 Winding 2 Phase CT Ratio
1000 Range = 1-5000

W2CTC Winding 2 CT Conn. Compensation
12 Range = 0-12

VWDG2 Winding 2 Line-to-Line Voltage (kV)
13.80 Range = 0.20-1000.00

CTRN1 Neutral (IN1) CT Ratio
120 Range = 1-5000

PTR PT Ratio
120.00 Range = 1.00-10000.00

VNOM Protected Winding L-L Voltage (kV)
13.80 Range = 0.20-1000.00

DELTA_Y Potential Transformer Connection
DELTA Select: DELTA, WYE

VIWDG Voltage-Current Winding
2 Select: 1, 2

COMPANG Compensation Angle (Deg)
0 Range = 0-360

Figure 47 SEL 787 Configuration settings

For this project the following settings for the relay were enabled

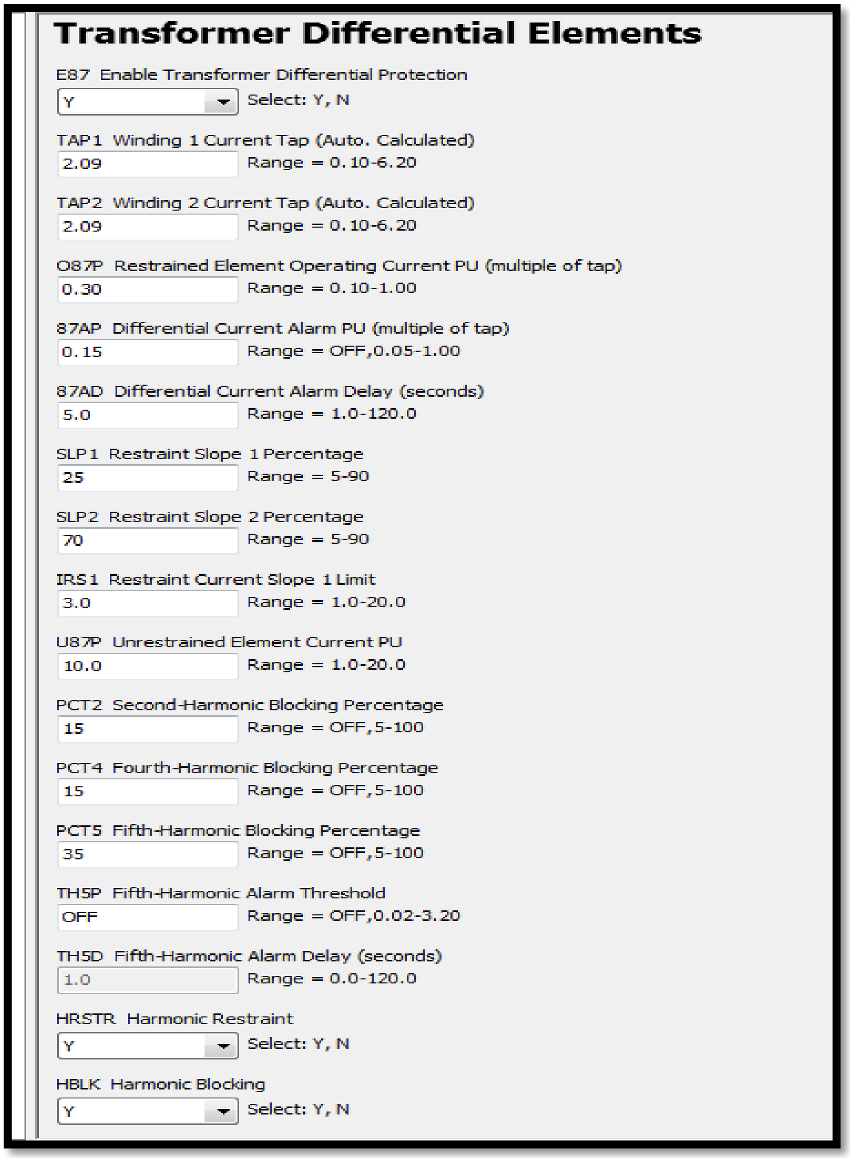
MVA: Maximum transformer capacity = 50 {transformer rating}. The maximum transformer rating is used for this taking into account the cooling process like forced air cooling and pump cooling [9].

ICOM Define internal CT Conn. Compensation = N this defines the phase shift compensation if required to accommodate phase shifts in transformer winding connections and also the current transformer connections. The transformer vector group phase shift and current transformer wiring compensation is done with this setting. This compensation accommodates for phase shift and removal of zero-sequence current components [9].

Winding 1 and Winding 2: This denotes the transformer winding configuration. For this project a two winding transformer with a star primary winding and a star secondary winding.

8.2.3 Differential relay setting

Figure 52 below shows the SEL 787 differential element settings used for the project.



Transformer Differential Elements

E87 Enable Transformer Differential Protection
Y Select: Y, N

TAP1 Winding 1 Current Tap (Auto. Calculated)
2.09 Range = 0.10-6.20

TAP2 Winding 2 Current Tap (Auto. Calculated)
2.09 Range = 0.10-6.20

O87P Restrained Element Operating Current PU (multiple of tap)
0.30 Range = 0.10-1.00

87AP Differential Current Alarm PU (multiple of tap)
0.15 Range = OFF,0.05-1.00

87AD Differential Current Alarm Delay (seconds)
5.0 Range = 1.0-120.0

SLP1 Restraint Slope 1 Percentage
25 Range = 5-90

SLP2 Restraint Slope 2 Percentage
70 Range = 5-90

IRS1 Restraint Current Slope 1 Limit
3.0 Range = 1.0-20.0

U87P Unrestrained Element Current PU
10.0 Range = 1.0-20.0

PCT2 Second-Harmonic Blocking Percentage
15 Range = OFF,5-100

PCT4 Fourth-Harmonic Blocking Percentage
15 Range = OFF,5-100

PCT5 Fifth-Harmonic Blocking Percentage
35 Range = OFF,5-100

TH5P Fifth-Harmonic Alarm Threshold
OFF Range = OFF,0.02-3.20

TH5D Fifth-Harmonic Alarm Delay (seconds)
1.0 Range = 0.0-120.0

HRSTR Harmonic Restraint
Y Select: Y, N

HBLK Harmonic Blocking
Y Select: Y, N

Figure 48 Transformer differential settings

8.2.4 O87P Differential Element

This function defines the minimum current required to operate the differential restrained element. An alarm setting associated with this element 87AT can be set depending on the application [9]. The protection function was tested using the ramping method to establish the minimum value to initiate operation of the element. Both input channels for winding 1 and winding 2 were injected with current. Winding one current was increased in steps of 0.01 Amps until the protection relay operated. The 87AT differential alarm function was activated first when the pickup current was reached and with further increase in the fault current the restrained minimum pickup element operated. The results are analysed in detailed in the results and analysis section of this report. Figure 49 below show the differential function logic.

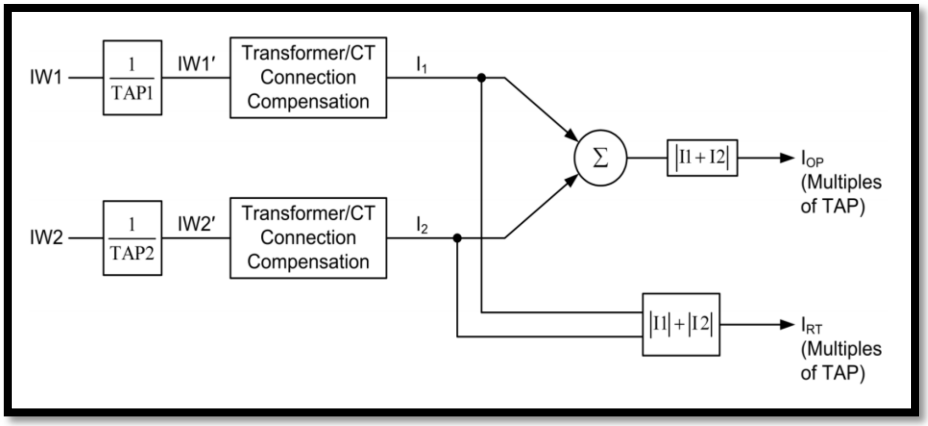
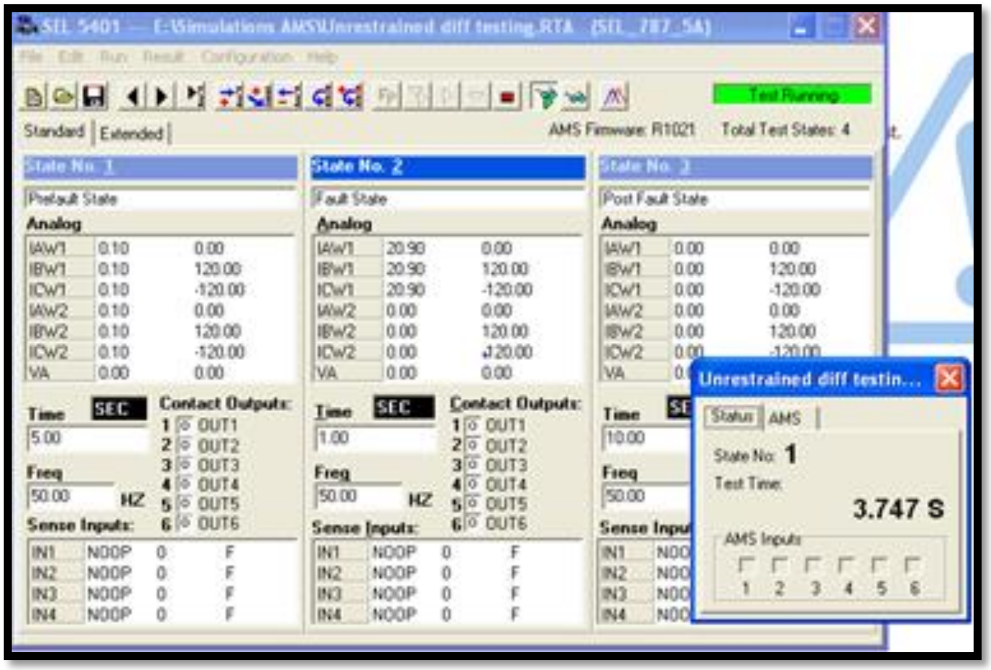


Figure 49 SEL 787 Differential element logic [24]

8.2.5 U87P Unrestrained differential element

This protection element as the name implies is not affected by harmonics or restrained elements activated in the protection relay. It is set to operate instantaneously and react quickly when there are high current levels that indicate an internal fault. It only operates for fault currents with the fundamental frequency component current for the differential quantity. As stated earlier, it is not affected by the restraint settings of the relay which are SLP1, SLP2, PCT2, PCT5 and IRS1, shown in figure 48. It is recommended to set this protection element high enough so that it does not respond to large inrush currents [9]. For this project the setting for this protection function was 10 that is ten times the tap setting of the relay as indicated in Figure 48 above. To carry out the fault simulation the fault data on the test template was set to 20.9 Amps for the three phases. Figure 50 below shows the state sequence test template used for this simulation with three states: Prefault, fault and post-fault.



SEL 5401 — E:\Simulations AMS\Unrestrained diff testing.RTA (SEL_787_5A)

AMS Firmware: R1021 Total Test States: 4

State No. 1

Prefault State

Analog

IAW1	0.10	0.00
IBW1	0.10	120.00
ICW1	0.10	-120.00
IAW2	0.10	0.00
IBW2	0.10	120.00
ICW2	0.10	-120.00
VA	0.00	0.00

Time SEC 5.00

Freq 50.00 HZ

Contact Outputs:
- 1 ○ OUT1
- 2 ○ OUT2
- 3 ○ OUT3
- 4 ○ OUT4
- 5 ○ OUT5
- 6 ○ OUT6

Sense Inputs:

IN1	NOOP	0	F
IN2	NOOP	0	F
IN3	NOOP	0	F
IN4	NOOP	0	F

State No. 2

Fault State

Analog

IAW1	20.90	0.00
IBW1	20.90	120.00
ICW1	20.90	-120.00
IAW2	0.00	0.00
IBW2	0.00	120.00
ICW2	0.00	-120.00
VA	0.00	0.00

Time SEC 1.00

Freq 50.00 HZ

Contact Outputs:
- 1 ○ OUT1
- 2 ○ OUT2
- 3 ○ OUT3
- 4 ○ OUT4
- 5 ○ OUT5
- 6 ○ OUT6

Sense Inputs:

IN1	NOOP	0	F
IN2	NOOP	0	F
IN3	NOOP	0	F
IN4	NOOP	0	F

State No. 3

Post Fault State

Analog

IAW1	0.00	0.00
IBW1	0.00	120.00
ICW1	0.00	-120.00
IAW2	0.00	0.00
IBW2	0.00	120.00
ICW2	0.00	-120.00
VA	0.0	

Time 10.00

Freq 50.00

Sense Input

IN1	NOO
IN2	NOO
IN3	NOO
IN4	NOO

Unrestrained diff testin...

Status AMS

State No: 1

Test Time: 3.747 S

AMS Inputs ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Figure 50 Test template for unrestrained differential element

8.2.6 Differential element slope 1

One test point was used to investigate the operation of the restrained differential element in the slope one region. To correctly simulate the operation characteristic in this region the value of the operation point has to be greater than the intersection of slope 1 and the minimum operating restriction (0.87P) which has a value of 0.3 shown in Figure 47 [24]. The restraint value for this operating point has to be less than the value of the restraint current slope limit IRS, which is the break point between slope 1 and slope 2 as illustrated in Figure 47 [24].

The following equation illustrates the operation point $087P = \frac{100}{SLP1} \leq IRT \leq IRS$

Equation 1 Slope restraint value calculation [27]

To carry out the simulation, current had to be injected in both winding inputs.

Substituting equation (1) with values in the setting $0.3\frac{100}{25} = \leq IRT \leq 3pu$

For an IRT of 2 per unit the following operation current is expected for slope 1

$$IOP = \frac{SLP}{100} * IRT = 2 * 0.25 = 0.5pu$$

Referring to the equations in Figure 45, the input current IW1 an IW2 can be determined by dividing IRT by the value 2. This calculates the amount of the restraint current. Addition of half the required value of the operating current to 1W1 and subtracting half of the operating current from IW2 will result in the operate and restraint values [24]:

$$IW1 \ = \frac{(IRT + IOP)}{2} = \frac{(2.0 + 0.5)}{2} = 1.25pu$$

Equation 2 Winding 1 test current in per unit [27]

$$IW2 \ = \frac{(IRT - IOP)}{2} = \frac{(2.0 - 0.5)}{2} = 0.75pu$$

Equation 3 Winding 2 test current in per unit [27]

To determine the test currents, the above calculated values are multiplied by the relay setting tap value.

IAW1 = IW1*Tap *CC =1.25*2.09=2.6125Amps

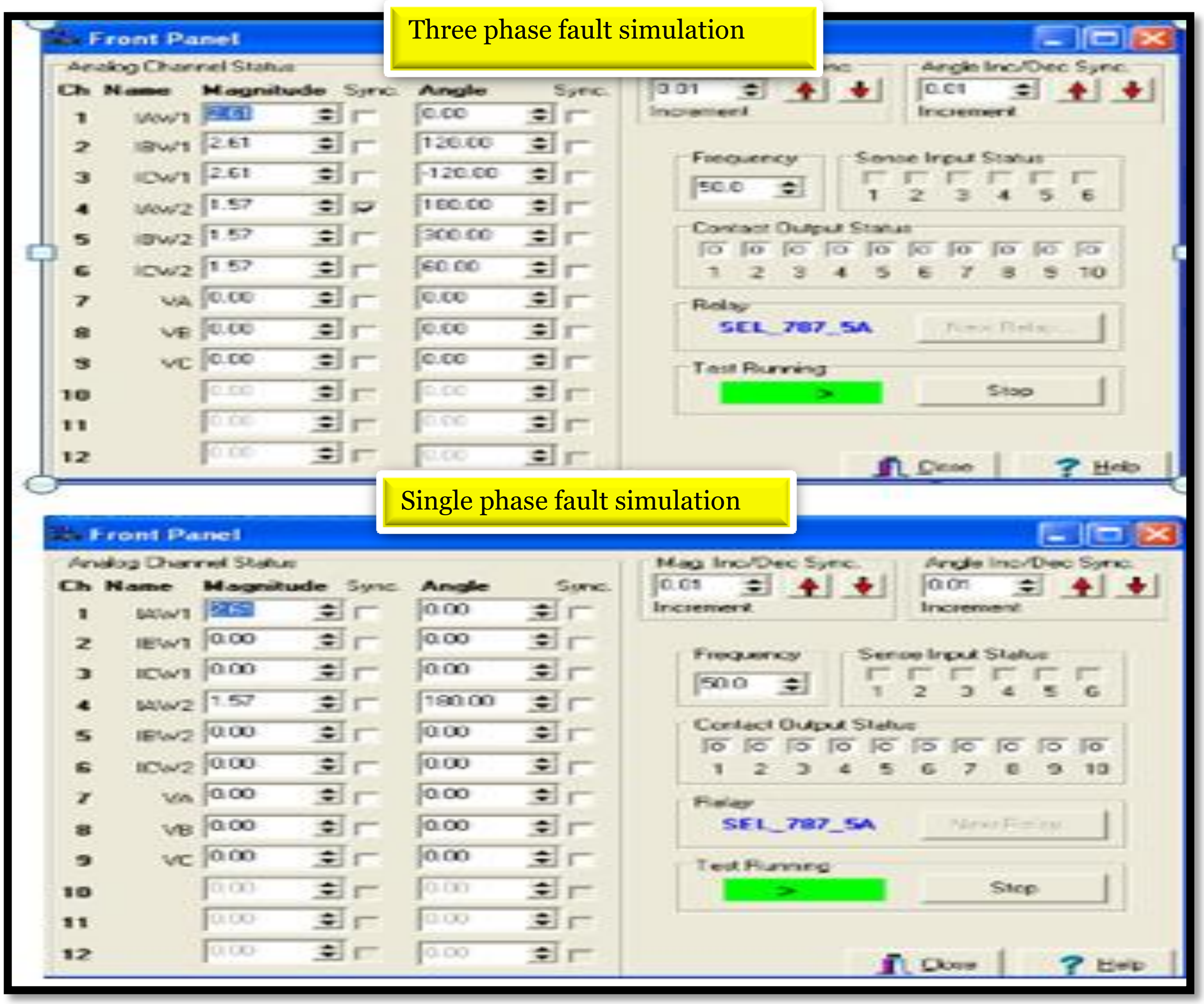
Equation 4 Winding 1 test current in Amps [27]

IAW2 = IW2*Tap *CC =0.75*2.09=1.5675Amps

Equation 5 Winding 2 test current in Amps [27]

For simulation winding 1 was set as the reference 0 degrees and winding 2 set at 180 degrees.

This fault simulation current was injected into the relay, as shown in Figure 55 below.


Three phase fault simulation

Front Panel

Analog Channel Status

Ch	Name	Magnitude	Sync	Angle	Sync
1	IAW1	2.61	☐	0.00	☐
2	IBW1	2.61	☐	120.00	☐
3	ICW1	2.61	☐	-120.00	☐
4	IAW2	1.57	☑	180.00	☐
5	IBW2	1.57	☐	300.00	☐
6	ICW2	1.57	☐	60.00	☐
7	VA	0.00	☐	0.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag Inc/Dec Sync: Increment 0.01

Angle Inc/Dec Sync: Increment 0.01

Frequency: 50.0

Relay: SEL_787_5A

Single phase fault simulation

Front Panel

Analog Channel Status

Ch	Name	Magnitude	Sync	Angle	Sync
1	IAW1	2.65	☐	0.00	☐
2	IBW1	0.00	☐	0.00	☐
3	ICW1	0.00	☐	0.00	☐
4	IAW2	1.57	☐	180.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	0.00	☐
7	VA	0.00	☐	0.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag Inc/Dec Sync: Increment 0.01

Angle Inc/Dec Sync: Increment 0.01

Frequency: 50.0

Relay: SEL_787_5A

Figure 51 Three phase and single phase fault simulation

8.2.7 Differential element slope 2

To verify correct operation of the relay in the slope 2 region of the differential operation characteristic, a similar approach to that of slope 1 was undertaken. The difference between the slopes, as shown in Figure 46, is that the slope 1 curve is a straight line passing through the origin but slope 2 does not pass through the origin but has an offset. Slope 2 has an offset which intersects slope 1 at IRS1 hence slope 2 exists only for values greater than IRS1 [24].

To correctly simulate a fault in this region the following condition has to be satisfied IRT > IRS1. The setting for IRS1 is 3 as shown in Figure 48. A test point for a value of 5 pu was selected [24].

The operate current for this test point in slope 2 can be calculated:

$$IOP = \frac{SLP2}{100} * IRT + IRS1 * \left(\frac{SLP1 - SLP2}{100}\right)$$

$$= \frac{50}{100} * 5 + 3 * \left(\frac{25 - 70}{100}\right) = 2.05PU$$

Equation 6 Slope 2 test point [27]

$$IW1 = \frac{(IRT + IOP)}{2} = \frac{(5 + 2.05)}{2} = 3.525pu$$

Equation 7 Slope 2 Winding 1 test current per unit [27]

$$IW2 = \frac{(IRT + IOP)}{2} = \frac{(5 - 2.05)}{2} = 1.475pu$$

Equation 8 Slope 2 Winding 2 test current per unit [27]

IAW1 = IW1*Tap *CC =3.525*2.09=7.367Amps

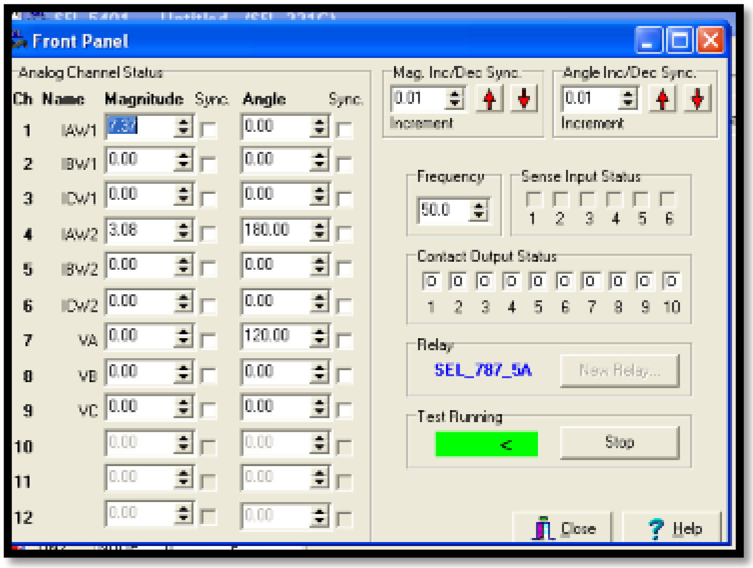
Equation 9 Slope 2 Winding 1 test current in Amps [27]

IAW2 = IW2*Tap *CC =1.475*2.09=3.083Amps

Equation 10 Slope 2 Winding 2 test current in Amps [27]

This simulation was conducted by injecting the calculated values of the IAW1 and IAW2.and ramping the winding 2 current down by a value of 0.01 Amps.

The simulation template is shown below:



Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	7.37	☐	0.00	☐
2	IBW1	0.00	☐	0.00	☐
3	ICW1	0.00	☐	0.00	☐
4	IAW2	3.08	☐	180.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	0.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync. Increment: 0.01

Angle Inc/Dec Sync. Increment: 0.01

Frequency: 50.0

Relay: SEL_787_5A

Test Running: <

Figure 52 Slope 2 test card

8.2.8 Magnetization inrush suppression

8.2.8.1 Harmonic blocking

The SEL 787 transformer relay has the capability to provide harmonic blocking for the second and fourth harmonic content to cater for the transformer inrush currents. The fifth–harmonic content blocking for transformer over-excitation is also catered for as indicated in Figure 53, the harmonic blocking logic diagram. The relay has the added feature to perform cross blocking; that is, if one phase of the transformer has the second and fourth harmonic currents, blocking is done on all the phases. [9]

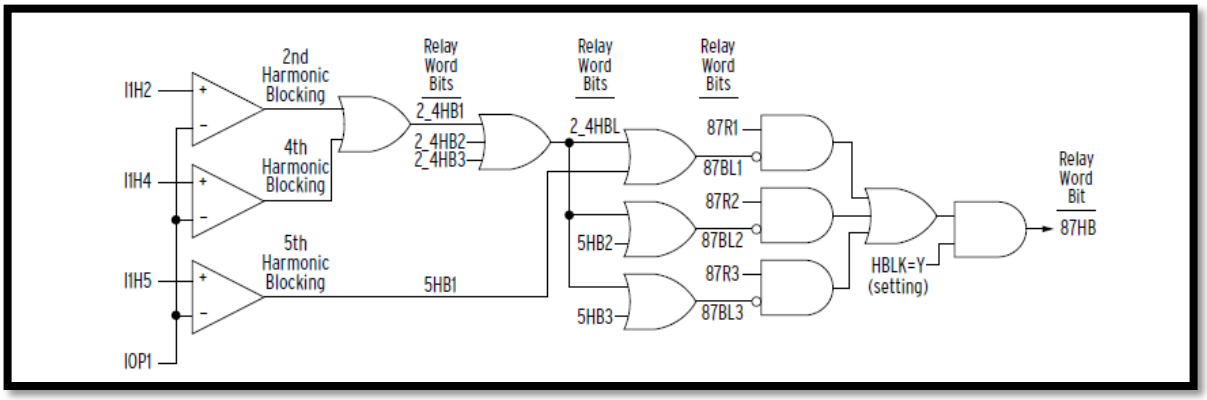


Figure 53 Harmonic blocking logic [9]

8.2.8.2

8.2.8.3 Harmonic restraint

The harmonic restraint function operates differently from the harmonic blocking element in that it moves the differential relay characteristic slope line relative to the magnitude of the harmonic differential current measured by the relay as an input from the current transformer [27].

8.2.9 Out of zone / through fault operation suppression

Differential protection is a unit scheme protection which only operates for faults in the protected area demarcated by the location of the current transformers that is F1, shown in Figure 54 below, and shall not operate for out of zone faults F2, as shown below in Figure 54 [9].

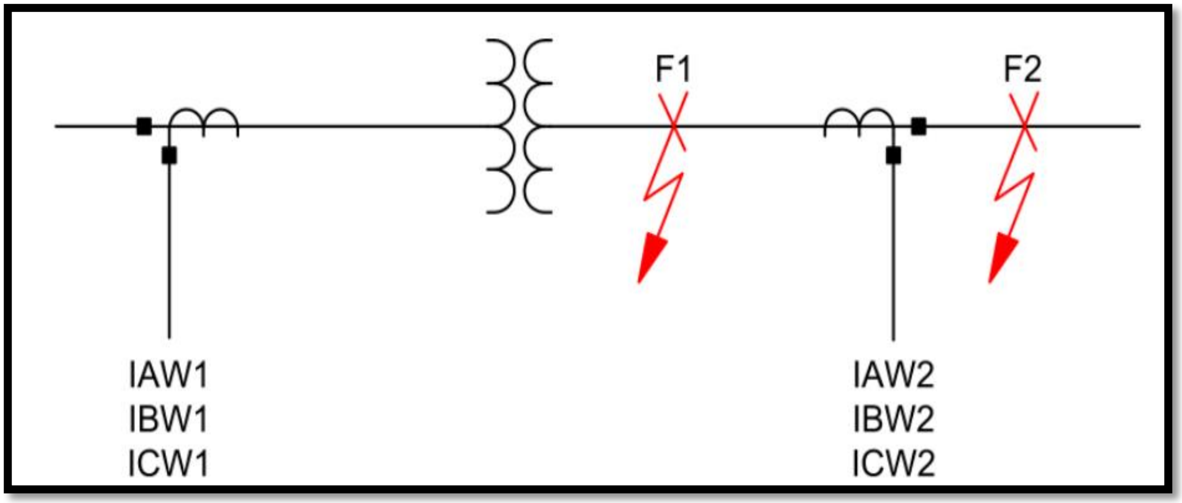


Figure 54 In zone and out of zone faults

Out of zone faults or through faults take place outside the protected zone, as shown in Figure 56. These faults subject the transformer windings and insulation to mechanical and thermal stress. Figure 55 shows the category IV transformers time versus current through fault curves [9].

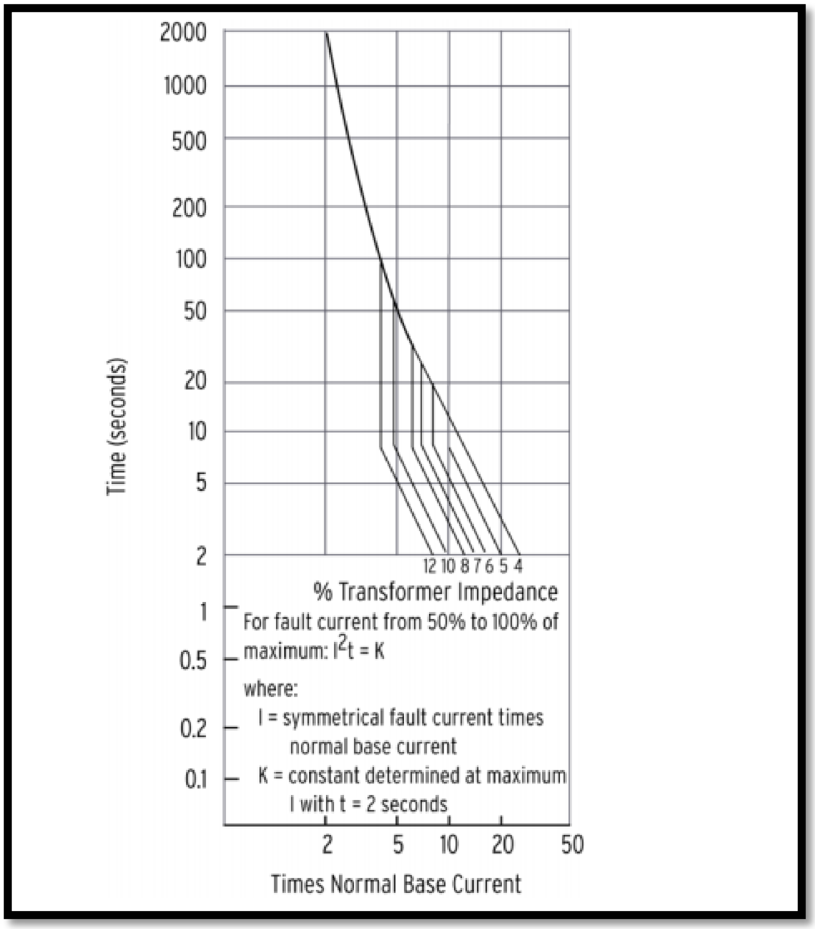


Figure 55 Transformer Time/ Current through fault curves [9]

The transformer protection relay offers an out of zone fault or through fault event monitor for faults shown in Figure 56. This captures the fault current magnitudes, time and date and the duration of the through fault [9]. The following settings have to be specified to enable the through fault monitor:

Through fault winding: this specifies which transformer winding to use in calculating the through fault current [9].

Enable Through-fault monitor: the logic setting to select the different conditions for the through fault monitor [9].

Through fault pick up alarm: this can be set as a percentage of the predetermined setting [9].

Transformer impedance: setting of the transformer percentage impedance to detect the through fault [9].

Sequential Event Report: to monitor the event the through fault alarm, relay word bits have to be entered in the SER trigger equation TFLTALA, TFLTALB and TFLTALC [9].

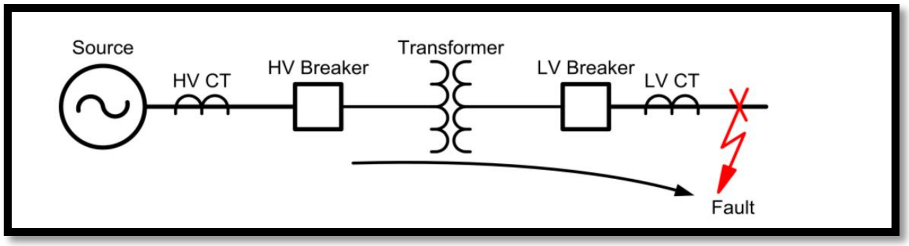
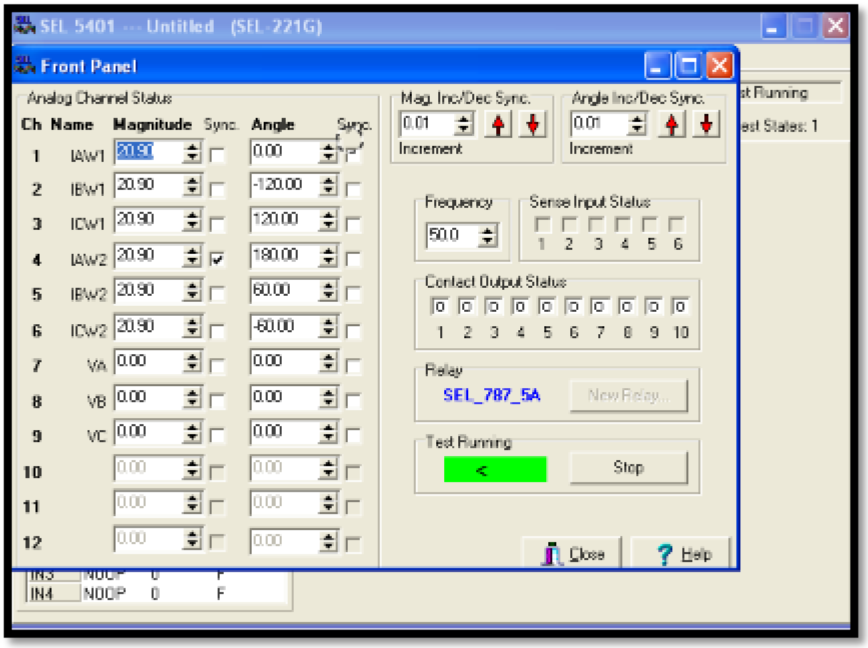


Figure 56 Transformer through fault [9]

The test template for the through fault event is shown in Figure 57.



Analog Channel Status

Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	20.90	☐	0.00	☐
2	IBW1	20.90	☐	-120.00	☐
3	ICW1	20.90	☐	120.00	☐
4	IAW2	20.90	☑	180.00	☐
5	IBW2	20.90	☐	60.00	☐
6	ICW2	20.90	☐	-60.00	☐
7	VA	0.00	☐	0.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync. Increment: 0.01

Angle Inc/Dec Sync. Increment: 0.01

Frequency: 50.0

Sense Input Status: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Contact Output Status: 1: 0, 2: 0, 3: 0, 4: 0, 5: 0, 6: 0, 7: 0, 8: 0, 9: 0, 10: 0

Relay: SEL_787_5A

IN4 NOOP 0 F

Figure 57 Test template for through fault simulation

8.3 Restricted Earth fault protection

This protection element employs the differential protection philosophy similar the overall transformer differential protection. It is also a unit protection scheme .and only operates for earth faults which occur inside the protected zone, as illustrated in Figure 58. The zone of protection is governed by the location of the current transformers [10].

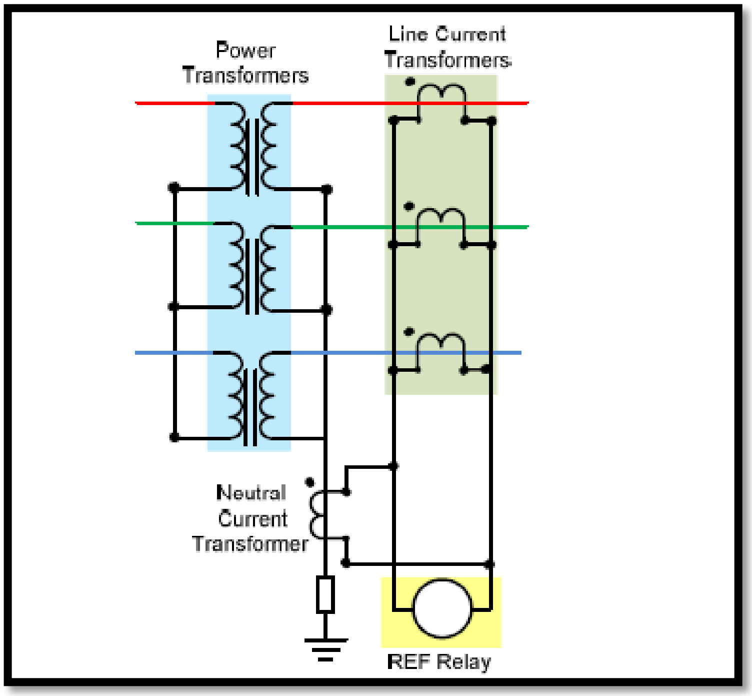


Figure 58 Restricted earth fault protection [10]

The SEL 787 transformer protection relay as Murdoch University does not have restricted earth fault hardware circuit board housed in slot E of the relay. It was not possible to explore the protection element functionality via fault simulations.

8.4 Volts/Hertz

This protection element is also known as over-fluxing. Transformer over-fluxing occurs when the transformer core becomes saturated due to abnormal conditions arising in the power system. Any conditions occurring in the power system network which will cause changes to voltage and frequency magnitudes beyond acceptable levels will affect the voltage and frequency relationship and cause over-fluxing [9]. This protection function is voltage based and, as stated earlier, the SEL 787 protection relay housed at Murdoch University does not have the voltage input channel card in slot E, therefore, the operation of this protection element was not investigated.

Chapter 9 Results and Analysis

This chapter covers in detail the simulation results of the tests carried out on the SEL 787 protection relay for the protection elements already discussed. Verification of correct functional operation and confirmation of operation within the specified manufacture tolerances is also discussed in this chapter.

9.1 List of Experiments conducted on the relay

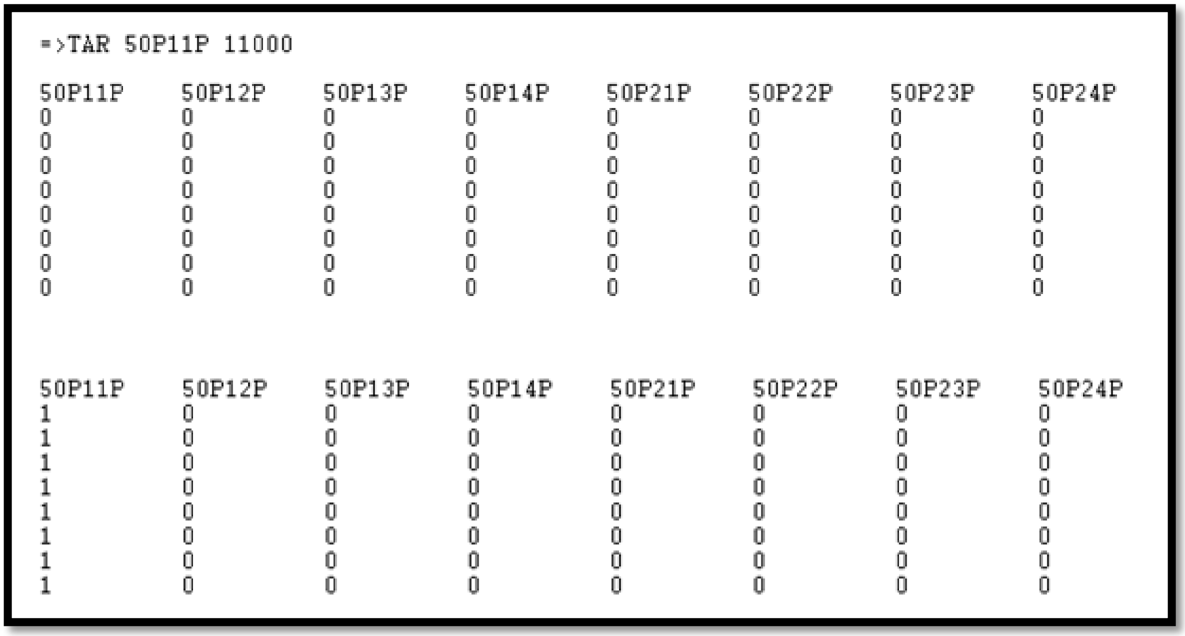
The following protection relay elements were investigated through carrying out simulations on the relay using the ramping and state sequence techniques:

- Instantaneous overcurrent
- Negative sequence overcurrent
- Residual ground overcurrent
- Breaker failure
- Unrestrained differential
- Restrained differential

- Slope 1 restrained differential
- Slope 2 restrained differential
- Through fault monitor

9.2 Instantaneous Overcurrent

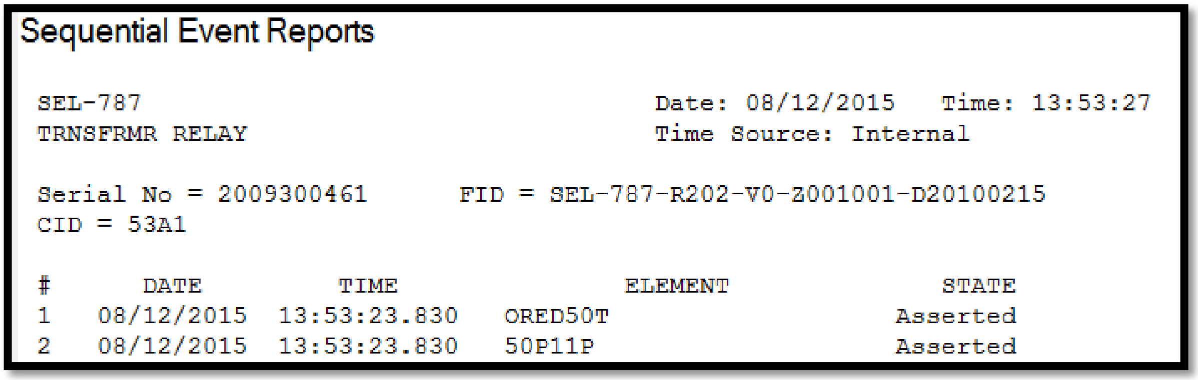
To verify correct operation of the instantaneous over current element, the associated relay word bit was monitored using the TAR 50P11p 11000 command in the terminal window of the Acselerator software platform shown in Figure 59. Figure 59 shows the word bit deasserted with the value 0 prior to fault simulation and asserted with the value 1 after fault simulation.



```
=>TAR 50P11P 11000

50P11P    50P12P    50P13P    50P14P    50P21P    50P22P    50P23P    50P24P
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0


50P11P    50P12P    50P13P    50P14P    50P21P    50P22P    50P23P    50P24P
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
```

Figure 59 Terminal window showing assertion of overcurrent relay word bit

A single phase simulation was carried out on the red phase of winding one. The simulation was initially done without an intentional time delay. A time delay of 5 seconds was later introduced. Figure 60 shows the results of the first simulation without a time delay .The event report shows the element ORED50T which is the logical OR bit for the current instatenteneous elements to initiate tripping, and 50P11P which is the relay word bit for the level 1 instatenteneous element, both being activated at the same time. This element operated as expected because there was no intentional time delay applied on the setting.

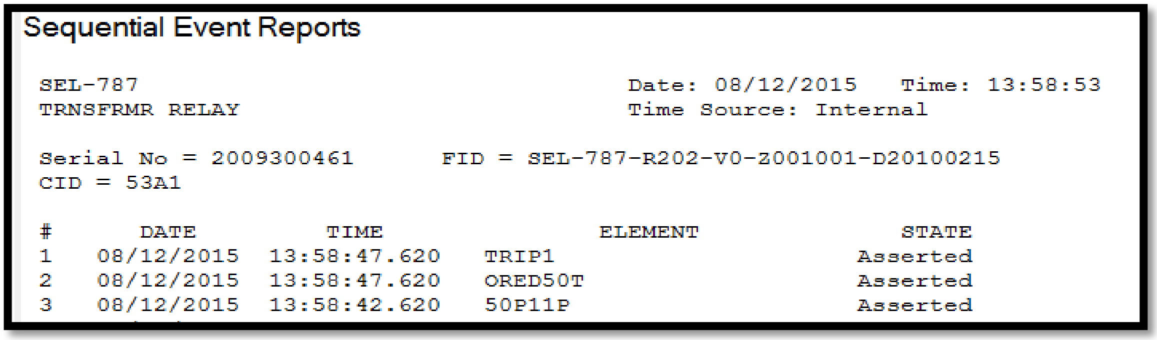


Sequential Event Reports

```
SEL-787                                          Date: 08/12/2015    Time: 13:53:27
TRNSFRMR RELAY                                   Time Source: Internal

Serial No = 2009300461       FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#       DATE          TIME                ELEMENT                 STATE
1    08/12/2015   13:53:23.830    ORED50T                       Asserted
2    08/12/2015   13:53:23.830    50P11P                        Asserted
```

Figure 60 SER showing operation of overcurrent element

In comparison, for the same overcurrent setting but with a setting change on the time delay of 5 seconds: the element relay word bit 50P11P asserted first and after 5 seconds the ORED50T word bit and a trip signal was sent after a period of 5 seconds, as shown in Figure 61 below.



Sequential Event Reports

```
SEL-787                                          Date: 08/12/2015    Time: 13:58:53
TRNSFRMR RELAY                                   Time Source: Internal

Serial No = 2009300461       FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#       DATE          TIME                ELEMENT                 STATE
1    08/12/2015   13:58:47.620    TRIP1                         Asserted
2    08/12/2015   13:58:47.620    ORED50T                       Asserted
3    08/12/2015   13:58:42.620    50P11P                        Asserted
```

Figure 61 SER showing time delay for overcurrent

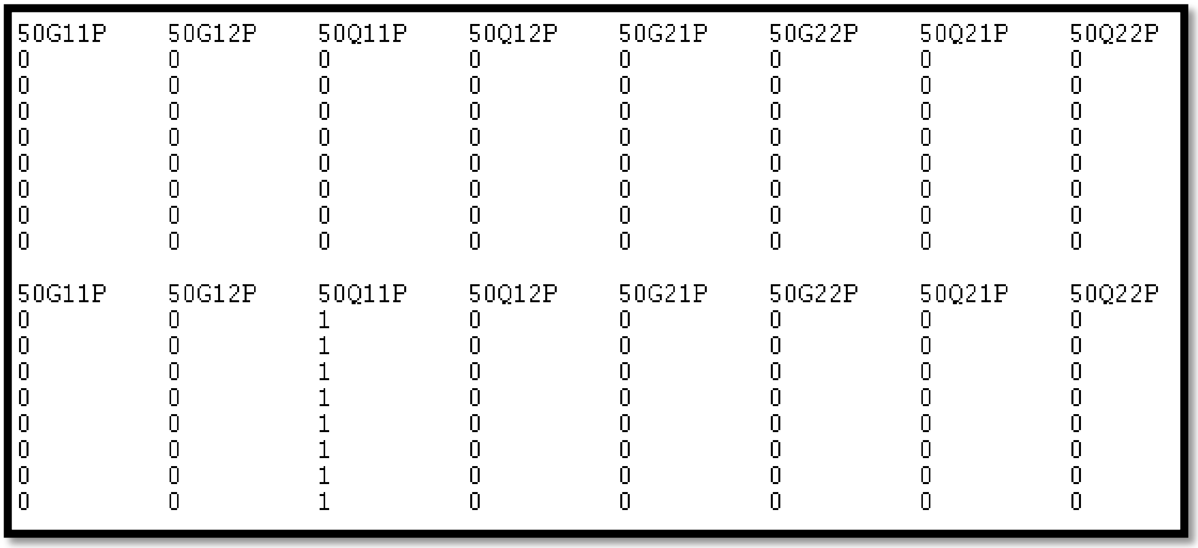
Appendix D of this report details the visual indication tools which were used to verify operation for the phase overcurrent element. The following information can be deduced from these which element has operated, trip output contact, location of the fault winding one, the magnitude of the fault current in primary values and the time taken to send the trip signal.

From the simulation results obtained, the protection relay operated as expected. The protection relay element specifications, which can be found in the appendix C of this report, state that the relay accuracy should be ±5% of setting $\pm 0.02 * I_{Nom}$ A secondary current. The relay setting was 0.5 A and it operated at 0.48A. This value is within the acceptable tolerance range. The time delay accuracy stated in the specifications is ±0.5% seconds. The time delay setting for this element was changed from 0 seconds to 5 seconds and, as shown in the SER in Table 1, it took 5 seconds for the protection relay to send out a trip signal. The relay operated as desired for the set time setting.

9.3 Negative sequence overcurrent

The relay word bit for the negative sequence protection element asserted during the fault simulation, as shown in Figure 62 below showing the terminal window report with the relay word bit 50Q11P changing state from low to high.

Terminal window showing assertion of negative sequence relay word bit



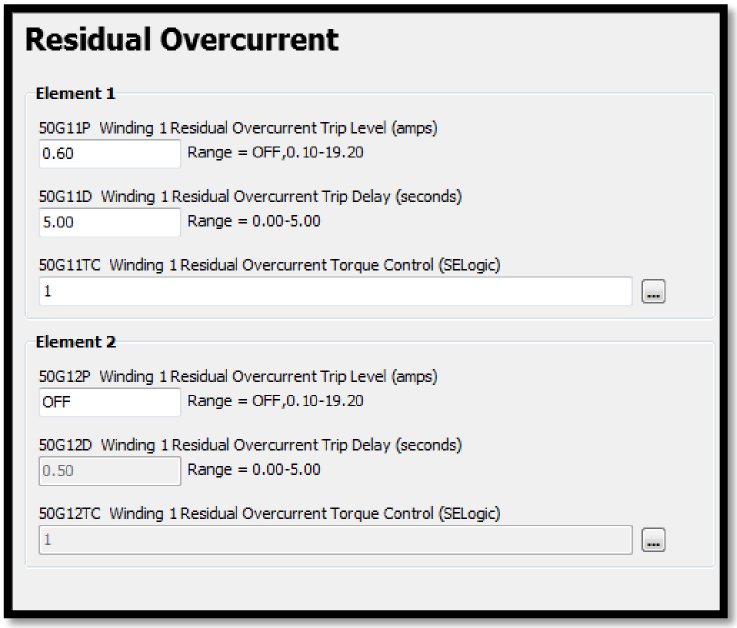
```
50G11P    50G12P    50Q11P    50Q12P    50G21P    50G22P    50Q21P    50Q22P
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0

50G11P    50G12P    50Q11P    50Q12P    50G21P    50G22P    50Q21P    50Q22P
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
0         0         1         0         0         0         0         0
```

Figure 62 Terminal window showing assertion of negative sequence relay word bit

Appendix E of this report shows the tools used to verify the operation of the negative phase sequence protection element. The relay operated correctly for the specified setting of 0.3Amps. Figure 40 shows the actual fault simulation values of 0.1Amps injected into the relay winding 1 input. From Figure 38, three times the negative sequence current will cause the relay to operate and as stated before for all relay elements the accuracy has to be ±5% of the nominal setting as per relay specifications.

9.4 Residual ground overcurrent

For the residual overcurrent setting, shown in Figure 63, with current 0.6Amps and 5 seconds time delay, the relay operated as expected. The relay operated for a value of 0.68 Amps on the red phase and the relay word bit 50G11P asserted, as shown in Figure 65. The protection relay element operated accurately for the time delay setting of 5 seconds, as shown in the sequential event report shown in Figure 66.



Residual Overcurrent

Element 1

50G11P Winding 1 Residual Overcurrent Trip Level (amps)
0.60 Range = OFF,0.10-19.20

50G11D Winding 1 Residual Overcurrent Trip Delay (seconds)
5.00 Range = 0.00-5.00

50G11TC Winding 1 Residual Overcurrent Torque Control (SELogic)
1

Element 2

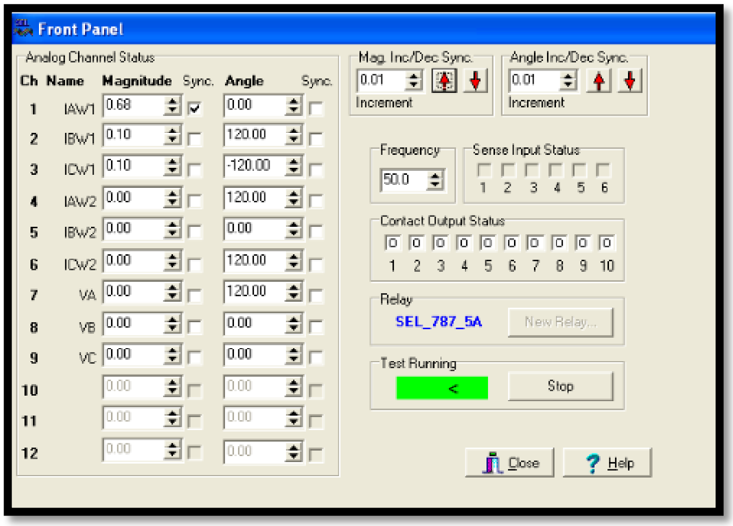
50G12P Winding 1 Residual Overcurrent Trip Level (amps)
OFF Range = OFF,0.10-19.20

50G12D Winding 1 Residual Overcurrent Trip Delay (seconds)
0.50 Range = 0.00-5.00

50G12TC Winding 1 Residual Overcurrent Torque Control (SELogic)
1

Figure 63 Residual overcurrent setting page

Figure 64 below show the simulation template used to carry out the test.



Analog Channel Status

Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	0.68	☑	0.00	☐
2	IBW1	0.10	☐	120.00	☐
3	ICW1	0.10	☐	-120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync.: 0.01 Increment

Angle Inc/Dec Sync.: 0.01 Increment

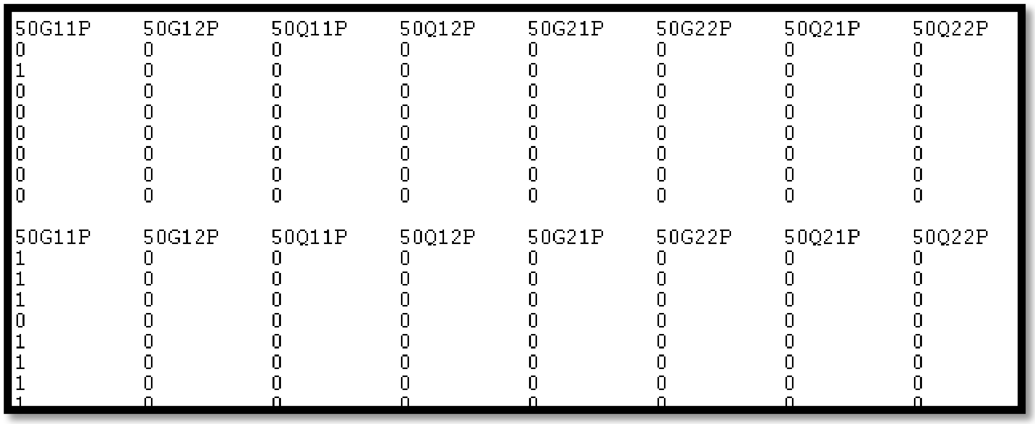
Frequency: 50.0

Sense Input Status: 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

Contact Output Status: 1 0 2 0 3 0 4 0 5 0 6 0 7 0 8 0 9 0 10 0

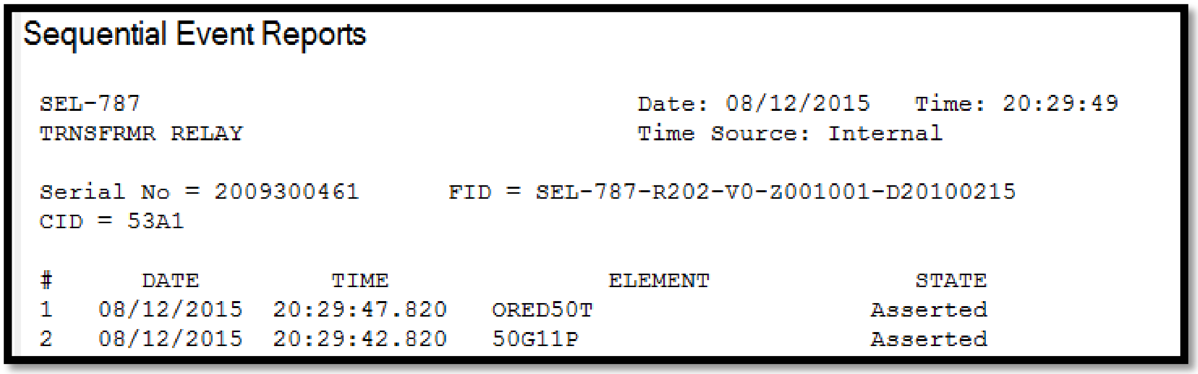
Relay: SEL_787_5A

Figure 64 Test template for residual overcurrent



```
50G11P    50G12P    50Q11P    50Q12P    50G21P    50G22P    50Q21P    50Q22P
0         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0

50G11P    50G12P    50Q11P    50Q12P    50G21P    50G22P    50Q21P    50Q22P
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
1         0         0         0         0         0         0         0
```

Figure 65 Terminal window showing assertion of residual ground overcurrent relay word bit



Sequential Event Reports

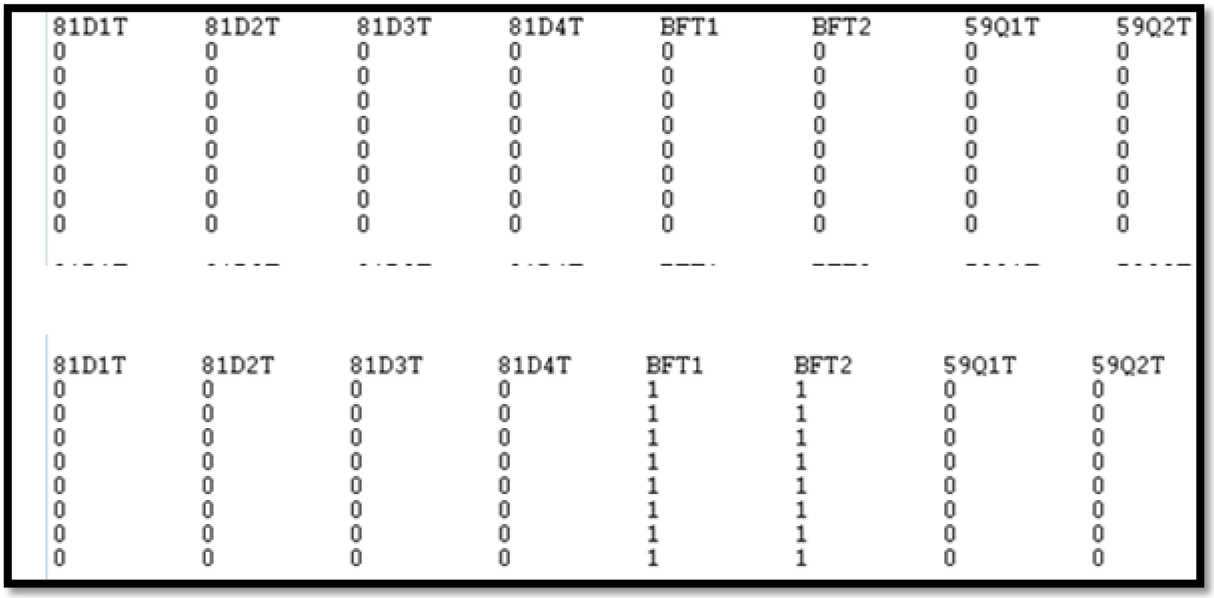
```
SEL-787                                   Date: 08/12/2015   Time: 20:29:49
TRNSFRMR RELAY                            Time Source: Internal

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#       DATE          TIME                ELEMENT                STATE
1   08/12/2015   20:29:47.820   ORED50T                       Asserted
2   08/12/2015   20:29:42.820   50G11P                        Asserted
```

Figure 66 SER showing operation of residual overcurrent element

Appendix F of this report shows the visual indications verifying operation of the protection element.

9.5 Breaker Failure

This back up protection function operated as desired after the trip signal had been sent to trip the circuit breaker and the input from the auxiliary contact of the breaker was not received by the relay to indicate circuit breaker operation. Figure 67 shows the breaker failure word bit BFT getting asserted.

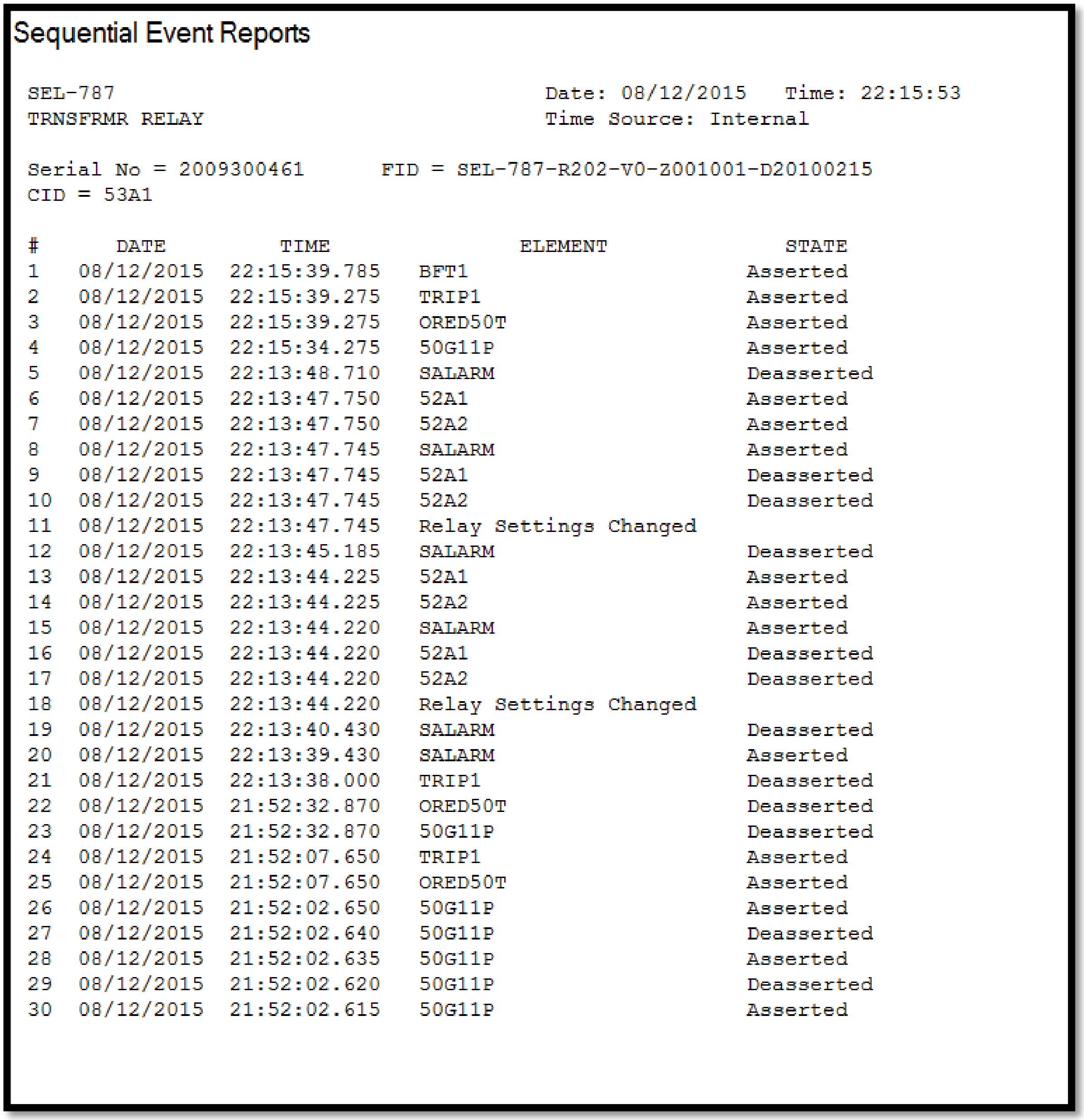


```
81D1T     81D2T     81D3T     81D4T     BFT1      BFT2      59Q1T     59Q2T
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
```

```
81D1T     81D2T     81D3T     81D4T     BFT1      BFT2      59Q1T     59Q2T
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
0         0         0         0         1         1         0         0
```

Figure 67 Assertion of breaker failure

The sequential event report below shows all the relay word bits associated with the simulation getting asserted. The time taken to activate the relay word bits is also shown. The function operated correctly, as indicated by the sequence of events shown in Figure 68.



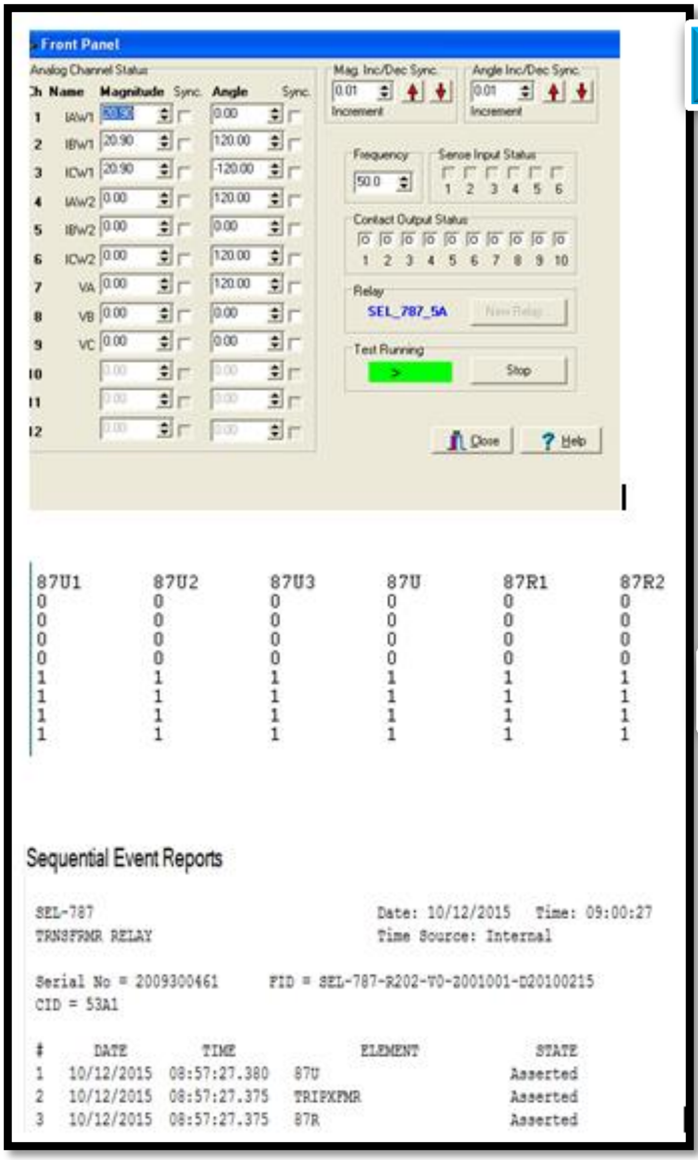
Sequential Event Reports

```
SEL-787                                     Date: 08/12/2015   Time: 22:15:53
TRNSFRMR RELAY                              Time Source: Internal

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#      DATE         TIME                 ELEMENT                 STATE
1   08/12/2015  22:15:39.785   BFT1                          Asserted
2   08/12/2015  22:15:39.275   TRIP1                         Asserted
3   08/12/2015  22:15:39.275   ORED50T                       Asserted
4   08/12/2015  22:15:34.275   50G11P                        Asserted
5   08/12/2015  22:13:48.710   SALARM                        Deasserted
6   08/12/2015  22:13:47.750   52A1                          Asserted
7   08/12/2015  22:13:47.750   52A2                          Asserted
8   08/12/2015  22:13:47.745   SALARM                        Asserted
9   08/12/2015  22:13:47.745   52A1                          Deasserted
10  08/12/2015  22:13:47.745   52A2                          Deasserted
11  08/12/2015  22:13:47.745   Relay Settings Changed
12  08/12/2015  22:13:45.185   SALARM                        Deasserted
13  08/12/2015  22:13:44.225   52A1                          Asserted
14  08/12/2015  22:13:44.225   52A2                          Asserted
15  08/12/2015  22:13:44.220   SALARM                        Asserted
16  08/12/2015  22:13:44.220   52A1                          Deasserted
17  08/12/2015  22:13:44.220   52A2                          Deasserted
18  08/12/2015  22:13:44.220   Relay Settings Changed
19  08/12/2015  22:13:40.430   SALARM                        Deasserted
20  08/12/2015  22:13:39.430   SALARM                        Asserted
21  08/12/2015  22:13:38.000   TRIP1                         Deasserted
22  08/12/2015  21:52:32.870   ORED50T                       Deasserted
23  08/12/2015  21:52:32.870   50G11P                        Deasserted
24  08/12/2015  21:52:07.650   TRIP1                         Asserted
25  08/12/2015  21:52:07.650   ORED50T                       Asserted
26  08/12/2015  21:52:02.650   50G11P                        Asserted
27  08/12/2015  21:52:02.640   50G11P                        Deasserted
28  08/12/2015  21:52:02.635   50G11P                        Asserted
29  08/12/2015  21:52:02.620   50G11P                        Deasserted
30  08/12/2015  21:52:02.615   50G11P                        Asserted
```

Figure 68 SER indicating operation of the breaker failure element

9.6 Unrestrained differential element

The unrestrained relay word bit was activated when the setting value of 20.9 Amps was reached, as shown in the simulation template in Figure 69. Figure 69 also shows the relay word bit for the unrestrained element 87U changing state and the sequential event report generated. The restrained differential word bit also changed state as the restrained differential element minimum pick up setting is much lower than the unrestrained pick up value, hence the relay word bit 87R also got activated.



Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	20.90	☐	0.00	☐
2	IBW1	20.90	☐	120.00	☐
3	ICW1	20.90	☐	-120.00	☐
4	IAW2	0.00	☐	120.00	☐
5	IBW2	0.00	☐	0.00	☐
6	ICW2	0.00	☐	120.00	☐
7	VA	0.00	☐	120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync. Increment: 0.01

Angle Inc/Dec Sync. Increment: 0.01

Frequency: 50.0

Sense Input Status: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Contact Output Status: 1: 0, 2: 0, 3: 0, 4: 0, 5: 0, 6: 0, 7: 0, 8: 0, 9: 0, 10: 0

Relay: SEL_787_5A

```
87U1      87U2      87U3      87U       87R1      87R2
0         0         0         0         0         0
0         0         0         0         0         0
0         0         0         0         0         0
0         0         0         0         0         0
1         1         1         1         1         1
1         1         1         1         1         1
1         1         1         1         1         1
1         1         1         1         1         1
```

Sequential Event Reports

```
SEL-787                                     Date: 10/12/2015   Time: 09:00:27
TRNSFRMR RELAY                              Time Source: Internal

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#     DATE         TIME            ELEMENT              STATE
1   10/12/2015  08:57:27.380   87U                      Asserted
2   10/12/2015  08:57:27.375   TRIPXFMR                 Asserted
3   10/12/2015  08:57:27.375   87R                      Asserted
```

Simulation Template

Relay word bit activated

Figure 69 Unrestrained differential element operation

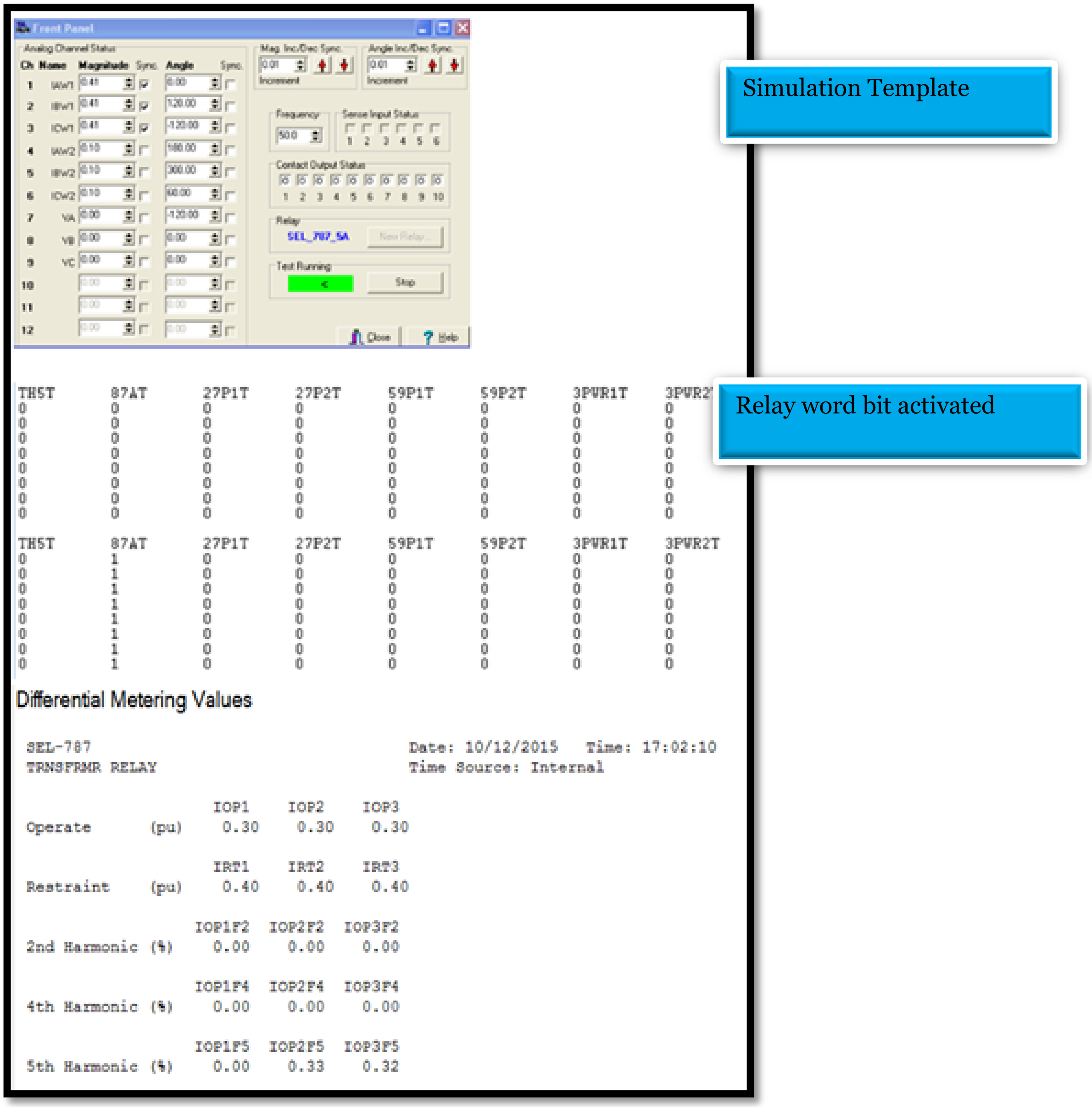
9.7 Restrained differential

The relay word bit for the differential alarm function 87AT element asserted during the fault simulation, as shown in Figure 70. The time delay for the alarm was set at 5 seconds. The protection function was tested at a setting of 0.15 with a 2.09 tap value. The alarm word bit asserted for a three phase fault simulation with a value of 0.41 Amps on all three phases for winding 1, as shown in Figure 70.

From the equation for the operate current $I_{OP}=(|\overleftarrow{IW}_1+I\overleftarrow{W2}|)$,

Equation 11 Differential operate current [9]

Using one of the phases as an example, the differential current can be calculated for this simulation as $0.14<0^{o}+0.1<180^{o}=0.31$Amps. The expected operating current for the alarm from the settings is $0.15*2.09=0.3135$. The simulation results are accurate as specified by the accuracy limits with a tolerance of ±2%. Figure 70 also shows the differential metering values for the , restraint current and differential operating current in per unit (pu). From the metering display it can also be verified that the relay operated correctly for a differential current of 0.3pu which is exactly the same as the setting value of 0.3pu.



Analog Channel Status

Ch	Name	Magnitude	Sync.	Angle	Sync.
1	IAW1	0.41	☑	0.00	☐
2	IBW1	0.41	☑	120.00	☐
3	ICW1	0.41	☑	-120.00	☐
4	IAW2	0.10	☐	180.00	☐
5	IBW2	0.10	☐	300.00	☐
6	ICW2	0.10	☐	60.00	☐
7	VA	0.00	☐	-120.00	☐
8	VB	0.00	☐	0.00	☐
9	VC	0.00	☐	0.00	☐
10		0.00	☐	0.00	☐
11		0.00	☐	0.00	☐
12		0.00	☐	0.00	☐

Mag. Inc/Dec Sync.: Increment 0.01

Angle Inc/Dec Sync.: Increment 0.01

Frequency: 50.0

Sense Input Status: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Contact Output Status: 1 2 3 4 5 6 7 8 9 10

Relay: SEL_787_5A

```
THST      87AT      27P1T     27P2T     59P1T     59P2T     3PWR1T    3PWR2
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0

THST      87AT      27P1T     27P2T     59P1T     59P2T     3PWR1T    3PWR2T
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
0         1         0         0         0         0         0         0
```

Differential Metering Values

```
SEL-787                                  Date: 10/12/2015    Time: 17:02:10
TRNSFRMR RELAY                           Time Source: Internal

                       IOP1     IOP2     IOP3
Operate         (pu)    0.30     0.30     0.30

                       IRT1     IRT2     IRT3
Restraint       (pu)    0.40     0.40     0.40

                     IOP1F2   IOP2F2   IOP3F2
2nd Harmonic  (%)      0.00     0.00     0.00

                     IOP1F4   IOP2F4   IOP3F4
4th Harmonic  (%)      0.00     0.00     0.00

                     IOP1F5   IOP2F5   IOP3F5
5th Harmonic  (%)      0.00     0.33     0.32
```

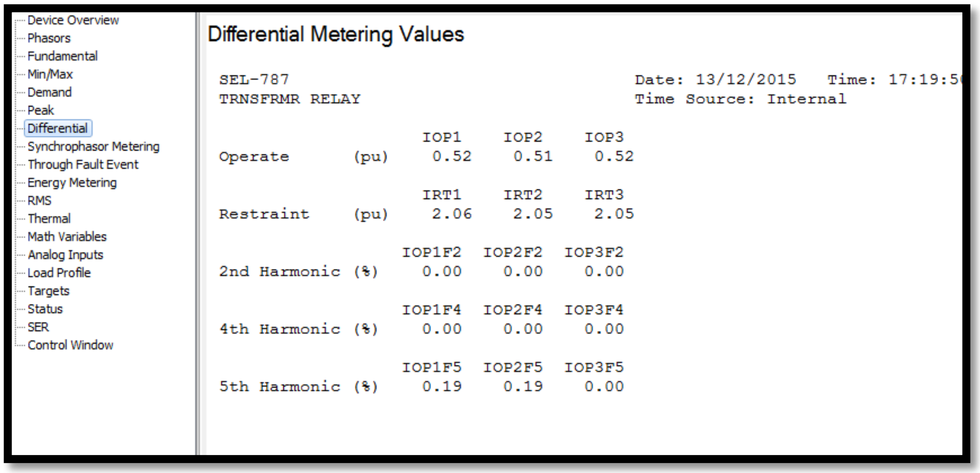
Simulation Template

Relay word bit activated

Figure 70 Restrained differential element simulation template and results

9.8 Slope 1 Restrained differential element

The protection element operated as expected in the slope one region on single phase and three phase fault simulations, as indicated in Figure 71. From Figure 71, the relay operated as desired in the slope one region with a differential operating current of 0.52pu and restraint current of 2.06 verifying the region of operation from the characteristic curve shown in Figure 44.



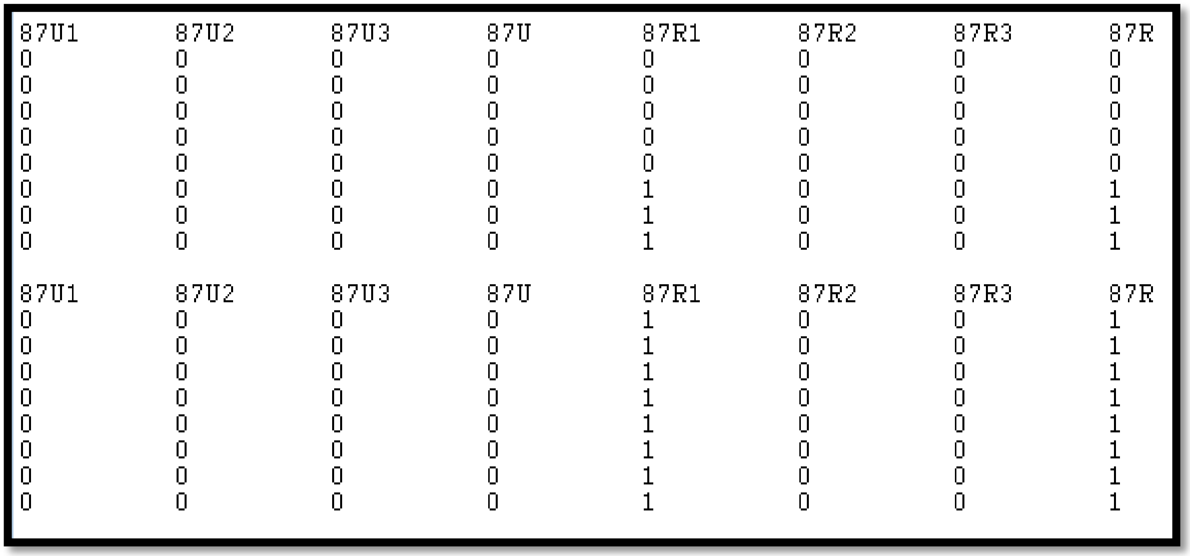
Differential Metering Values

```
SEL-787                                      Date: 13/12/2015   Time: 17:19:5
TRNSFRMR RELAY                               Time Source: Internal

                          IOP1     IOP2     IOP3
Operate        (pu)        0.52     0.51     0.52

                          IRT1     IRT2     IRT3
Restraint      (pu)        2.06     2.05     2.05

                        IOP1F2   IOP2F2   IOP3F2
2nd Harmonic  (%)         0.00     0.00     0.00

                        IOP1F4   IOP2F4   IOP3F4
4th Harmonic  (%)         0.00     0.00     0.00

                        IOP1F5   IOP2F5   IOP3F5
5th Harmonic  (%)         0.19     0.19     0.00
```

Figure 71 Slope 1 differential element operation results

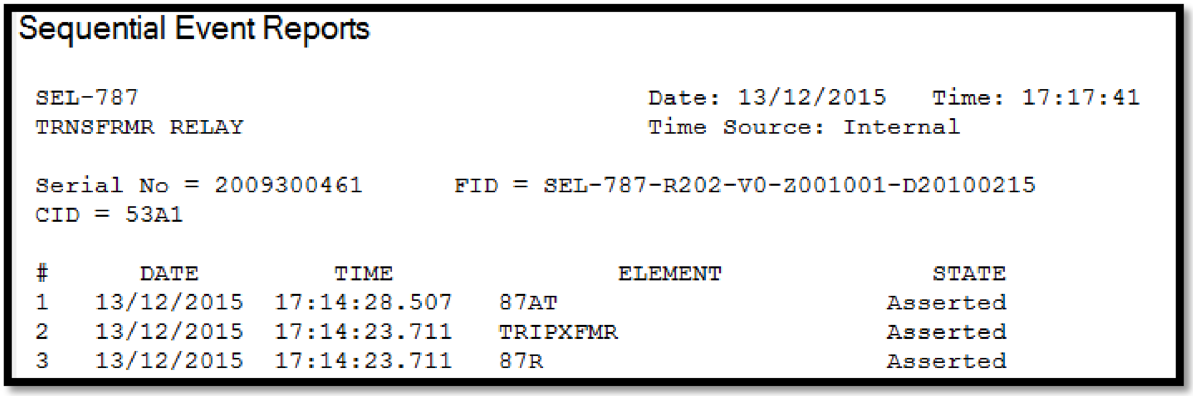
Figure 72 shows the differential element restrained word bit being activated for the slope 1 simulation, and the sequential event report shown in Figure 73 details the time and date the event occurred and the element word bits which were asserted are the differential alarm 87AT, restrained differential 87R and the transformer trip

TRIPXFMR. The device overview metering display Figure 74 shows the primary values of the injected current during the simulation.



```
87U1      87U2      87U3      87U       87R1      87R2      87R3      87R
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1

87U1      87U2      87U3      87U       87R1      87R2      87R3      87R
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
0         0         0         0         1         0         0         1
```

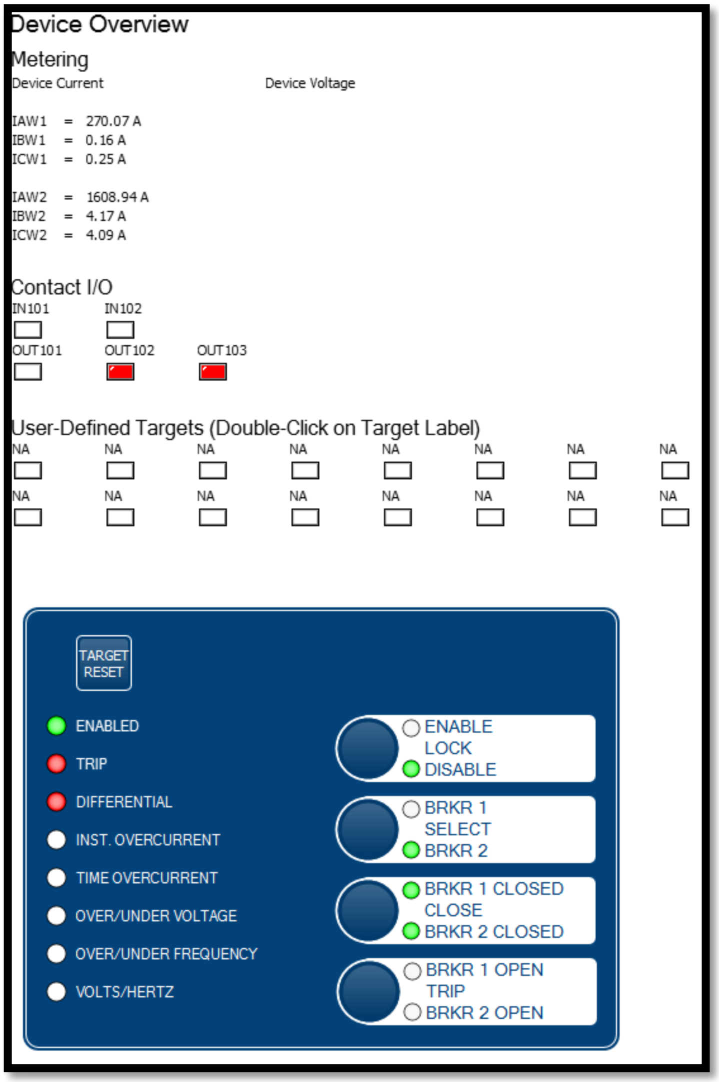
Figure 72 Restrained element relay word bit activation



Sequential Event Reports

```
SEL-787                                     Date: 13/12/2015   Time: 17:17:41
TRNSFRMR RELAY                              Time Source: Internal

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#       DATE          TIME              ELEMENT                  STATE
1   13/12/2015   17:14:28.507   87AT                          Asserted
2   13/12/2015   17:14:23.711   TRIPXFMR                      Asserted
3   13/12/2015   17:14:23.711   87R                           Asserted
```

Figure 73 SER report for restrained element operation



Device Overview

Metering

Device Current

IAW1 = 270.07 A
IBW1 = 0.16 A
ICW1 = 0.25 A

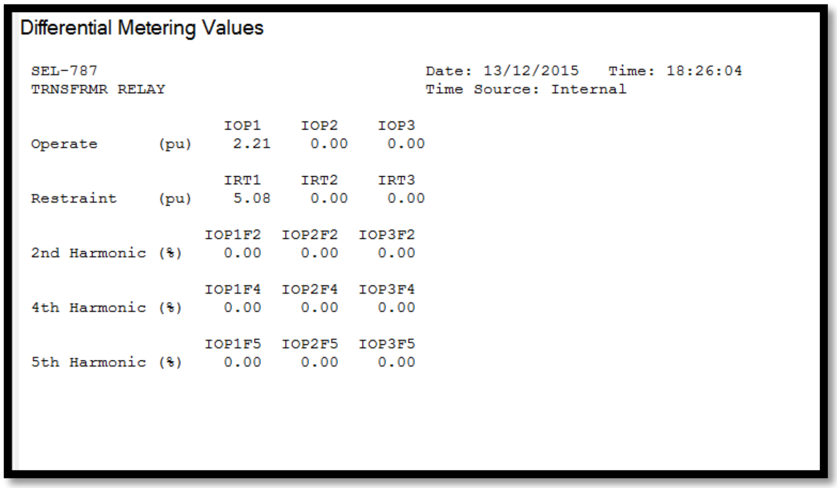
IAW2 = 1608.94 A
IBW2 = 4.17 A
ICW2 = 4.09 A

Figure 74 Slope 1 Differential simulation values in primary values

9.9 Slope 2 Restrained differential element

The protection element operated as expected in the slope two region on single phase and three phase fault simulations, as indicated in Figure 75.

From Figure 75 showing the differential metering values during the fault simulation, the relay operated correctly in the slope two region with a differential operating current of 2.21pu and restraint current of 5.08, verifying the region of operation from the characteristic settings shown in Figure 48. The restraint current is above 3pu, as shown in Figure 75, which is the IRS value confirming that the fault simulation is in second slope region.

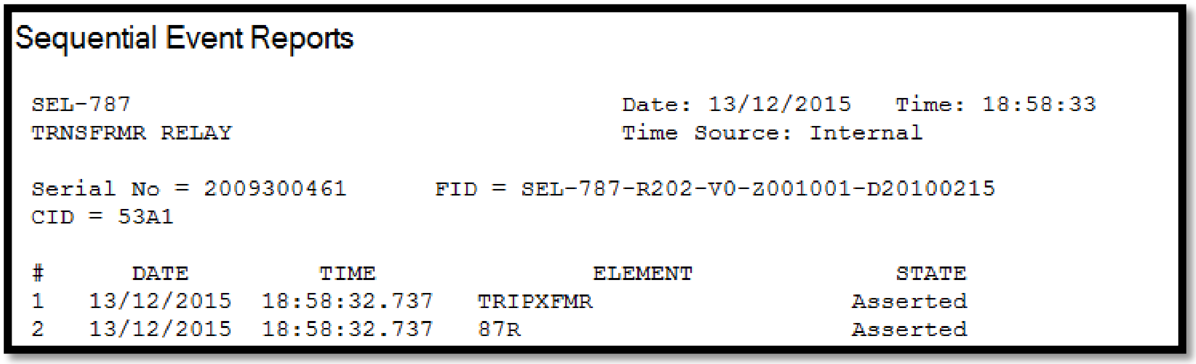


Differential Metering Values

```
SEL-787                                   Date: 13/12/2015   Time: 18:26:04
TRNSFRMR RELAY                            Time Source: Internal

                    IOP1     IOP2     IOP3
Operate       (pu)    2.21     0.00     0.00

                    IRT1     IRT2     IRT3
Restraint     (pu)    5.08     0.00     0.00

                  IOP1F2   IOP2F2   IOP3F2
2nd Harmonic  (%)   0.00     0.00     0.00

                  IOP1F4   IOP2F4   IOP3F4
4th Harmonic  (%)   0.00     0.00     0.00

                  IOP1F5   IOP2F5   IOP3F5
5th Harmonic  (%)   0.00     0.00     0.00
```

Figure 75 Slope 2 differential element operation results

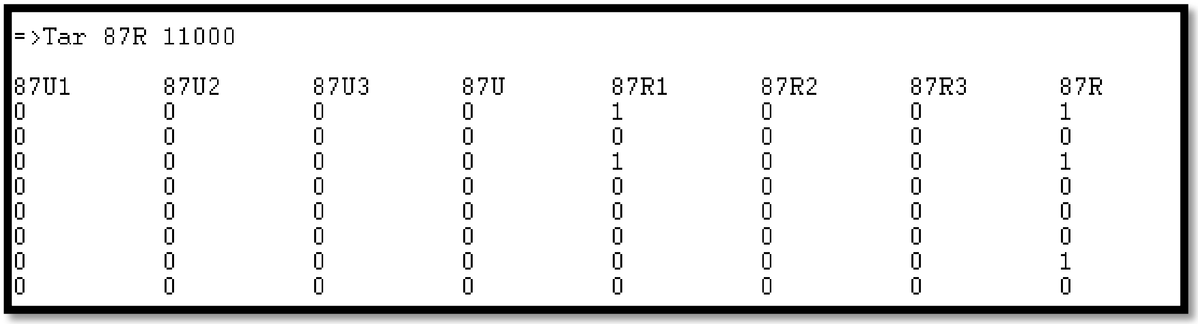
Figure 76 shows the event summary of the differential restrain element 87R operating in the slope 2 region. The associated relay word bit was asserted as shown by the terminal window report in Figure 77.



Sequential Event Reports

```
SEL-787                                       Date: 13/12/2015    Time: 18:58:33
TRNSFRMR RELAY                                Time Source: Internal

Serial No = 2009300461       FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#      DATE          TIME                 ELEMENT                  STATE
1    13/12/2015  18:58:32.737    TRIPXFMR                       Asserted
2    13/12/2015  18:58:32.737    87R                            Asserted
```

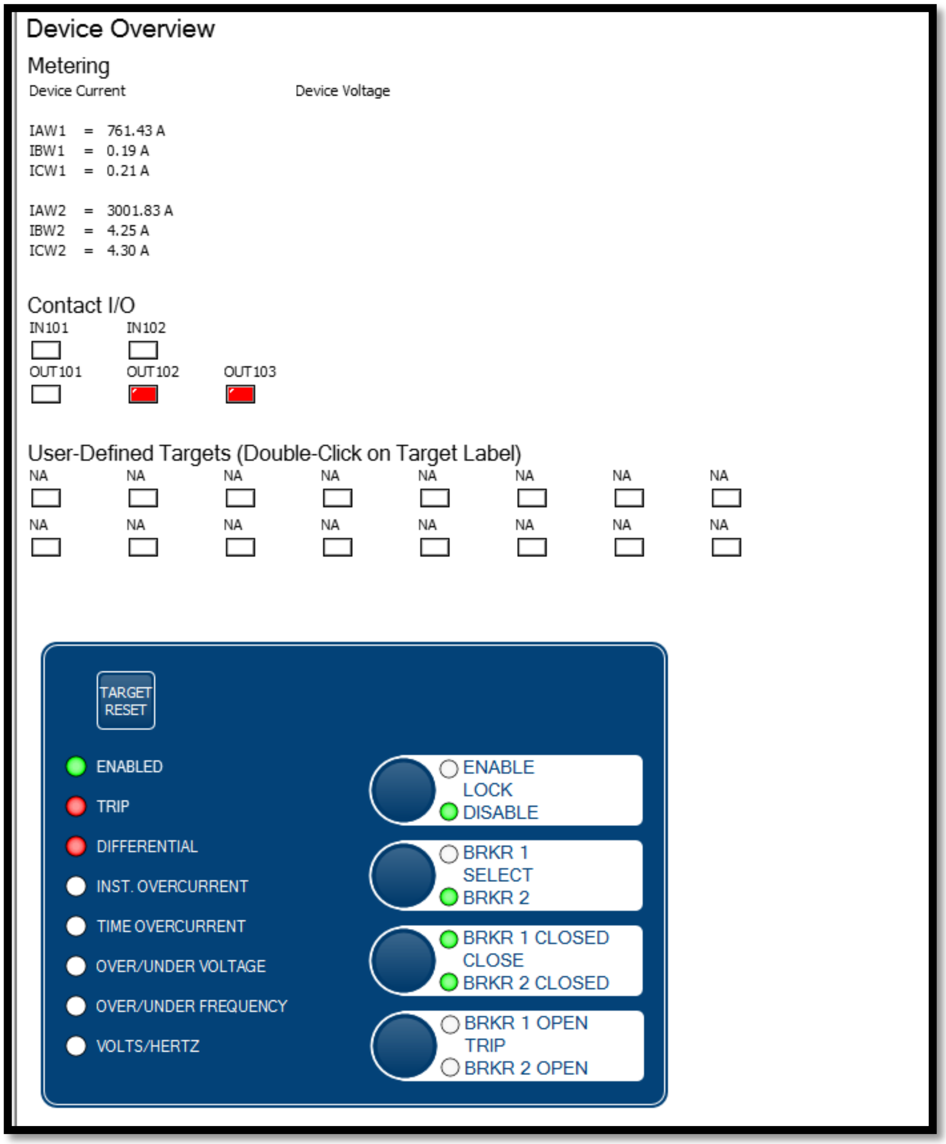
Figure 76 SER report for restrained element slope 2 operation



```
=>Tar 87R 11000

87U1      87U2      87U3      87U       87R1      87R2      87R3      87R
0         0         0         0         1         0         0         1
0         0         0         0         0         0         0         0
0         0         0         0         1         0         0         1
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         1
0         0         0         0         0         0         0         0
```

Figure 77 Slope 2 Restrained element relay word bit activation

The device overview metering displaying primary values of the injected current and indicators confirming correct operation of the protection element are shown in Figure 78 below.



Device Overview

Metering

Device Current

IAW1 = 761.43 A
IBW1 = 0.19 A
ICW1 = 0.21 A

IAW2 = 3001.83 A
IBW2 = 4.25 A
ICW2 = 4.30 A

Device Voltage

Contact I/O

IN101 ☐
IN102 ☐
OUT101 ☐
OUT102 🟥
OUT103 🟥

User-Defined Targets (Double-Click on Target Label)

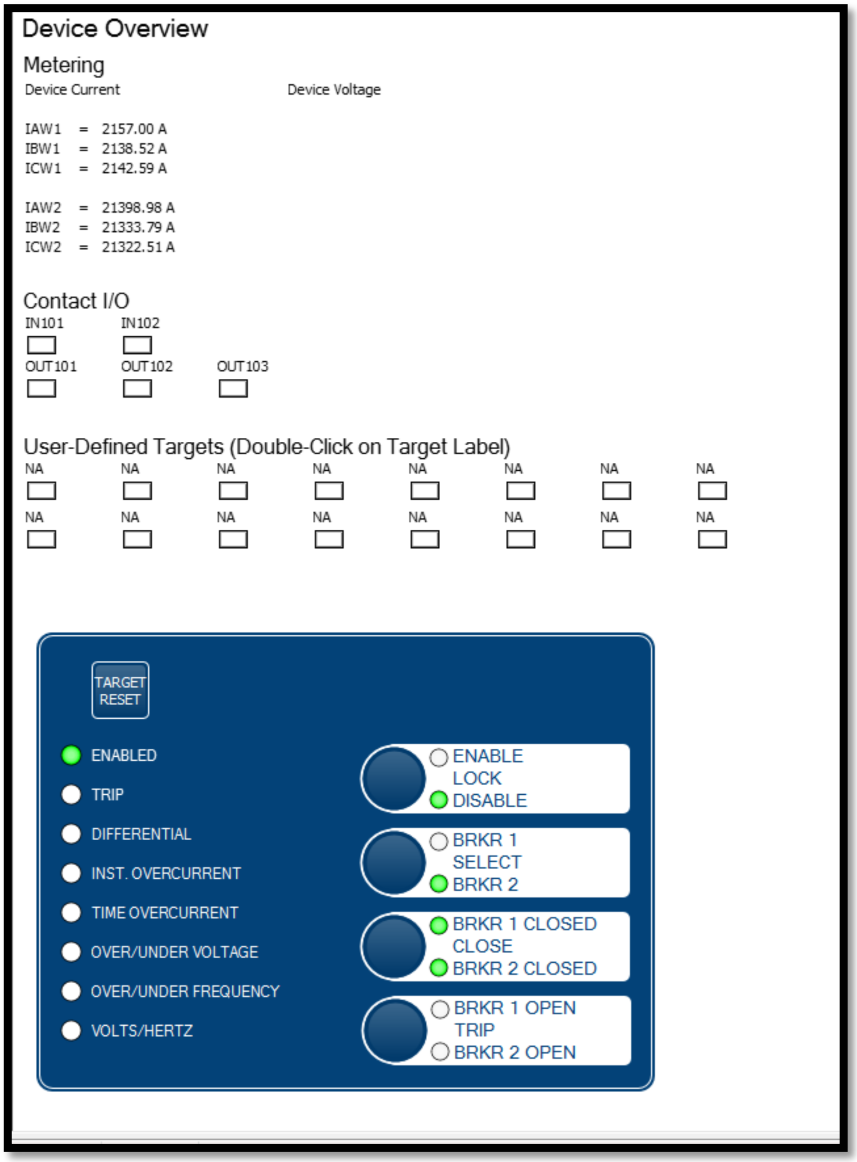
NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐
NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐

Figure 78 Slope 2 Differential simulation values in primary values

9.10 Through fault monitor

The values injected into the relay were 20.9 Amps above the unrestrained pick up value, and the relay did not operate. Through fault measurement for injected current of 20.9 A on all phases: on the primary side, the currents have a phase displacement of 120 degrees; and on the secondary side, as seen by the relay, the currents are displaced 180 degrees. This is for a three phase fault hence all the currents are the same. The relay did not operate because the simulation was for an out of zone fault.

The device metering overview display below shows the primary values of the through fault event as seen by the relay. No output trip was activated as the relay restrained and did not operate.



Device Overview

Metering

Device Current

Device Voltage

IAW1 = 2157.00 A
IBW1 = 2138.52 A
ICW1 = 2142.59 A

IAW2 = 21398.98 A
IBW2 = 21333.79 A
ICW2 = 21322.51 A

Contact I/O

IN101 ☐ IN102 ☐
OUT101 ☐ OUT102 ☐ OUT103 ☐

User-Defined Targets (Double-Click on Target Label)

NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐
NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐ NA ☐

● ENABLED
○ TRIP
○ DIFFERENTIAL
○ INST. OVERCURRENT
○ TIME OVERCURRENT
○ OVER/UNDER VOLTAGE
○ OVER/UNDER FREQUENCY
○ VOLTS/HERTZ

○ ENABLE
LOCK
● DISABLE

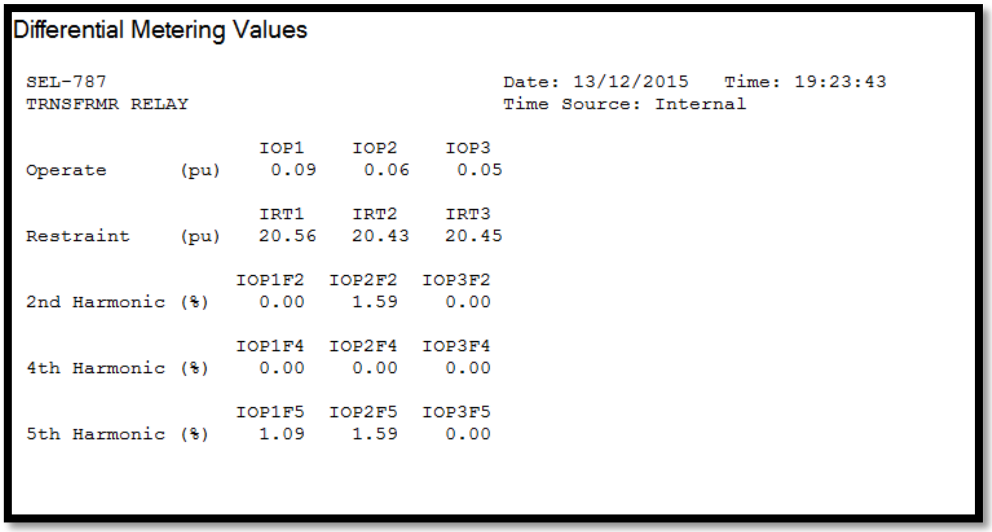
○ BRKR 1
SELECT
● BRKR 2

● BRKR 1 CLOSED
CLOSE
● BRKR 2 CLOSED

○ BRKR 1 OPEN
TRIP
○ BRKR 2 OPEN

Figure 79 Through fault simulation metering overview

The differential metering values, as can be seen below in Figure 80, is 0, hence the relay did not operate. The restrain current shot up to 20pu, also indicating that the relay is restraining operation, as shown in Figure 80.

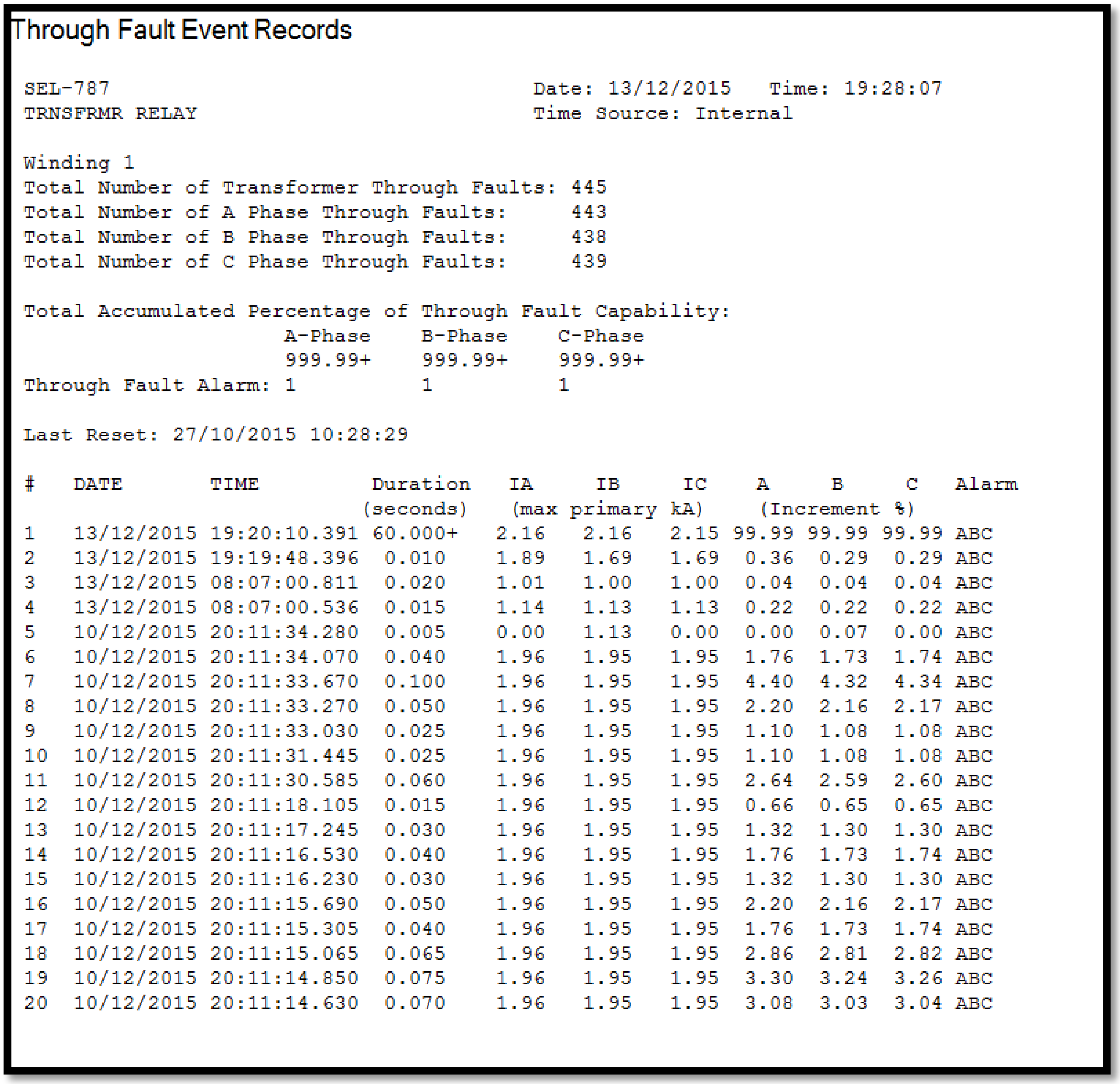


Differential Metering Values

```
SEL-787                                   Date: 13/12/2015   Time: 19:23:43
TRNSFRMR RELAY                            Time Source: Internal

                    IOP1     IOP2     IOP3
Operate       (pu)   0.09     0.06     0.05

                    IRT1     IRT2     IRT3
Restraint     (pu)  20.56    20.43    20.45

                  IOP1F2   IOP2F2   IOP3F2
2nd Harmonic  (%)   0.00     1.59     0.00

                  IOP1F4   IOP2F4   IOP3F4
4th Harmonic  (%)   0.00     0.00     0.00

                  IOP1F5   IOP2F5   IOP3F5
5th Harmonic  (%)   1.09     1.59     0.00
```

Figure 80 Differential metering view through fault

Even without the relay operating, the through fault event report indicates this event. The through fault event report in Figure 81 shows the number of through fault events, and the latest event on the 13th of December is associated with the differential metering report above.

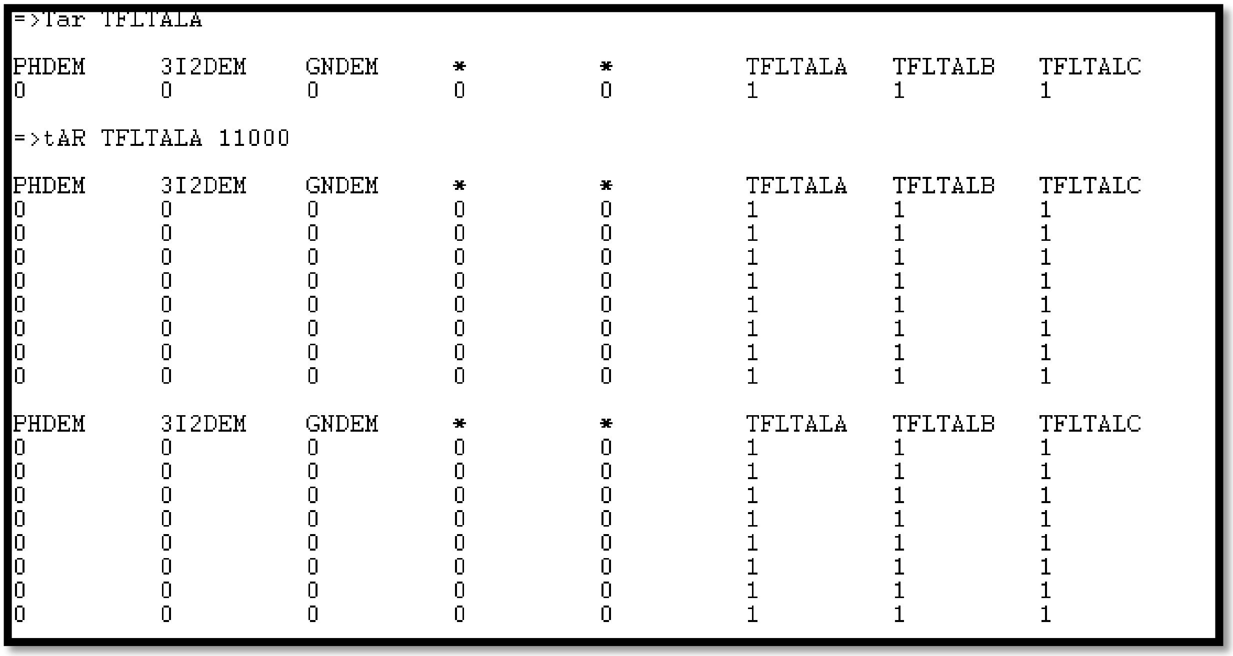


Through Fault Event Records

```
SEL-787                                  Date: 13/12/2015   Time: 19:28:07
TRNSFRMR RELAY                           Time Source: Internal

Winding 1
Total Number of Transformer Through Faults: 445
Total Number of A Phase Through Faults:     443
Total Number of B Phase Through Faults:     438
Total Number of C Phase Through Faults:     439

Total Accumulated Percentage of Through Fault Capability:
                     A-Phase    B-Phase    C-Phase
                     999.99+    999.99+    999.99+
Through Fault Alarm: 1          1          1

Last Reset: 27/10/2015 10:28:29

#   DATE       TIME         Duration   IA     IB     IC    A     B     C    Alarm
                           (seconds)   (max primary kA)    (Increment %)
1   13/12/2015 19:20:10.391 60.000+   2.16   2.16   2.15 99.99 99.99 99.99 ABC
2   13/12/2015 19:19:48.396  0.010    1.89   1.69   1.69  0.36  0.29  0.29 ABC
3   13/12/2015 08:07:00.811  0.020    1.01   1.00   1.00  0.04  0.04  0.04 ABC
4   13/12/2015 08:07:00.536  0.015    1.14   1.13   1.13  0.22  0.22  0.22 ABC
5   10/12/2015 20:11:34.280  0.005    0.00   1.13   0.00  0.00  0.07  0.00 ABC
6   10/12/2015 20:11:34.070  0.040    1.96   1.95   1.95  1.76  1.73  1.74 ABC
7   10/12/2015 20:11:33.670  0.100    1.96   1.95   1.95  4.40  4.32  4.34 ABC
8   10/12/2015 20:11:33.270  0.050    1.96   1.95   1.95  2.20  2.16  2.17 ABC
9   10/12/2015 20:11:33.030  0.025    1.96   1.95   1.95  1.10  1.08  1.08 ABC
10  10/12/2015 20:11:31.445  0.025    1.96   1.95   1.95  1.10  1.08  1.08 ABC
11  10/12/2015 20:11:30.585  0.060    1.96   1.95   1.95  2.64  2.59  2.60 ABC
12  10/12/2015 20:11:18.105  0.015    1.96   1.95   1.95  0.66  0.65  0.65 ABC
13  10/12/2015 20:11:17.245  0.030    1.96   1.95   1.95  1.32  1.30  1.30 ABC
14  10/12/2015 20:11:16.530  0.040    1.96   1.95   1.95  1.76  1.73  1.74 ABC
15  10/12/2015 20:11:16.230  0.030    1.96   1.95   1.95  1.32  1.30  1.30 ABC
16  10/12/2015 20:11:15.690  0.050    1.96   1.95   1.95  2.20  2.16  2.17 ABC
17  10/12/2015 20:11:15.305  0.040    1.96   1.95   1.95  1.76  1.73  1.74 ABC
18  10/12/2015 20:11:15.065  0.065    1.96   1.95   1.95  2.86  2.81  2.82 ABC
19  10/12/2015 20:11:14.850  0.075    1.96   1.95   1.95  3.30  3.24  3.26 ABC
20  10/12/2015 20:11:14.630  0.070    1.96   1.95   1.95  3.08  3.03  3.04 ABC
```

Figure 81 Summary of through fault events

Figure 82 shows the relay word bits for the through fault asserted when the event occurred. This also is verification of operation of the through fault event.



```
=>Tar TFLTALA

PHDEM      3I2DEM     GNDEM      *          *          TFLTALA    TFLTALB    TFLTALC
0          0          0          0          0          1          1          1

=>tAR TFLTALA 11000

PHDEM      3I2DEM     GNDEM      *          *          TFLTALA    TFLTALB    TFLTALC
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1

PHDEM      3I2DEM     GNDEM      *          *          TFLTALA    TFLTALB    TFLTALC
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
0          0          0          0          0          1          1          1
```

Figure 82 Through fault relay word bit assertion

Chapter 10 LabVIEW/CompactDaq system

10.1 CompactDaq

The CompactDaq system by National Instruments is a robust modular data acquisition platform. The system is mainly used in the chemical and process industries to capture process data from sensors and to facilitate its measurement and analysis through software programs like LabVIEW. In this project, the Ethernet chassis consisted of eight slots where the analog or digital modules are inserted. The chassis is robust and can withstand shocks of 30Kg to 50Kg. Figure 83 shows the Ethernet chassis [26].

Figure 83 **Ethernet CompactDaq chassis [26]**

The modules, both analog and digital, have a signal converter, circuitry for filtering, conditioning circuitry excitation and signal amplification. Figure 84 shows the different types of modules [26].

Figure 84 CompactDaq Modules [26]

For this project, the NI9263 was used to provide the necessary analog signals to carry out fault simulations. The module has an output analog range of ±10V. Figure 85 shows the module and the test setup for fault simulation. The wiring configuration of the module and specifications can be found in the appendix A section of this report [26].

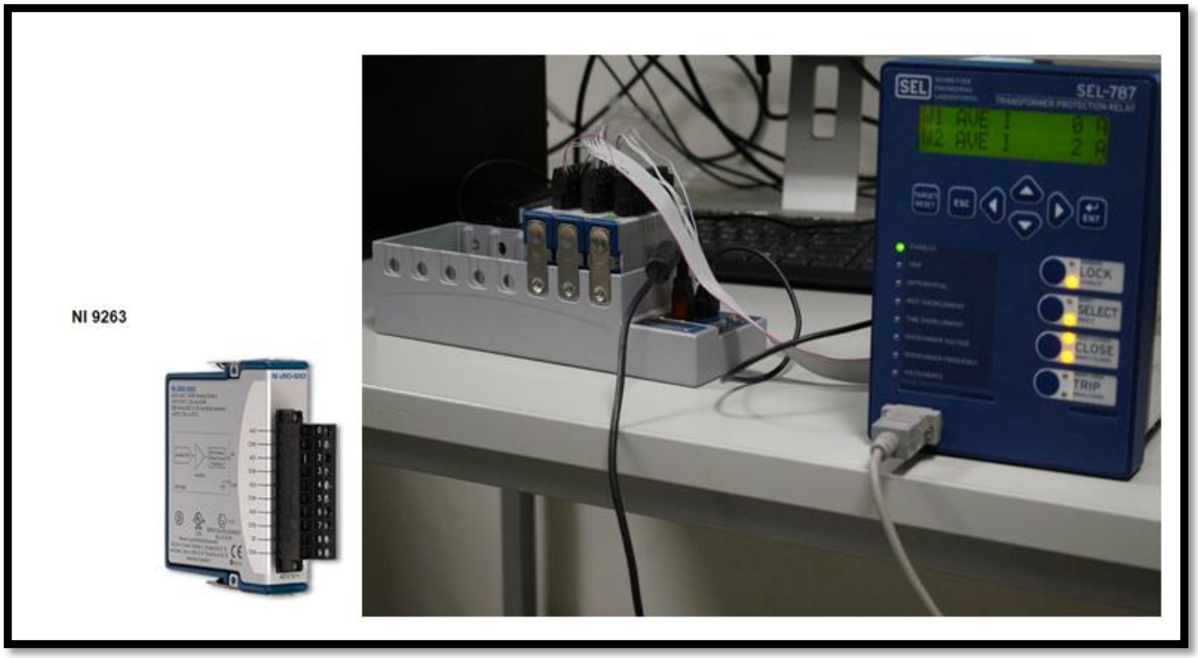
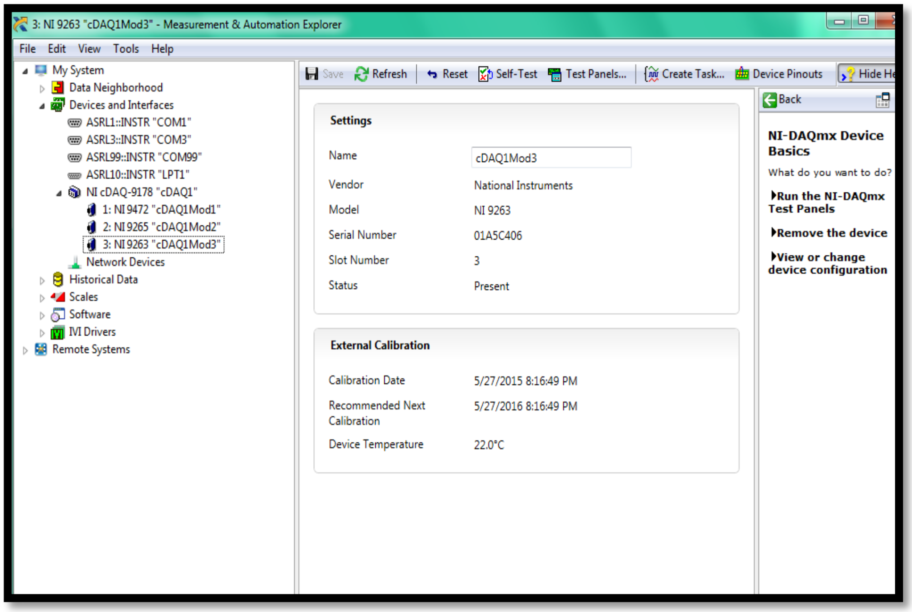


Figure 85 CompactDaq test setup

10.2 NI Max

LabVIEW is a graphical programming language developed by National Instruments. It is a powerful tool used in many industries for data acquisition, measurement and analysis. LabVIEW can be used in conjunction with the CompactDaq system via NI-DAQmx drivers. Figure 86 shows the NI Max platform which was used to conduct the fault simulation via the test panel.



Settings

Name	cDAQ1Mod3
Vendor	National Instruments
Model	NI 9263
Serial Number	01A5C406
Slot Number	3
Status	Present

External Calibration

Calibration Date	5/27/2015 8:16:49 PM
Recommended Next Calibration	5/27/2016 8:16:49 PM
Device Temperature	22.0°C

Figure 86 NI Max test panel

10.3 Signal output measurement and analysis

Prior to using the CompactDaq system for testing, the fault simulation signals to the protection relay slot Z input card needed to be analysed to determine the condition of the signal. This was carried out using an oscilloscope to measure the signal inputs as shown in Figure 87.

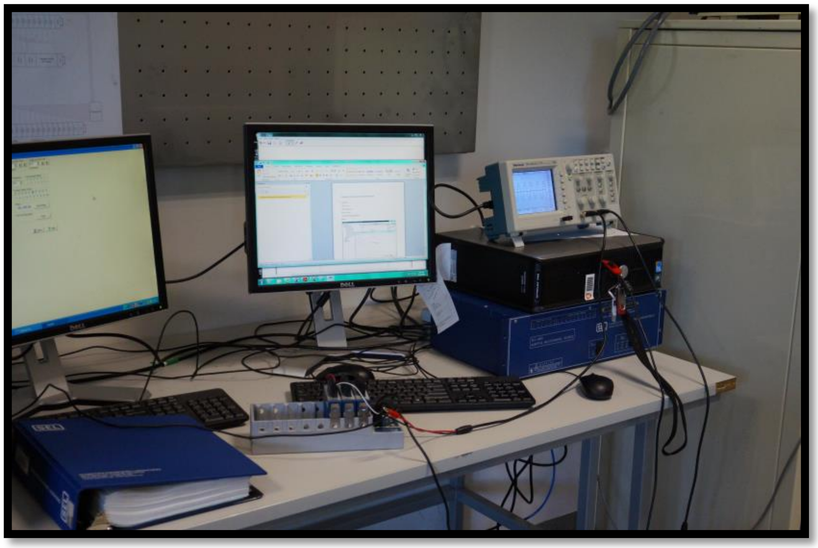


Figure 87 Signal analysis test setup

The signal outputs from the CompactDaq system and the analog inputs to the relay from the simulator were measured via an oscilloscope and compared. Initially, the signals were compared at different output values to show the output waveform at low voltage values as shown in Figure 88. The input signal to the relay circuit board was found to be a voltage signal of a peak to peak value of 10V maximum for the SEL 787 relay as shown in Figure 89. After determining this value, the NI max analog output voltage value was set to match a peak to peak value of 10V at 50Hz.

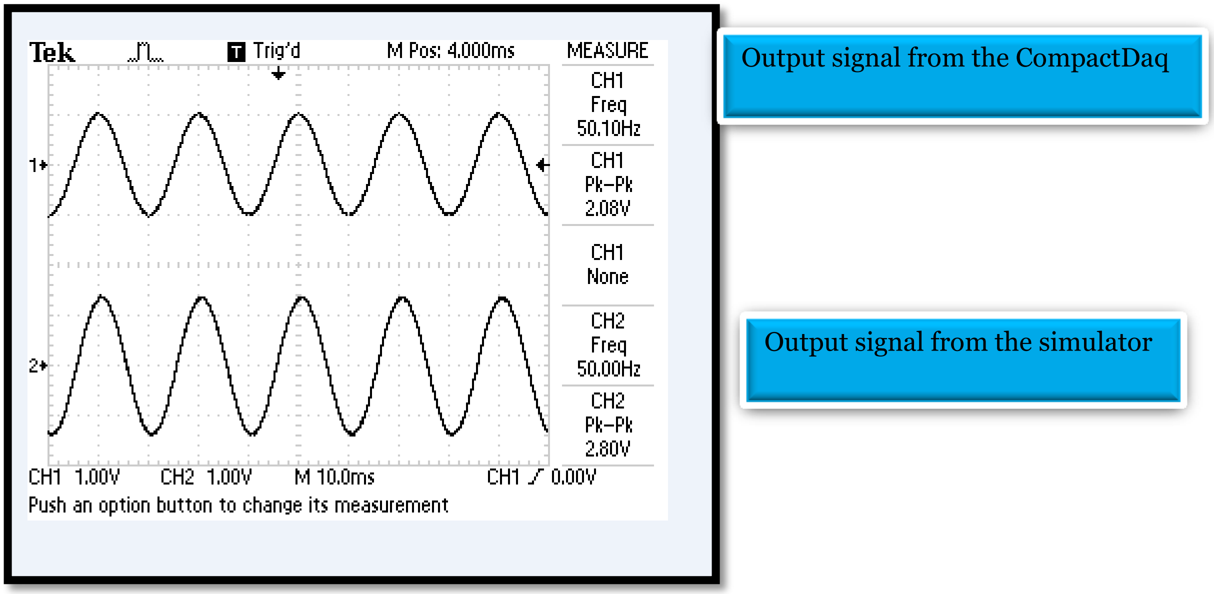


Figure 88 Initial test simulation of output voltages

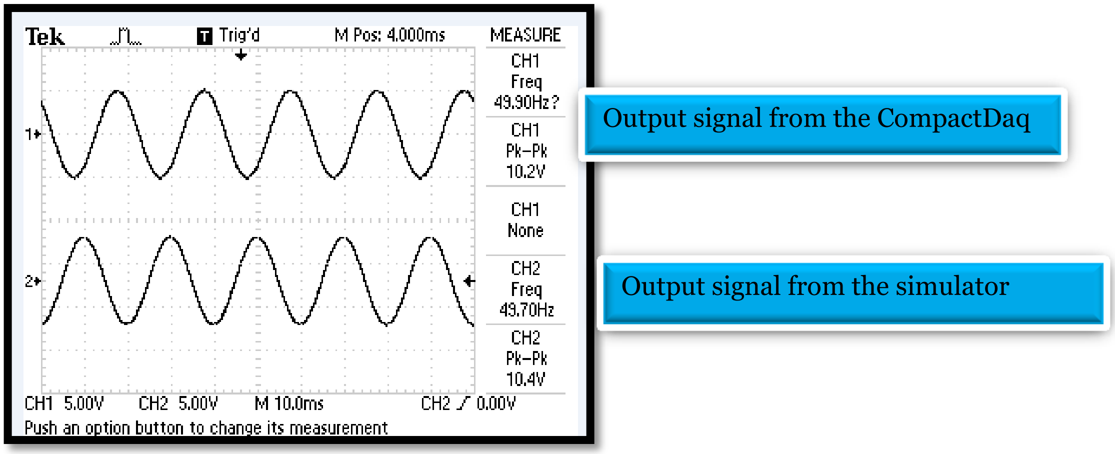
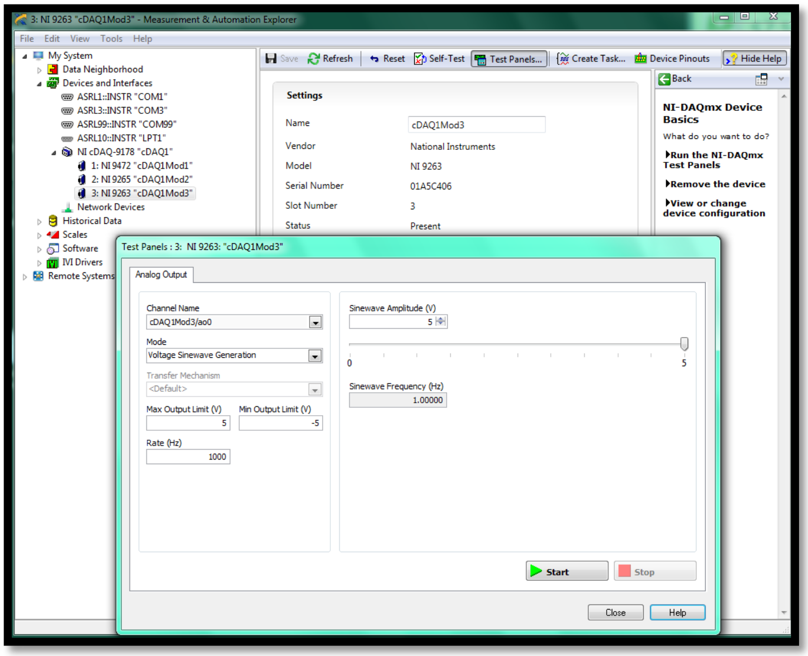


Figure 89 Maximum Output Voltages

10.4 Testing relay using NI Max

After establishing the maximum voltage, the slot Z circuit board can take the test panel setting in the NI. Max platform was set at the same maximum values. This was done to prevent damage to the circuit board through accidental injection of voltages above the maximum input voltage for the circuit board. Figure 90 shows the page where the test settings can be changed.



Settings

Name: cDAQ1Mod3
Vendor: National Instruments
Model: NI 9263
Serial Number: 01A5C406
Slot Number: 3
Status: Present

Test Panels : 3: NI 9263: "cDAQ1Mod3"

Analog Output

Channel Name: cDAQ1Mod3/ao0
Mode: Voltage Sinewave Generation
Transfer Mechanism: <Default>
Max Output Limit (V): 5
Min Output Limit (V): -5
Rate (Hz): 1000
Sinewave Amplitude (V): 5
Sinewave Frequency (Hz): 1.00000

Figure 90 NI Max test platform

The relay was successfully tested using the CompactDaq system. The differential protection element 87, as previously described, was tested and the relay operated, as shown in Figure 91 which shows the test setup.

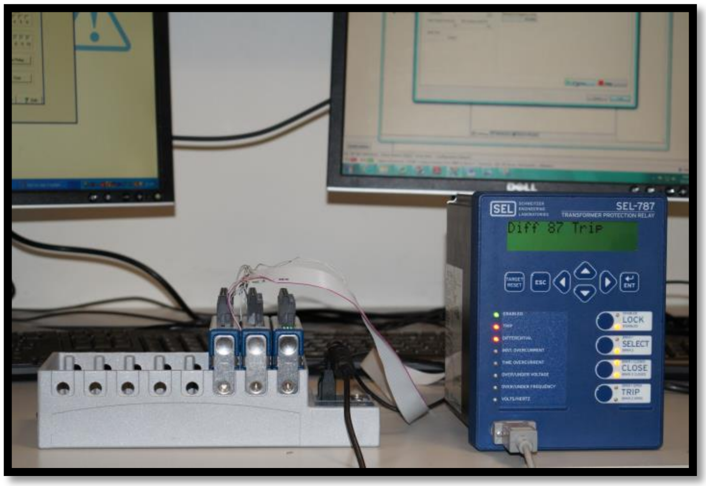


Figure 91 Fault simulation using CompactDaq system

Chapter 11 Conclusion

This thesis has reviewed power transformer operation and protection. Work has been successfully conducted on the use of low level simulators in showcasing the capabilities of microprocessor-based protection relays using the SEL 787 transformer protection relay.

This thesis described the different types of testing methodologies and analysis of simulation results for transformer protection relays. In the project the current based protection elements for the SEL 787 protection relay were successfully tested. The knowledge acquired throughout the project led to the initial development of a low level simulator using LabVIEW and the CompactDaq system, previous attempts by Murdoch University students had been unsuccessful.

Finally, the presented method of using low level simulators in relay testing has many benefits including the following:

- Providing low level signals that actual resemble the actual faults which occur in power systems.
- Setting up the hardware and wiring is less tedious hence a lot of time is saved. More time can then be spent on programming and testing the relay instead of wiring.
- It is a flexible, easy to implement low cost system compared to high level simulation.

Chapter 12 Future Work

While this thesis has showcased the capabilities of the SEL 787 transformer protection relay and the development of a low level simulator using LabVIEW and the CompactDaq system, the present study could be further extended. This section details some of the potential directions:

1. The protection relay functions for Harmonic restraint and blocking simulation was not investigated in the present study. This can be carried out by applying two current signals to the relay in parallel, one at the fundamental frequency of 50Hz and the other input at 2nd4th or 5th harmonics.
2. Simulations to verify the time current characteristics of the relay were not conducted. This can be done by monitoring the time it takes for the relay output contacts to operate for a specified fault current and plotting the data. This data can then be compared to the standard time current characteristic curves
3. Simulation using CompactDaq was done using the NI max test panel to conduct the testing of the relay elements. The next step is to design a robust CompactDaq system simulation station with the associated LabVIEW simulation program not to cater for all the relays housed at Murdoch University.

Chapter 13 References

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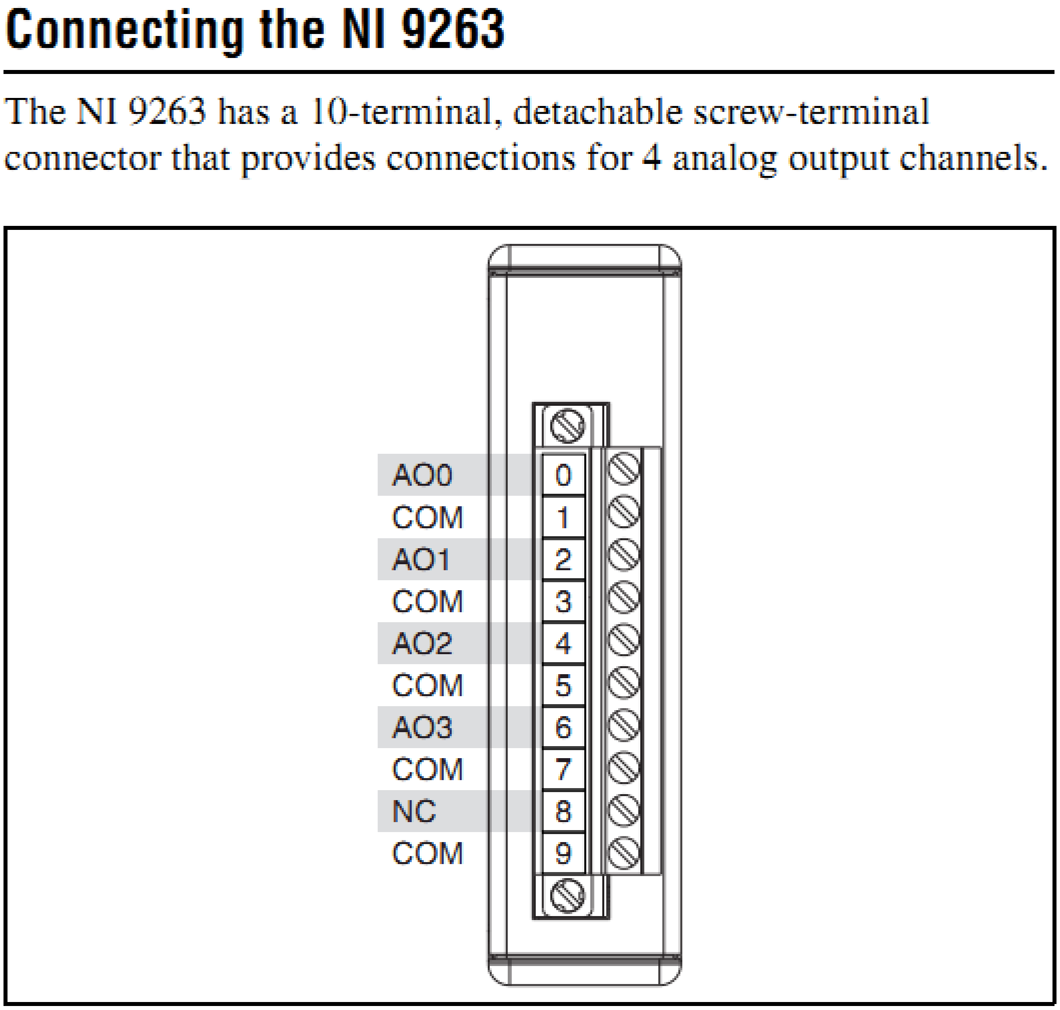
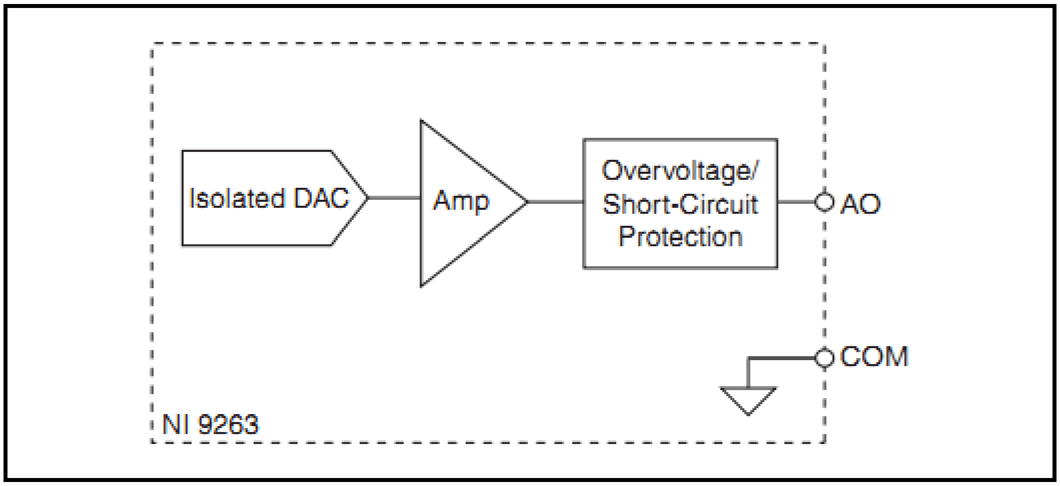
Chapter 14 Appendices

14.1 Appendix A CompactDaq Wiring Connection



Connecting the NI 9263

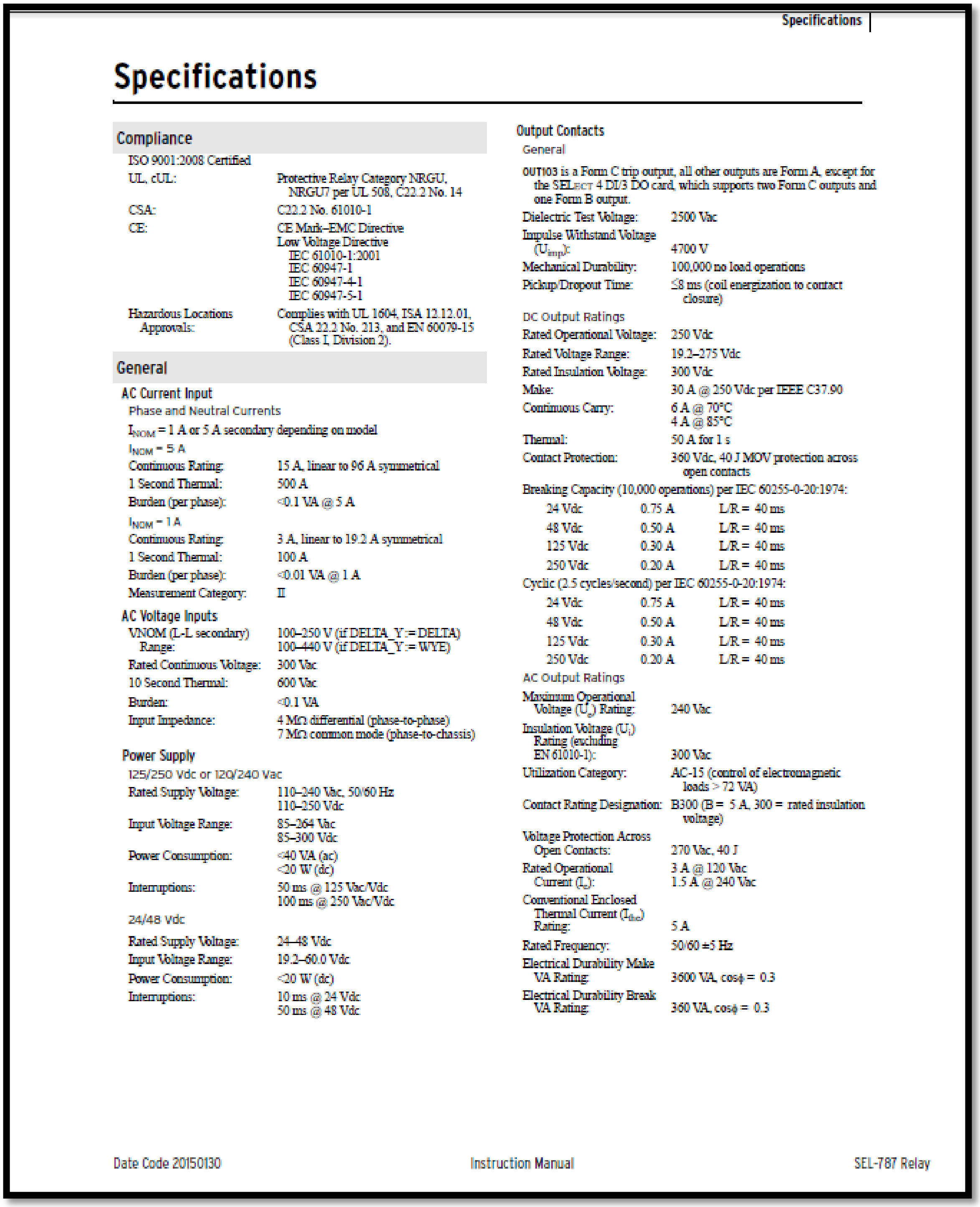
The NI 9263 has a 10-terminal, detachable screw-terminal connector that provides connections for 4 analog output channels.


Isolated DAC
Amp
Overvoltage/
Short-Circuit
Protection
AO
COM
NI 9263

14.2 Appendix B ANSI/IEEE Differential Relay Protection Functions

ANSI FUNCTION	Description
24	Volts Per Hertz
27P	Phase Under voltage
32	Directional Power
49	Temperature Alarm and Trip
50P	Phase Overcurrent
50G	Ground Overcurrent
50BF	Break Failure
50Q	Negative Sequence Overcurrent
51	Time Phase Overcurrent
51G	Time Ground Overcurrent
51N	Time Negative Sequence Overcurrent
59	Phase Overvoltage
59N	Negative Sequence Overvoltage
81O	Over Frequency
81U	Under Frequency
87	Current Differential
87G	Restricted Earth fault

14.3 Appendix C SEL 787 Relay Specifications



Specifications

Specifications

Compliance

ISO 9001:2008 Certified

UL, cUL:	Protective Relay Category NRGU, NRGU7 per UL 508, C22.2 No. 14
CSA:	C22.2 No. 61010-1
CE:	CE Mark–EMC Directive Low Voltage Directive IEC 61010-1:2001 IEC 60947-1 IEC 60947-4-1 IEC 60947-5-1
Hazardous Locations Approvals:	Complies with UL 1604, ISA 12.12.01, CSA 22.2 No. 213, and EN 60079-15 (Class I, Division 2).

General

AC Current Input

Phase and Neutral Currents

I_{NOM} = 1 A or 5 A secondary depending on model

I_{NOM} = 5 A

Continuous Rating:	15 A, linear to 96 A symmetrical
1 Second Thermal:	500 A
Burden (per phase):	<0.1 VA @ 5 A

I_{NOM} = 1 A

Continuous Rating:	3 A, linear to 19.2 A symmetrical
1 Second Thermal:	100 A
Burden (per phase):	<0.01 VA @ 1 A
Measurement Category:	II

AC Voltage Inputs

VNOM (L-L secondary) Range:	100–250 V (if DELTA_Y := DELTA) 100–440 V (if DELTA_Y := WYE)
Rated Continuous Voltage:	300 Vac
10 Second Thermal:	600 Vac
Burden:	<0.1 VA
Input Impedance:	4 MΩ differential (phase-to-phase) 7 MΩ common mode (phase-to-chassis)

Power Supply

125/250 Vdc or 120/240 Vac

Rated Supply Voltage:	110–240 Vac, 50/60 Hz 110–250 Vdc
Input Voltage Range:	85–264 Vac 85–300 Vdc
Power Consumption:	<40 VA (ac) <20 W (dc)
Interruptions:	50 ms @ 125 Vac/Vdc 100 ms @ 250 Vac/Vdc

24/48 Vdc

Rated Supply Voltage:	24–48 Vdc
Input Voltage Range:	19.2–60.0 Vdc
Power Consumption:	<20 W (dc)
Interruptions:	10 ms @ 24 Vdc 50 ms @ 48 Vdc

Output Contacts

General

OUT103 is a Form C trip output, all other outputs are Form A, except for the SELECT 4 DI/3 DO card, which supports two Form C outputs and one Form B output.

Dielectric Test Voltage:	2500 Vac
Impulse Withstand Voltage (U_{imp}):	4700 V
Mechanical Durability:	100,000 no load operations
Pickup/Dropout Time:	≤8 ms (coil energization to contact closure)

DC Output Ratings

Rated Operational Voltage:	250 Vdc
Rated Voltage Range:	19.2–275 Vdc
Rated Insulation Voltage:	300 Vdc
Make:	30 A @ 250 Vdc per IEEE C37.90
Continuous Carry:	6 A @ 70°C 4 A @ 85°C
Thermal:	50 A for 1 s
Contact Protection:	360 Vdc, 40 J MOV protection across open contacts

Breaking Capacity (10,000 operations) per IEC 60255-0-20:1974:

24 Vdc	0.75 A	L/R = 40 ms
48 Vdc	0.50 A	L/R = 40 ms
125 Vdc	0.30 A	L/R = 40 ms
250 Vdc	0.20 A	L/R = 40 ms

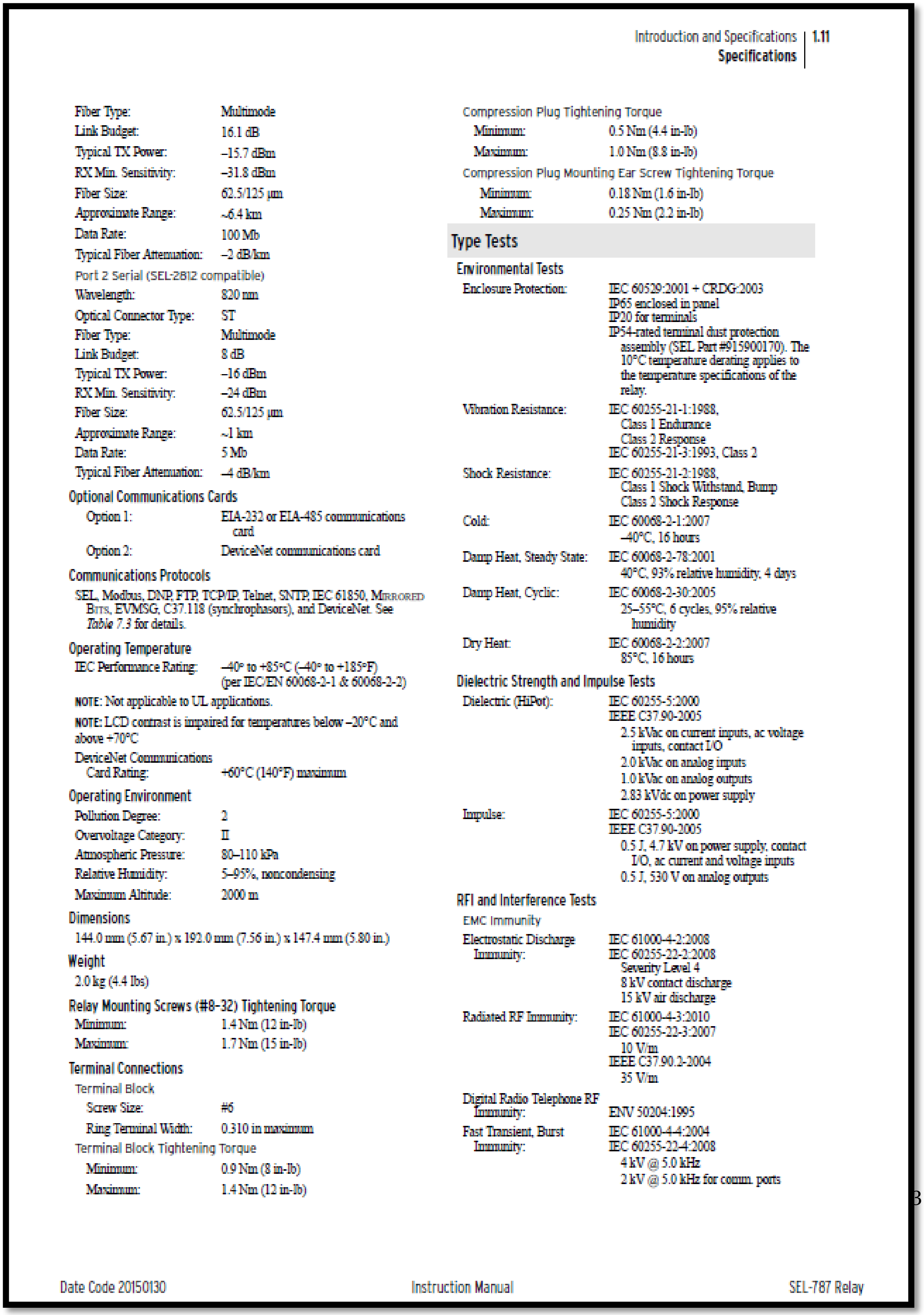
Cyclic (2.5 cycles/second) per IEC 60255-0-20:1974:

24 Vdc	0.75 A	L/R = 40 ms
48 Vdc	0.50 A	L/R = 40 ms
125 Vdc	0.30 A	L/R = 40 ms
250 Vdc	0.20 A	L/R = 40 ms

AC Output Ratings

Maximum Operational Voltage (U_e) Rating:	240 Vac
Insulation Voltage (U_i) Rating (excluding EN 61010-1):	300 Vac
Utilization Category:	AC-15 (control of electromagnetic loads > 72 VA)
Contact Rating Designation:	B300 (B = 5 A, 300 = rated insulation voltage)
Voltage Protection Across Open Contacts:	270 Vac, 40 J
Rated Operational Current (I_e):	3 A @ 120 Vac 1.5 A @ 240 Vac
Conventional Enclosed Thermal Current (I_{the}) Rating:	5 A
Rated Frequency:	50/60 ±5 Hz
Electrical Durability Make VA Rating:	3600 VA, cosϕ = 0.3
Electrical Durability Break VA Rating:	360 VA, cosϕ = 0.3

Date Code 20150130 Instruction Manual SEL-787 Relay



Fiber Type:	Multimode
Link Budget:	16.1 dB
Typical TX Power:	–15.7 dBm
RX Min. Sensitivity:	–31.8 dBm
Fiber Size:	62.5/125 µm
Approximate Range:	~6.4 km
Data Rate:	100 Mb
Typical Fiber Attenuation:	–2 dB/km

Port 2 Serial (SEL-2812 compatible)

Wavelength:	820 nm
Optical Connector Type:	ST
Fiber Type:	Multimode
Link Budget:	8 dB
Typical TX Power:	–16 dBm
RX Min. Sensitivity:	–24 dBm
Fiber Size:	62.5/125 µm
Approximate Range:	~1 km
Data Rate:	5 Mb
Typical Fiber Attenuation:	–4 dB/km

Optional Communications Cards

Option 1:	EIA-232 or EIA-485 communications card
Option 2:	DeviceNet communications card

Communications Protocols

SEL, Modbus, DNP, FTP, TCP/IP, Telnet, SNTP, IEC 61850, MIRRORED BITS, EVMSG, C37.118 (synchrophasors), and DeviceNet. See *Table 7.3* for details.

Operating Temperature

IEC Performance Rating:	–40° to +85°C (–40° to +185°F) (per IEC/EN 60068-2-1 & 60068-2-2)

NOTE: Not applicable to UL applications.

NOTE: LCD contrast is impaired for temperatures below –20°C and above +70°C

DeviceNet Communications Card Rating:	+60°C (140°F) maximum

Operating Environment

Pollution Degree:	2
Overvoltage Category:	II
Atmospheric Pressure:	80–110 kPa
Relative Humidity:	5–95%, noncondensing
Maximum Altitude:	2000 m

Dimensions

144.0 mm (5.67 in.) x 192.0 mm (7.56 in.) x 147.4 mm (5.80 in.)

Weight

2.0 kg (4.4 lbs)

Relay Mounting Screws (#8-32) Tightening Torque

Minimum:	1.4 Nm (12 in-lb)
Maximum:	1.7 Nm (15 in-lb)

Terminal Connections

Terminal Block

Screw Size:	#6
Ring Terminal Width:	0.310 in maximum

Terminal Block Tightening Torque

Minimum:	0.9 Nm (8 in-lb)
Maximum:	1.4 Nm (12 in-lb)

Compression Plug Tightening Torque

Minimum:	0.5 Nm (4.4 in-lb)
Maximum:	1.0 Nm (8.8 in-lb)

Compression Plug Mounting Ear Screw Tightening Torque

Minimum:	0.18 Nm (1.6 in-lb)
Maximum:	0.25 Nm (2.2 in-lb)

Type Tests

Environmental Tests

Enclosure Protection:	IEC 60529:2001 + CRDG:2003 IP65 enclosed in panel IP20 for terminals IP54-rated terminal dust protection assembly (SEL Part #915900170). The 10°C temperature derating applies to the temperature specifications of the relay.
Vibration Resistance:	IEC 60255-21-1:1988, Class 1 Endurance Class 2 Response IEC 60255-21-3:1993, Class 2
Shock Resistance:	IEC 60255-21-2:1988, Class 1 Shock Withstand, Bump Class 2 Shock Response
Cold:	IEC 60068-2-1:2007 –40°C, 16 hours
Damp Heat, Steady State:	IEC 60068-2-78:2001 40°C, 93% relative humidity, 4 days
Damp Heat, Cyclic:	IEC 60068-2-30:2005 25–55°C, 6 cycles, 95% relative humidity
Dry Heat:	IEC 60068-2-2:2007 85°C, 16 hours

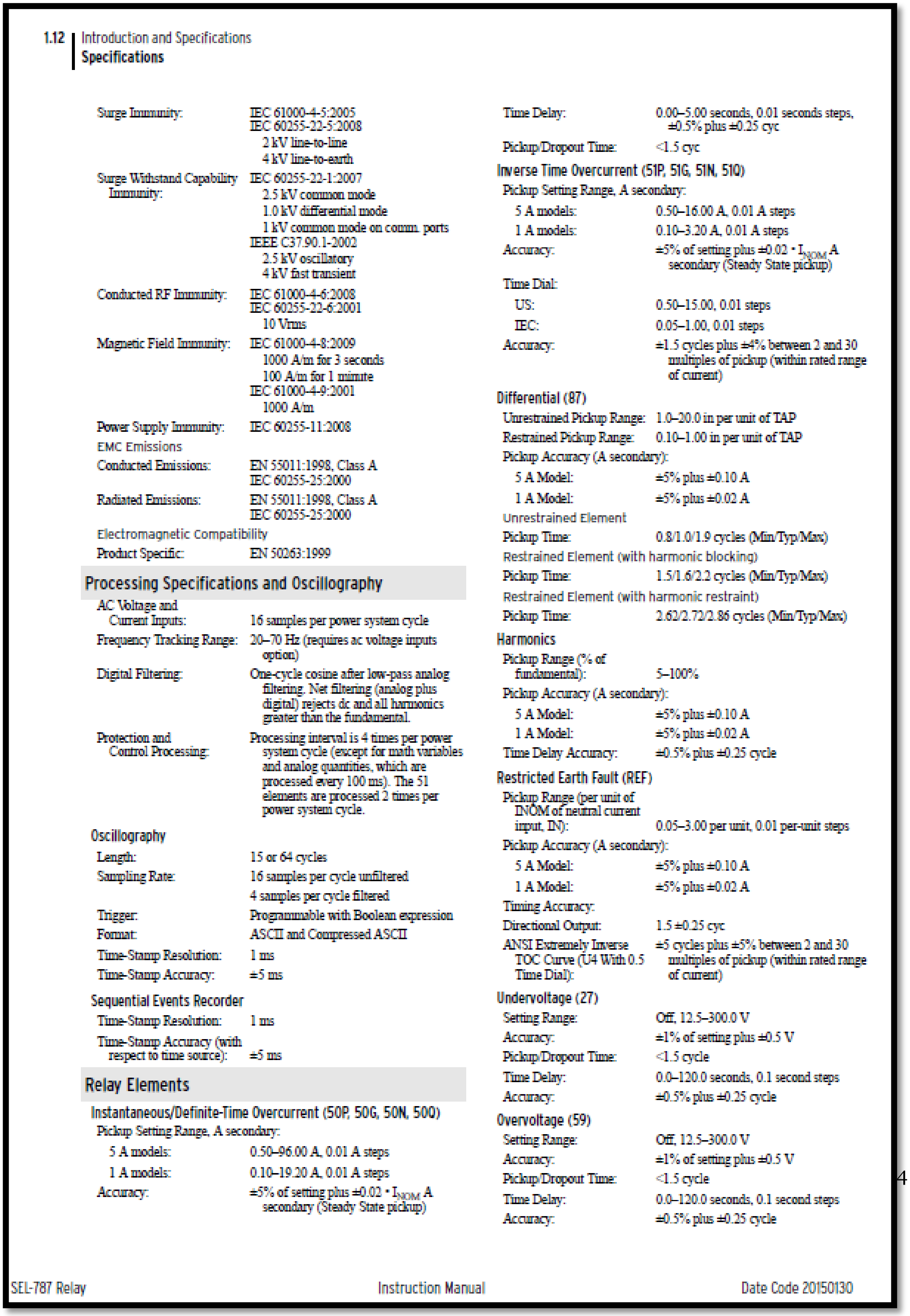
Dielectric Strength and Impulse Tests

Dielectric (HiPot):	IEC 60255-5:2000 IEEE C37.90-2005 2.5 kVac on current inputs, ac voltage inputs, contact I/O 2.0 kVac on analog inputs 1.0 kVac on analog outputs 2.83 kVdc on power supply
Impulse:	IEC 60255-5:2000 IEEE C37.90-2005 0.5 J, 4.7 kV on power supply, contact I/O, ac current and voltage inputs 0.5 J, 530 V on analog outputs

RFI and Interference Tests

EMC Immunity

Electrostatic Discharge Immunity:	IEC 61000-4-2:2008 IEC 60255-22-2:2008 Severity Level 4 8 kV contact discharge 15 kV air discharge
Radiated RF Immunity:	IEC 61000-4-3:2010 IEC 60255-22-3:2007 10 V/m IEEE C37.90.2-2004 35 V/m
Digital Radio Telephone RF Immunity:	ENV 50204:1995
Fast Transient, Burst Immunity:	IEC 61000-4-4:2004 IEC 60255-22-4:2008 4 kV @ 5.0 kHz 2 kV @ 5.0 kHz for comm. ports



Surge Immunity:	IEC 61000-4-5:2005 IEC 60255-22-5:2008 2 kV line-to-line 4 kV line-to-earth
Surge Withstand Capability Immunity:	IEC 60255-22-1:2007 2.5 kV common mode 1.0 kV differential mode 1 kV common mode on comm. ports IEEE C37.90.1-2002 2.5 kV oscillatory 4 kV fast transient
Conducted RF Immunity:	IEC 61000-4-6:2008 IEC 60255-22-6:2001 10 Vrms
Magnetic Field Immunity:	IEC 61000-4-8:2009 1000 A/m for 3 seconds 100 A/m for 1 minute IEC 61000-4-9:2001 1000 A/m
Power Supply Immunity:	IEC 60255-11:2008

EMC Emissions

Conducted Emissions:	EN 55011:1998, Class A IEC 60255-25:2000
Radiated Emissions:	EN 55011:1998, Class A IEC 60255-25:2000

Electromagnetic Compatibility

Product Specific:	EN 50263:1999

Processing Specifications and Oscillography

AC Voltage and Current Inputs:	16 samples per power system cycle
Frequency Tracking Range:	20–70 Hz (requires ac voltage inputs option)
Digital Filtering:	One-cycle cosine after low-pass analog filtering. Net filtering (analog plus digital) rejects dc and all harmonics greater than the fundamental.
Protection and Control Processing:	Processing interval is 4 times per power system cycle (except for math variables and analog quantities, which are processed every 100 ms). The 51 elements are processed 2 times per power system cycle.

Oscillography

Length:	15 or 64 cycles
Sampling Rate:	16 samples per cycle unfiltered 4 samples per cycle filtered
Trigger:	Programmable with Boolean expression
Format:	ASCII and Compressed ASCII
Time-Stamp Resolution:	1 ms
Time-Stamp Accuracy:	±5 ms

Sequential Events Recorder

Time-Stamp Resolution:	1 ms
Time-Stamp Accuracy (with respect to time source):	±5 ms

Relay Elements

Instantaneous/Definite-Time Overcurrent (50P, 50G, 50N, 50Q)

Pickup Setting Range, A secondary:	
5 A models:	0.50–96.00 A, 0.01 A steps
1 A models:	0.10–19.20 A, 0.01 A steps
Accuracy:	±5% of setting plus ±0.02 • I_{NOM} A secondary (Steady State pickup)
Time Delay:	0.00–5.00 seconds, 0.01 seconds steps, ±0.5% plus ±0.25 cyc
Pickup/Dropout Time:	<1.5 cyc

Inverse Time Overcurrent (51P, 51G, 51N, 51Q)

Pickup Setting Range, A secondary:	
5 A models:	0.50–16.00 A, 0.01 A steps
1 A models:	0.10–3.20 A, 0.01 A steps
Accuracy:	±5% of setting plus ±0.02 • I_{NOM} A secondary (Steady State pickup)
Time Dial:	
US:	0.50–15.00, 0.01 steps
IEC:	0.05–1.00, 0.01 steps
Accuracy:	±1.5 cycles plus ±4% between 2 and 30 multiples of pickup (within rated range of current)

Differential (87)

Unrestrained Pickup Range:	1.0–20.0 in per unit of TAP
Restrained Pickup Range:	0.10–1.00 in per unit of TAP
Pickup Accuracy (A secondary):	
5 A Model:	±5% plus ±0.10 A
1 A Model:	±5% plus ±0.02 A

Unrestrained Element

Pickup Time:	0.8/1.0/1.9 cycles (Min/Typ/Max)

Restrained Element (with harmonic blocking)

Pickup Time:	1.5/1.6/2.2 cycles (Min/Typ/Max)

Restrained Element (with harmonic restraint)

Pickup Time:	2.62/2.72/2.86 cycles (Min/Typ/Max)

Harmonics

Pickup Range (% of fundamental):	5–100%
Pickup Accuracy (A secondary):	
5 A Model:	±5% plus ±0.10 A
1 A Model:	±5% plus ±0.02 A
Time Delay Accuracy:	±0.5% plus ±0.25 cycle

Restricted Earth Fault (REF)

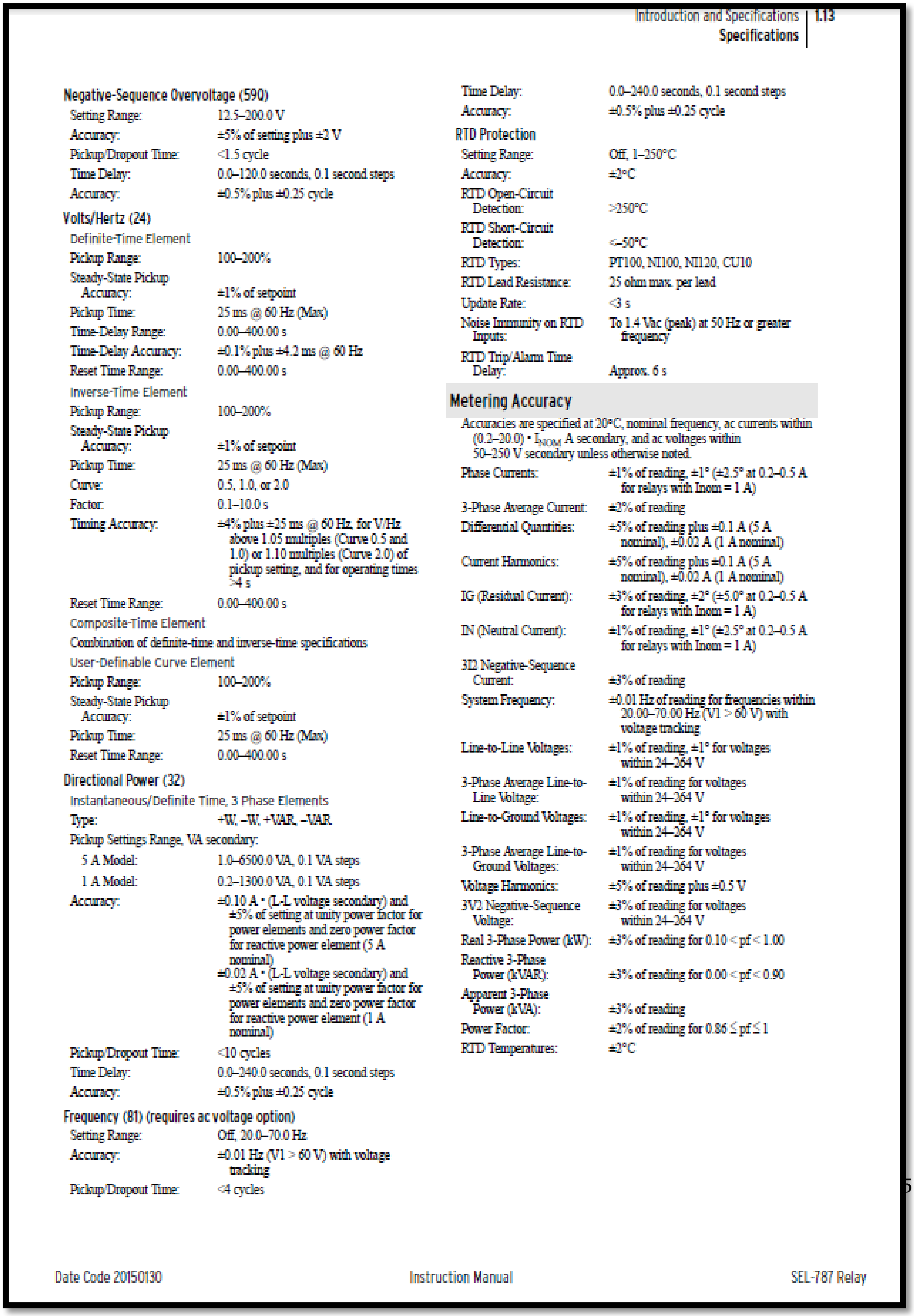
Pickup Range (per unit of INOM of neutral current input, IN):	0.05–3.00 per unit, 0.01 per-unit steps
Pickup Accuracy (A secondary):	
5 A Model:	±5% plus ±0.10 A
1 A Model:	±5% plus ±0.02 A
Timing Accuracy:	
Directional Output:	1.5 ±0.25 cyc
ANSI Extremely Inverse TOC Curve (U4 With 0.5 Time Dial):	±5 cycles plus ±5% between 2 and 30 multiples of pickup (within rated range of current)

Undervoltage (27)

Setting Range:	Off, 12.5–300.0 V
Accuracy:	±1% of setting plus ±0.5 V
Pickup/Dropout Time:	<1.5 cycle
Time Delay:	0.0–120.0 seconds, 0.1 second steps
Accuracy:	±0.5% plus ±0.25 cycle

Overvoltage (59)

Setting Range:	Off, 12.5–300.0 V
Accuracy:	±1% of setting plus ±0.5 V
Pickup/Dropout Time:	<1.5 cycle
Time Delay:	0.0–120.0 seconds, 0.1 second steps
Accuracy:	±0.5% plus ±0.25 cycle



Negative-Sequence Overvoltage (59Q)

Setting Range:	12.5–200.0 V
Accuracy:	±5% of setting plus ±2 V
Pickup/Dropout Time:	<1.5 cycle
Time Delay:	0.0–120.0 seconds, 0.1 second steps
Accuracy:	±0.5% plus ±0.25 cycle

Volts/Hertz (24)

Definite-Time Element

Pickup Range:	100–200%
Steady-State Pickup Accuracy:	±1% of setpoint
Pickup Time:	25 ms @ 60 Hz (Max)
Time-Delay Range:	0.00–400.00 s
Time-Delay Accuracy:	±0.1% plus ±4.2 ms @ 60 Hz
Reset Time Range:	0.00–400.00 s

Inverse-Time Element

Pickup Range:	100–200%
Steady-State Pickup Accuracy:	±1% of setpoint
Pickup Time:	25 ms @ 60 Hz (Max)
Curve:	0.5, 1.0, or 2.0
Factor:	0.1–10.0 s
Timing Accuracy:	±4% plus ±25 ms @ 60 Hz, for V/Hz above 1.05 multiples (Curve 0.5 and 1.0) or 1.10 multiples (Curve 2.0) of pickup setting, and for operating times >4 s
Reset Time Range:	0.00–400.00 s

Composite-Time Element

Combination of definite-time and inverse-time specifications

User-Definable Curve Element

Pickup Range:	100–200%
Steady-State Pickup Accuracy:	±1% of setpoint
Pickup Time:	25 ms @ 60 Hz (Max)
Reset Time Range:	0.00–400.00 s

Directional Power (32)

Instantaneous/Definite Time, 3 Phase Elements

Type:	+W, –W, +VAR, –VAR
Pickup Settings Range, VA secondary:	
5 A Model:	1.0–6500.0 VA, 0.1 VA steps
1 A Model:	0.2–1300.0 VA, 0.1 VA steps
Accuracy:	±0.10 A • (L-L voltage secondary) and ±5% of setting at unity power factor for power elements and zero power factor for reactive power element (5 A nominal) ±0.02 A • (L-L voltage secondary) and ±5% of setting at unity power factor for power elements and zero power factor for reactive power element (1 A nominal)
Pickup/Dropout Time:	<10 cycles
Time Delay:	0.0–240.0 seconds, 0.1 second steps
Accuracy:	±0.5% plus ±0.25 cycle

Frequency (81) (requires ac voltage option)

Setting Range:	Off, 20.0–70.0 Hz
Accuracy:	±0.01 Hz (V1 > 60 V) with voltage tracking
Pickup/Dropout Time:	<4 cycles
Time Delay:	0.0–240.0 seconds, 0.1 second steps
Accuracy:	±0.5% plus ±0.25 cycle

RTD Protection

Setting Range:	Off, 1–250°C
Accuracy:	±2°C
RTD Open-Circuit Detection:	>250°C
RTD Short-Circuit Detection:	<–50°C
RTD Types:	PT100, NI100, NI120, CU10
RTD Lead Resistance:	25 ohm max. per lead
Update Rate:	<3 s
Noise Immunity on RTD Inputs:	To 1.4 Vac (peak) at 50 Hz or greater frequency
RTD Trip/Alarm Time Delay:	Approx. 6 s

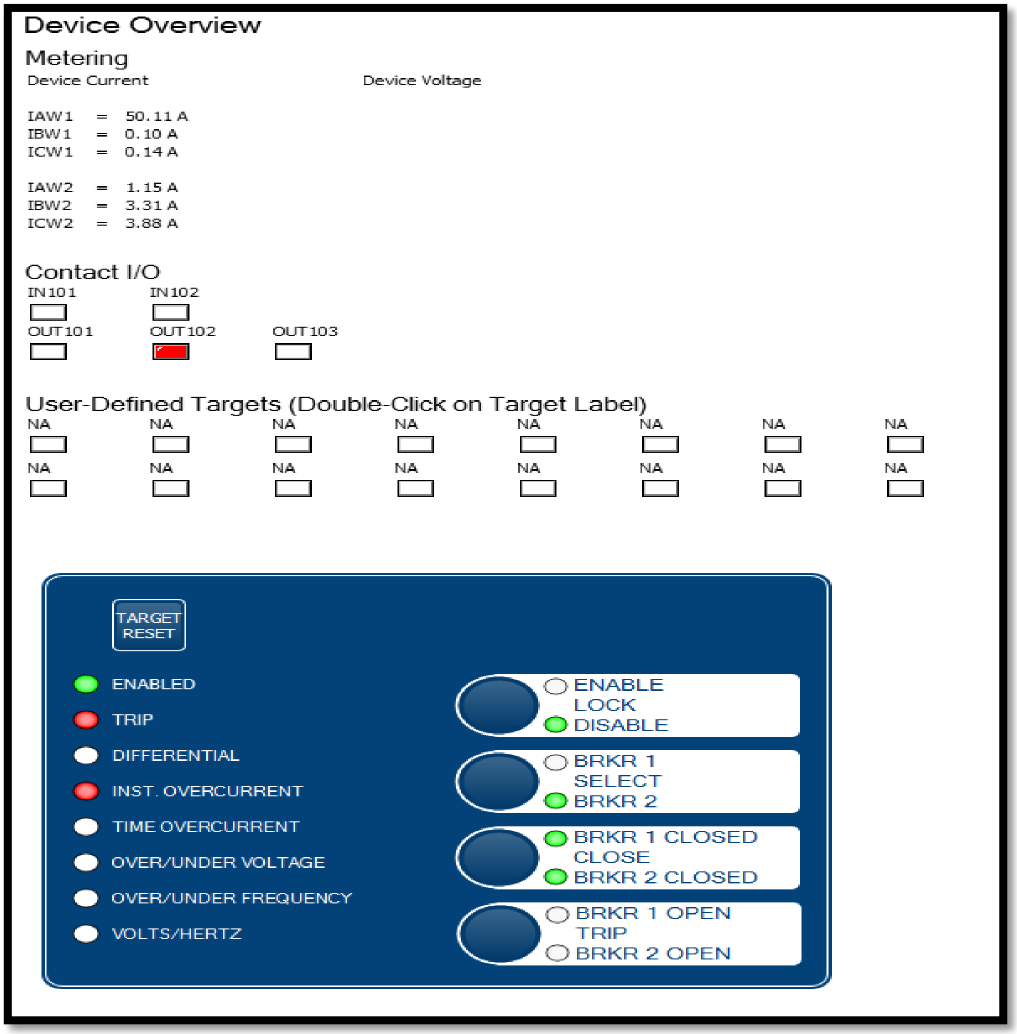
Metering Accuracy

Accuracies are specified at 20°C, nominal frequency, ac currents within $(0.2–20.0) \cdot I_{NOM}$ A secondary, and ac voltages within 50–250 V secondary unless otherwise noted.

Phase Currents:	±1% of reading, ±1° (±2.5° at 0.2–0.5 A for relays with Inom = 1 A)
3-Phase Average Current:	±2% of reading
Differential Quantities:	±5% of reading plus ±0.1 A (5 A nominal), ±0.02 A (1 A nominal)
Current Harmonics:	±5% of reading plus ±0.1 A (5 A nominal), ±0.02 A (1 A nominal)
IG (Residual Current):	±3% of reading, ±2° (±5.0° at 0.2–0.5 A for relays with Inom = 1 A)
IN (Neutral Current):	±1% of reading, ±1° (±2.5° at 0.2–0.5 A for relays with Inom = 1 A)
3I2 Negative-Sequence Current:	±3% of reading
System Frequency:	±0.01 Hz of reading for frequencies within 20.00–70.00 Hz (V1 > 60 V) with voltage tracking
Line-to-Line Voltages:	±1% of reading, ±1° for voltages within 24–264 V
3-Phase Average Line-to-Line Voltage:	±1% of reading for voltages within 24–264 V
Line-to-Ground Voltages:	±1% of reading, ±1° for voltages within 24–264 V
3-Phase Average Line-to-Ground Voltages:	±1% of reading for voltages within 24–264 V
Voltage Harmonics:	±5% of reading plus ±0.5 V
3V2 Negative-Sequence Voltage:	±3% of reading for voltages within 24–264 V
Real 3-Phase Power (kW):	±3% of reading for 0.10 < pf < 1.00
Reactive 3-Phase Power (kVAR):	±3% of reading for 0.00 < pf < 0.90
Apparent 3-Phase Power (kVA):	±3% of reading
Power Factor:	±2% of reading for 0.86 ≤ pf ≤ 1
RTD Temperatures:	±2°C

14.4 Appendix D Overcurrent protection element simulation results

Ascelerator human machine interface



Device Overview

Metering

Device Current

IAW1 = 50.11 A
IBW1 = 0.10 A
ICW1 = 0.14 A

IAW2 = 1.15 A
IBW2 = 3.31 A
ICW2 = 3.88 A

Device Voltage

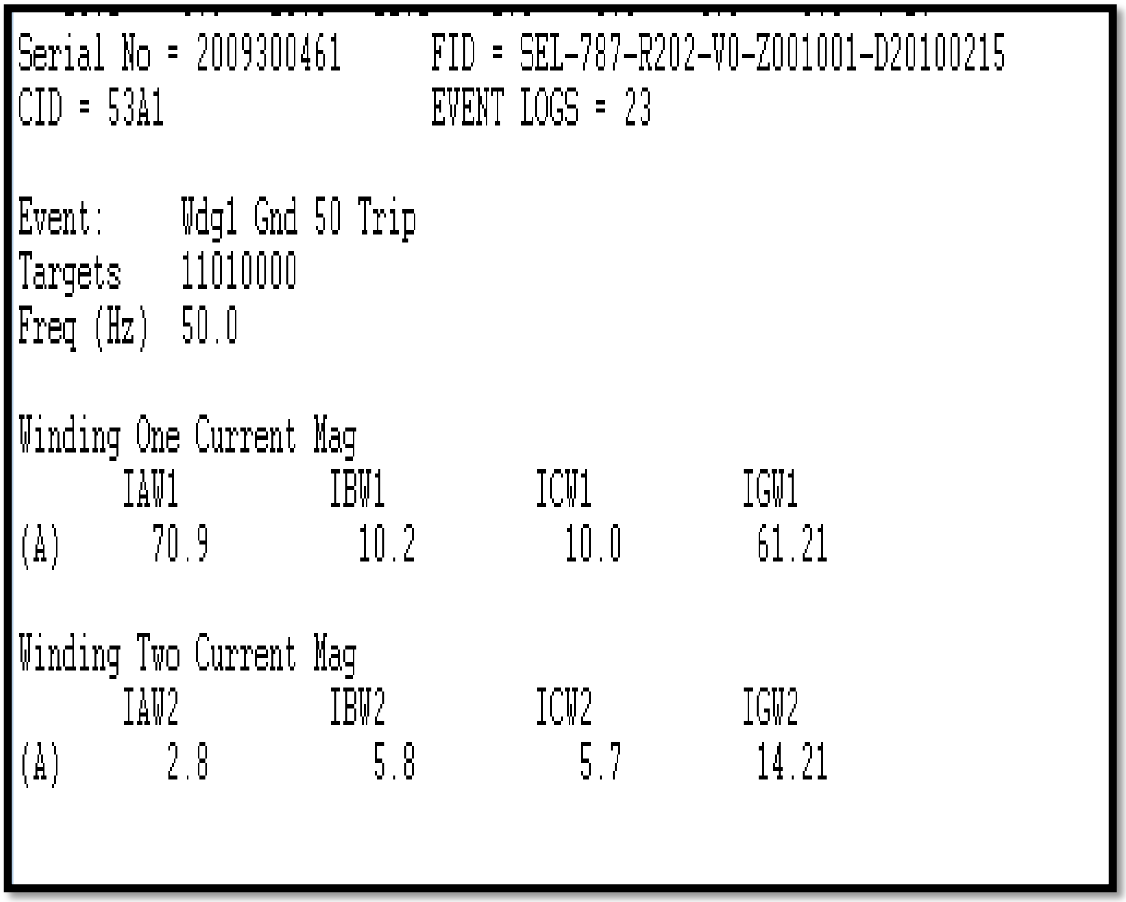
Contact I/O

IN101 ☐
IN102 ☐
OUT101 ☐
OUT102 🟥
OUT103 ☐

User-Defined Targets (Double-Click on Target Label)

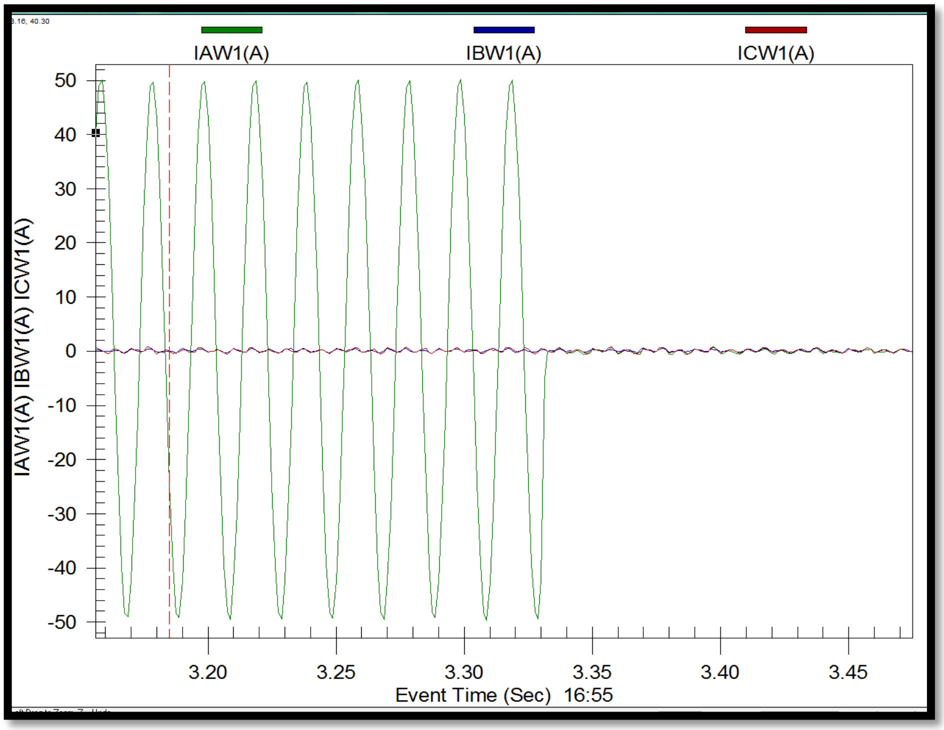
Relay front panel indication

Event summary verifying operation



```
Serial No = 2009300461     FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                 EVENT LOGS = 23

Event:     Wdg1 Gnd 50 Trip
Targets    11010000
Freq (Hz)  50.0

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)      70.9          10.2          10.0         61.21

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       2.8           5.8           5.7         14.21
```

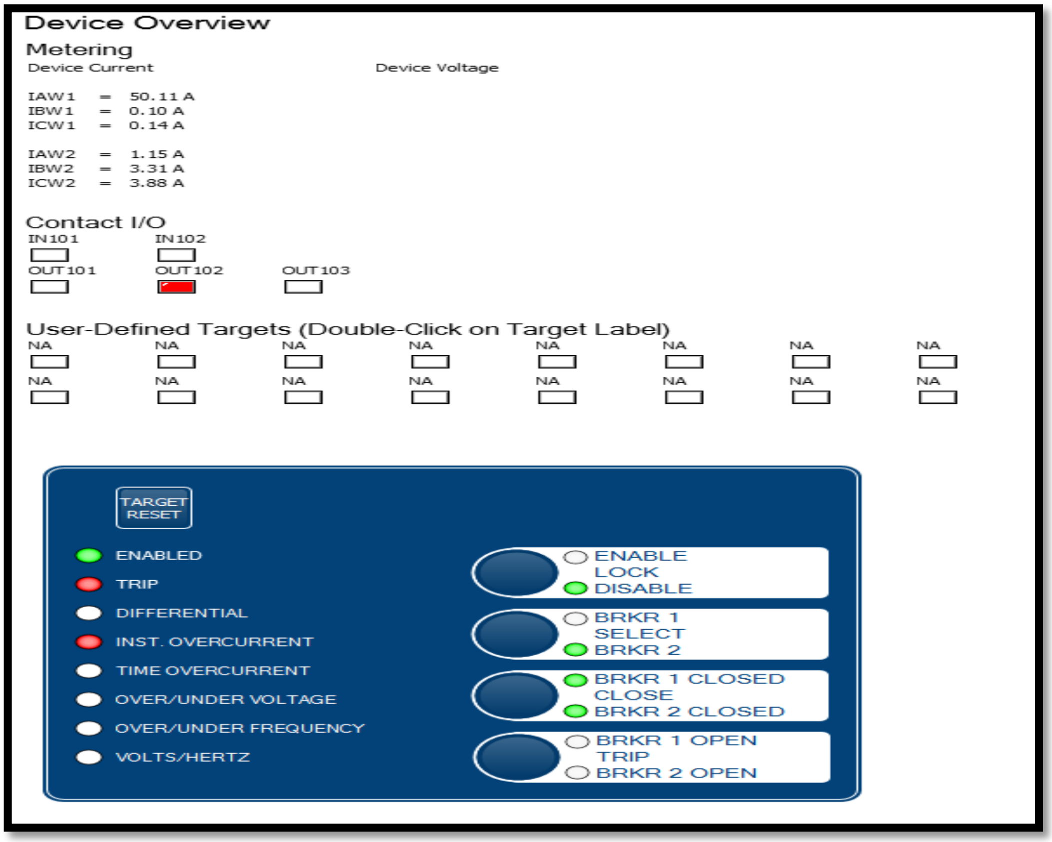
Event Oscillograph



14.5 Appendix E Negative Sequence element simulation results

Relay front panel indication

Ascelerator Human machine Interface



Device Overview

Metering

Device Current

Device Voltage

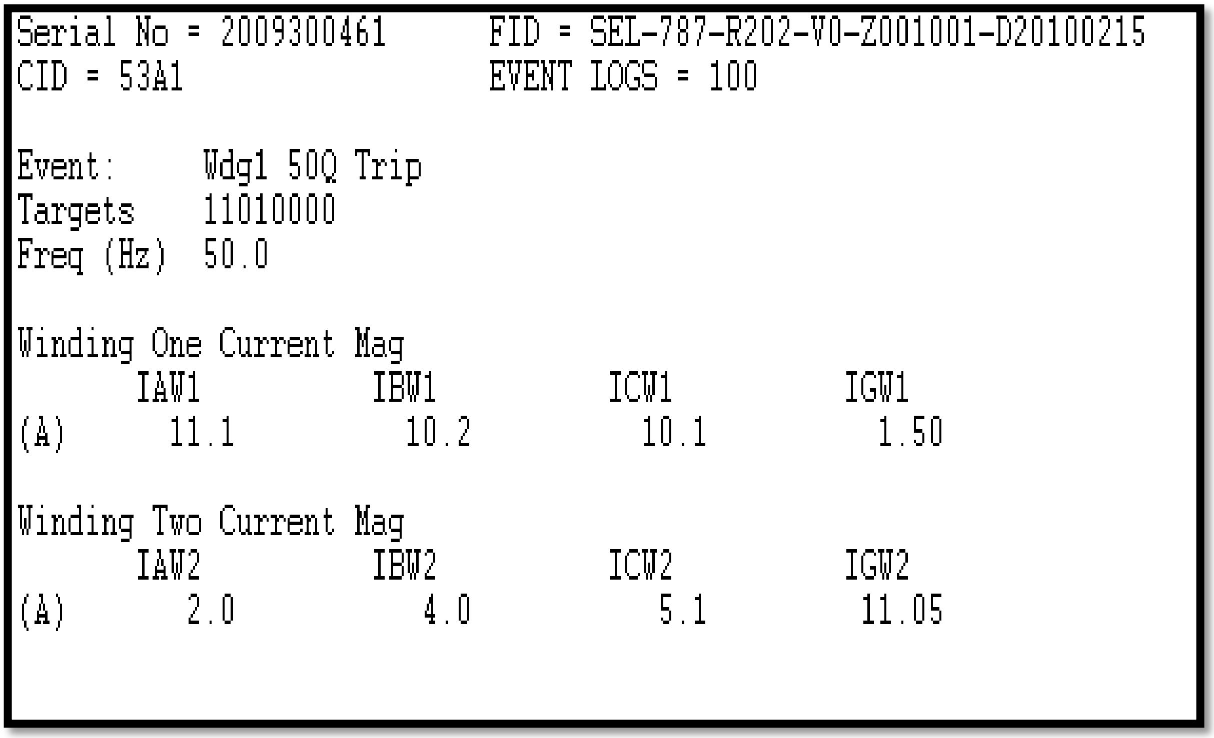
IAW1 = 50.11 A
IBW1 = 0.10 A
ICW1 = 0.14 A

IAW2 = 1.15 A
IBW2 = 3.31 A
ICW2 = 3.88 A

Contact I/O

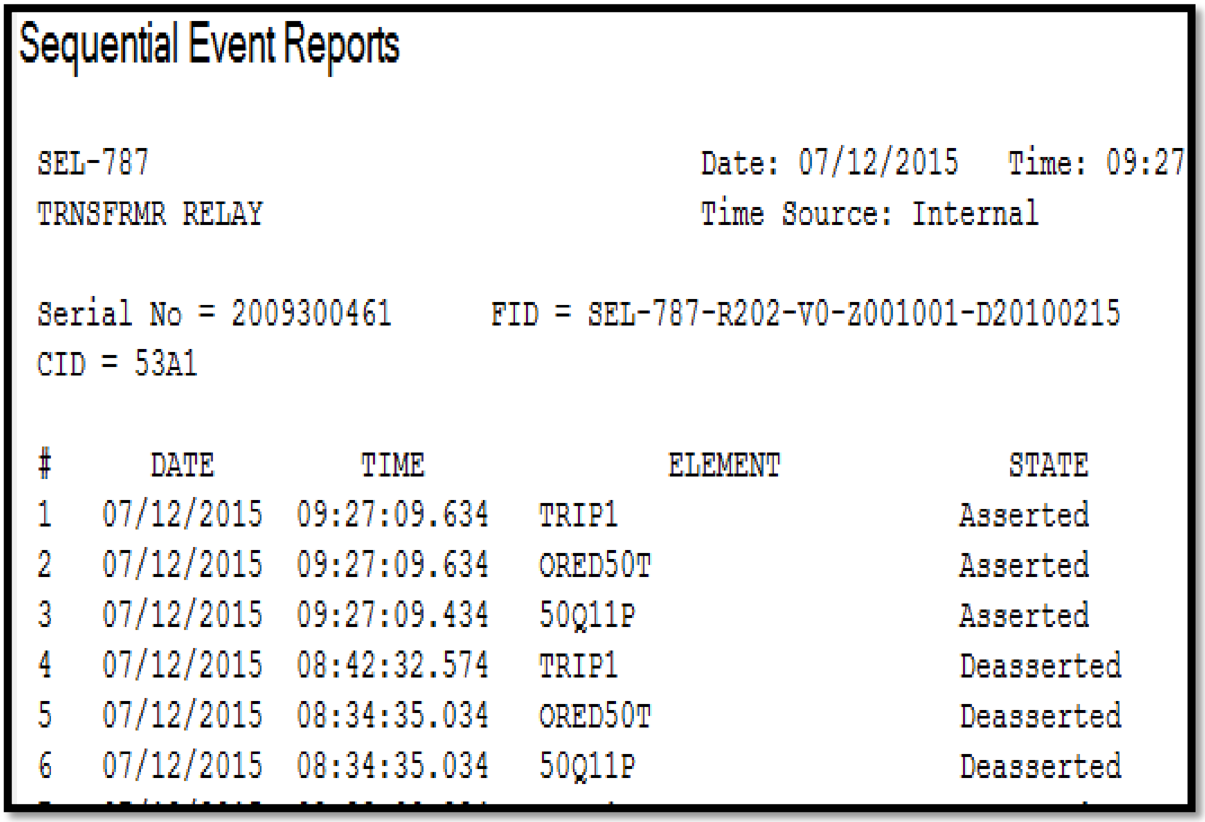
User-Defined Targets (Double-Click on Target Label)

Event summary verifying operation



```
Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  EVENT LOGS = 100

Event:     Wdg1 50Q Trip
Targets    11010000
Freq (Hz)  50.0

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)      11.1          10.2          10.1          1.50

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       2.0           4.0           5.1         11.05
```

Sequential Event Report



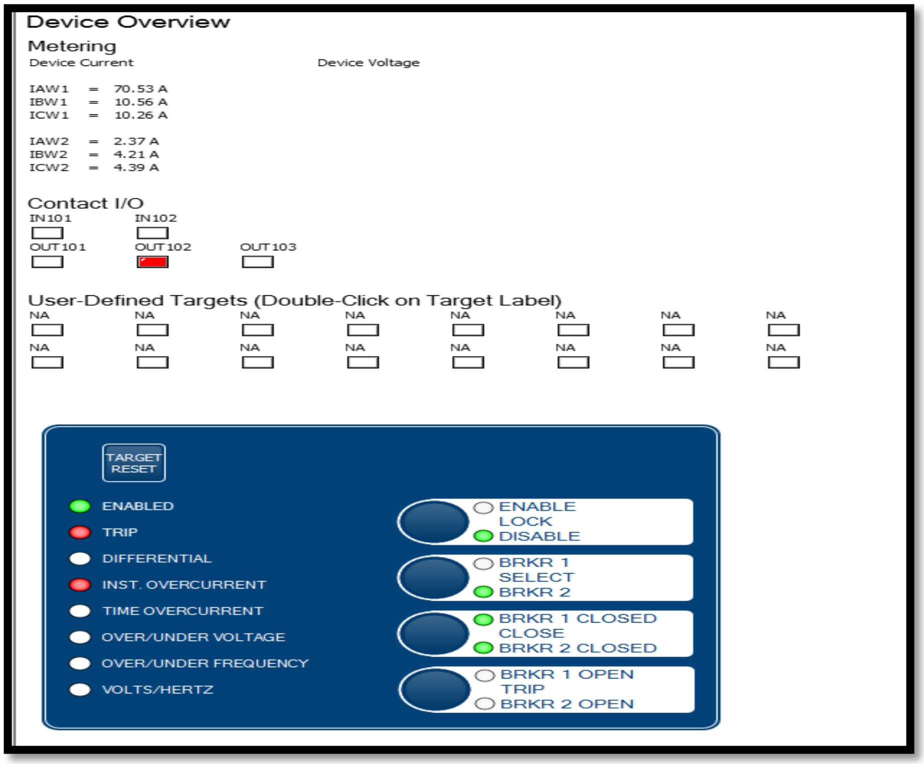
Sequential Event Reports

```
SEL-787                                   Date: 07/12/2015   Time: 09:27
TRNSFRMR RELAY                            Time Source: Internal

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1

#     DATE          TIME                ELEMENT                 STATE
1   07/12/2015  09:27:09.634   TRIP1                         Asserted
2   07/12/2015  09:27:09.634   ORED50T                       Asserted
3   07/12/2015  09:27:09.434   50Q11P                        Asserted
4   07/12/2015  08:42:32.574   TRIP1                         Deasserted
5   07/12/2015  08:34:35.034   ORED50T                       Deasserted
6   07/12/2015  08:34:35.034   50Q11P                        Deasserted
```

14.6 Appendix G Residual Ground (50G) element simulation results

Relay front panel indication

Ascelerator human to machine interface



Device Overview

Metering

Device Current

IAW1 = 70.53 A
IBW1 = 10.56 A
ICW1 = 10.26 A

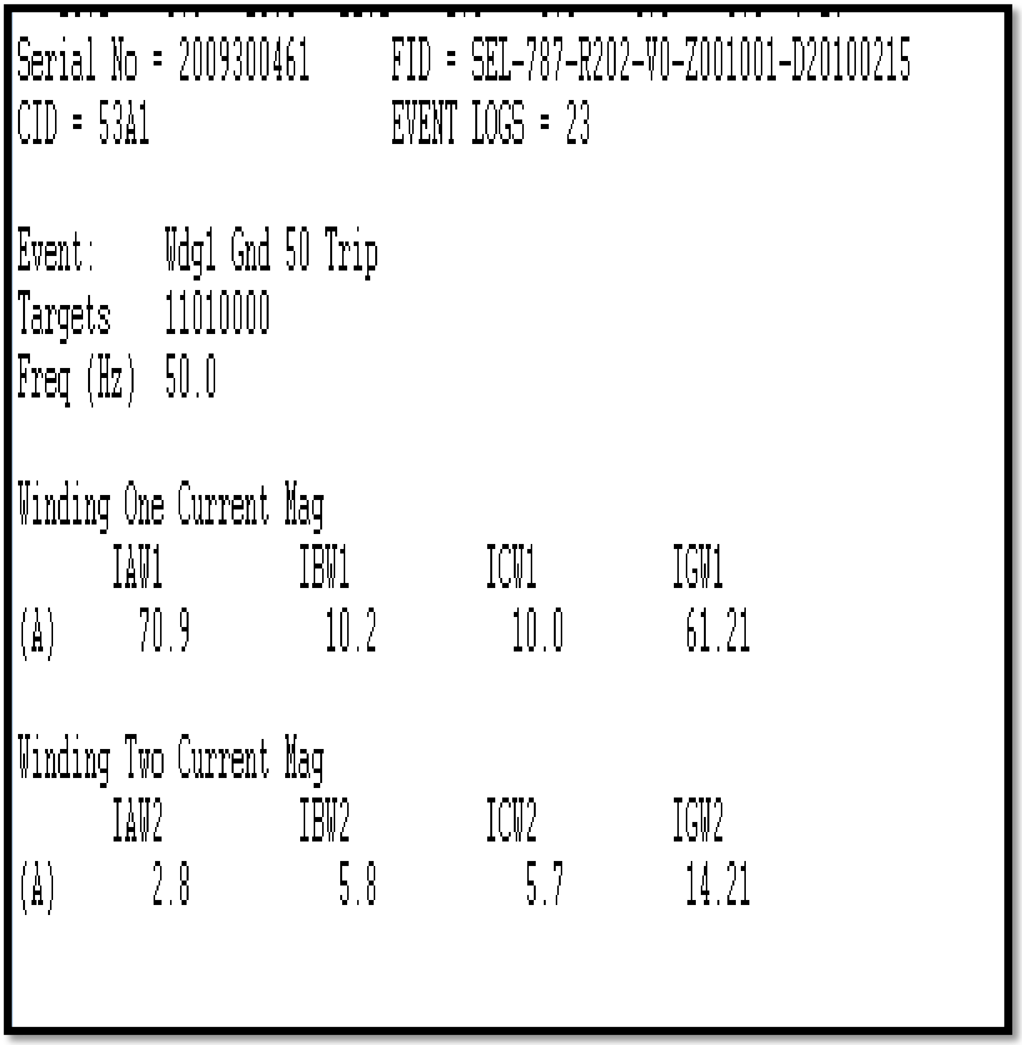
IAW2 = 2.37 A
IBW2 = 4.21 A
ICW2 = 4.39 A

Device Voltage

Contact I/O

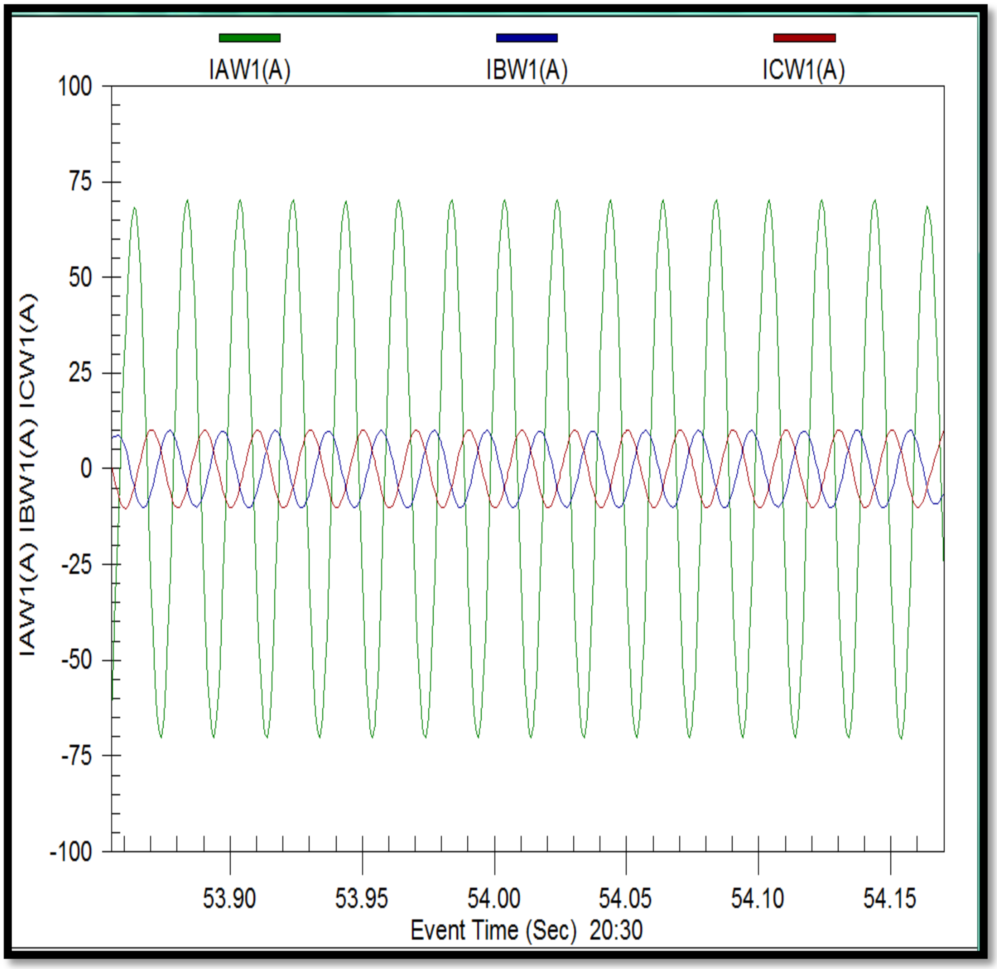
User-Defined Targets (Double-Click on Target Label)

Event summary verifying operation



```
Serial No = 2009300461     FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                 EVENT LOGS = 23

Event:     Wdg1 Gnd 50 Trip
Targets    11010000
Freq (Hz)  50.0

Winding One Current Mag
       IAW1         IBW1         ICW1         IGW1
(A)      70.9         10.2         10.0        61.21

Winding Two Current Mag
       IAW2         IBW2         ICW2         IGW2
(A)       2.8          5.8          5.7        14.21
```

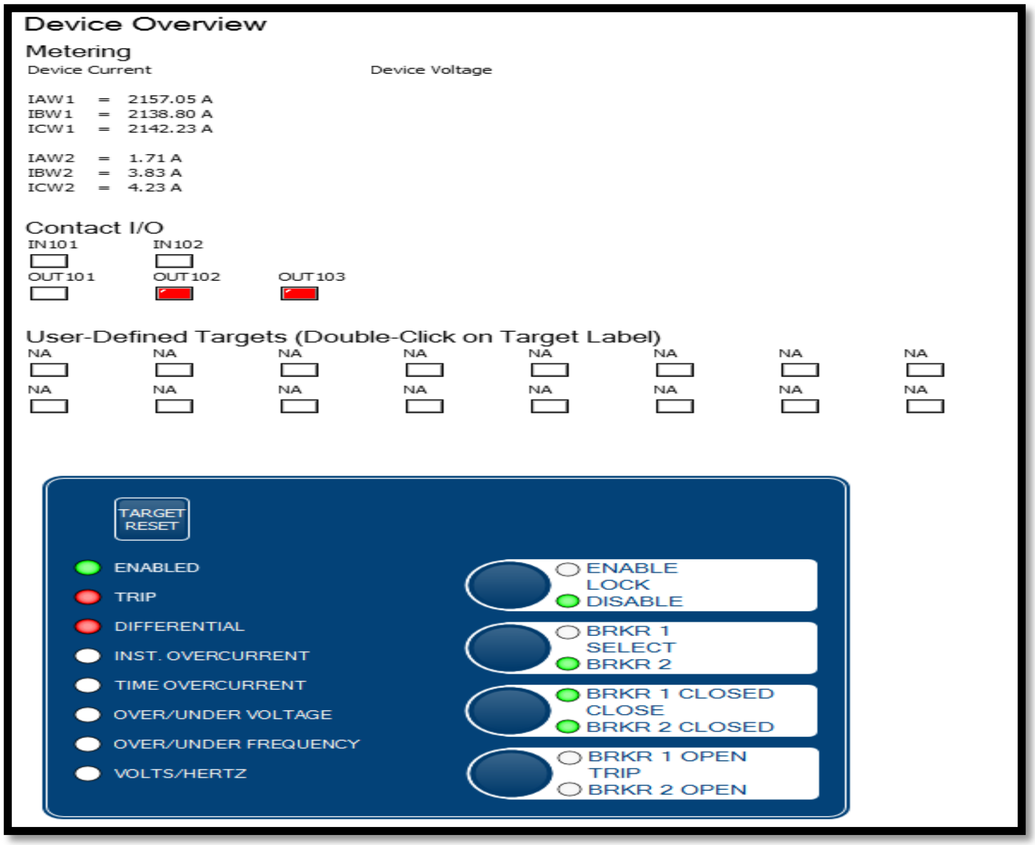
Event Oscillograph



14.7 Appendix G Unrestrained differential protection (87) element simulation results

Relay front panel indication

Ascelerator human to machine interface



Device Overview

Metering

Device Current

Device Voltage

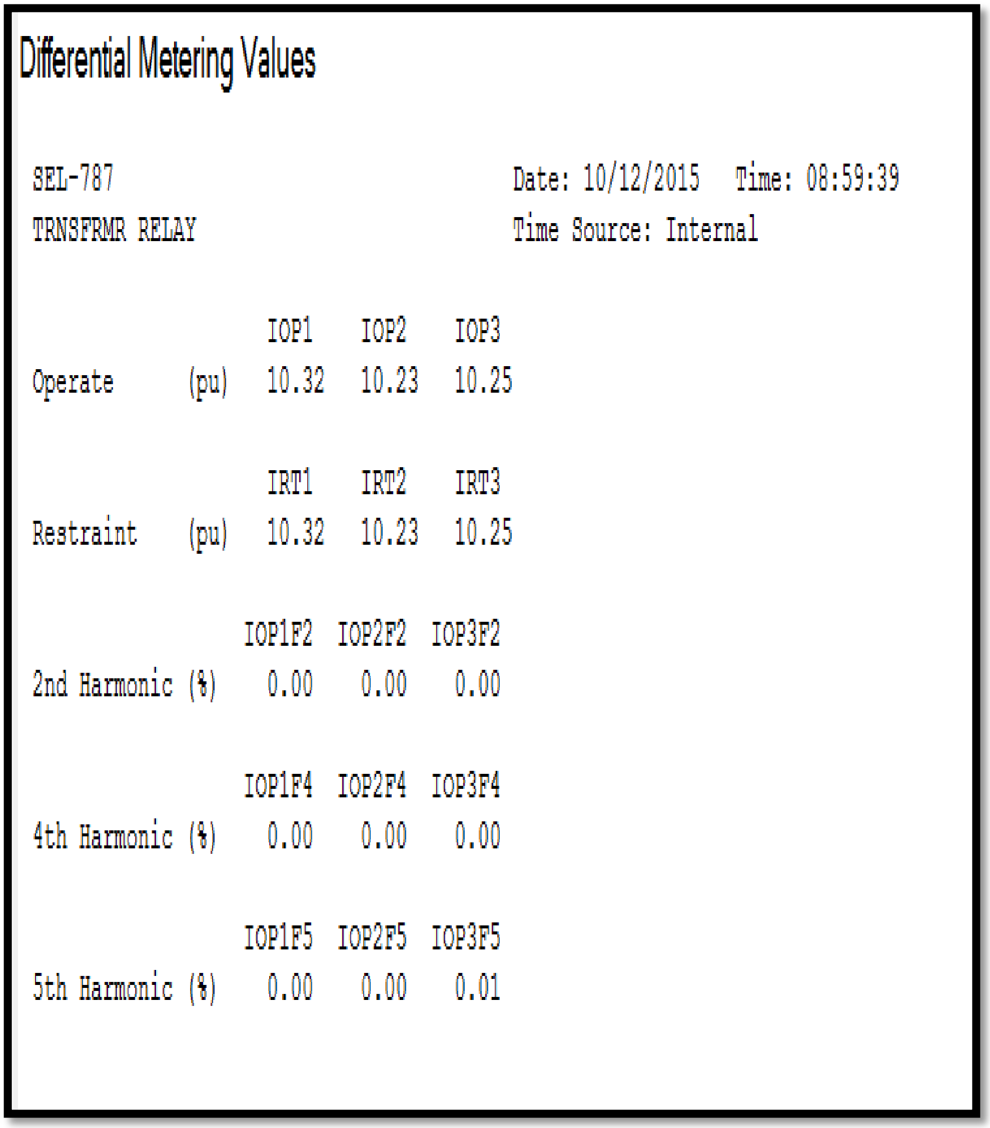
IAW1 = 2157.05 A
IBW1 = 2138.80 A
ICW1 = 2142.23 A

IAW2 = 1.71 A
IBW2 = 3.83 A
ICW2 = 4.23 A

Contact I/O

User-Defined Targets (Double-Click on Target Label)

Event summary verifying operation



Differential Metering Values

```
SEL-787                              Date: 10/12/2015   Time: 08:59:39
TRNSFRMR RELAY                       Time Source: Internal

                    IOP1    IOP2    IOP3
Operate       (pu)  10.32   10.23   10.25

                    IRT1    IRT2    IRT3
Restraint     (pu)  10.32   10.23   10.25

                  IOP1F2  IOP2F2  IOP3F2
2nd Harmonic (%)    0.00    0.00    0.00

                  IOP1F4  IOP2F4  IOP3F4
4th Harmonic (%)    0.00    0.00    0.00

                  IOP1F5  IOP2F5  IOP3F5
5th Harmonic (%)    0.00    0.00    0.01
```

Event Oscillograph