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SEL Protection and Monitoring System

"A report submitted to the School of Engineering and Information Technology, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering."

Nicholas Kilburn

Supervisor:
A/Prof Graeme Cole

Associate Supervisor:
Dr Greg Crebbin

Abstract

The protection of power distribution and transmission systems is a critical application in ensuring safe, reliable and efficient supply of electricity to the consumers. The protection allows for the mitigation of damage due to various network faults, preventing equipment damage and reducing downtime that can often result.

Within the University there is a collection of digital protective relays manufactured by Schweitzer Engineering Laboratories, where the functionality, requirements and operational knowledge of the available devices remains largely unknown. Thus this thesis was tasked with drawing out this knowledge and providing a means of demonstrating the functions of the available devices.

In order to develop this understanding the project was divided into several components; familiarisation, investigation, Simulator development and operations testing.

The familiarisation and investigation components of the project allowed for acquisition of the required level of knowledge about the devices to enable development of a suitable Simulation platform to demonstrate the functional operations and applications of the available devices. This portion of the project yielded the required details about the scope of the protective functionality, the mechanisms and requirements to program this functionality and the operation requirements. This resulted in the construction of a hardware based Simulation platform, provided through Lab-Volt equipment, demonstrating the functional capability of the Transformer Protection Relay. The testing component provided a mechanism to ensure that the simulation and relay would demonstrate the available functionality as expected.

The simulation platform can be used to demonstrate the overcurrent and differential protection functionality along with providing an operable insight into the relay monitoring and metering capabilities. Hardware limitations prevented a truly realistic simulation being developed and tested, notably the low fault levels and restricted fault types available. However the construction of this Simulator has demonstrated the acquired knowledge of the relays and provided the groundwork to extend the Simulator to incorporate further relays and protective functionality.

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1. Project Introduction

1.1 Background

Currently at Murdoch University within the Project Room of the Engineering and Energy Building, there is a collection of various SEL protective relay devices that remained an unknown entity until semester 1 2012, when the ENG454 students began investigating the devices. At that point in time knowledge of how these devices worked and what functionality they could provide was unknown, thus the ENG454 students began investigations into the devices. As a part of this exercise the students collected and organized the various instruction manuals, implemented an enclosure to securely mount the devices, installed the required software on associated Computer and began developing a NI LabView cDAQ simulation system. This system was to simulate a simple distribution network and a variety of different fault conditions to demonstrate operation of the devices. The network illustrated in Figure 1 depicts the intended simulated system, including the SEL units, as originally designed by Brenton Sherston and Simon Digby [1] in the final stage of the ENG454 unit.

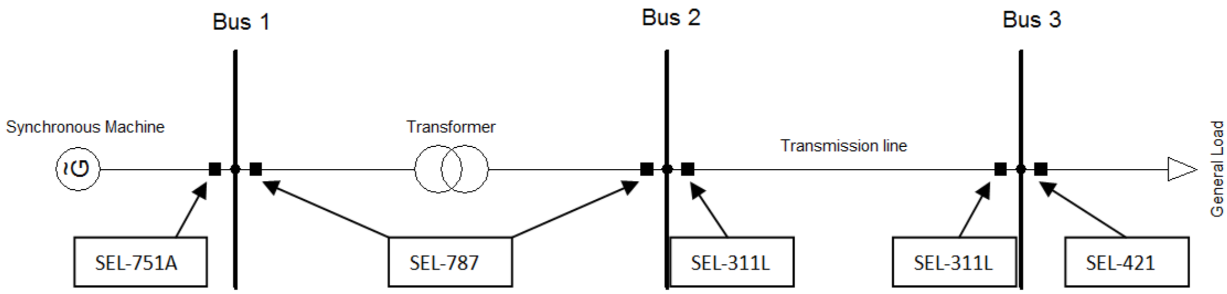

Figure 1 - Designed Simulation Network

Following the completion of ENG454 in semester 1 2012, the final simulation remained incomplete and most of the required knowledge regarding the functionality of the SEL devices remained unknown or improperly defined. The current state of the SEL Protection and Monitoring System is illustrated in Figure 2, showing all the relays mounted in their enclosure and the associated PC with required AcSELerator Quickset software installed in the Project Room. Not visible is the cDAQ, power supplies and I/O terminals, which are accessible from the rear of the retrofitted IP network server rack.

Figure 2 - SEL Protection and Monitoring Rack

1.2 Purpose

The SEL devices are intended for protection of high voltage distribution networks and all equipment types, including transformers, bus bars, feeders etc. As such, they offer a wide variety of different protection functionalities which, in some cases are quite complicated. Having a limited knowledge of the functionality and the requirements (wiring, programing and commissioning) to achieve this functionality makes the development of a suitable distribution protection simulation difficult and nearly impossible to achieve.

1.3 Objectives

The Primary Objective of this project is to continue on from the works conducted in ENG454 to develop a comprehensive understanding of the SEL devices to allow development of a suitable simulation platform to demonstrate the functionality that the SEL protection devices are capable of providing. This is to be achieved through the following steps:

- Acquire a comprehensive understanding of the available SEL protection equipment, including functionality, programing requirements, physical hardware, wiring and power requirements and any other necessities for successful operation.
- Develop/improve a suitable simulation platform, be it LabView or physical hardware based, of a basic power distribution system that can demonstrate the operational functionality of the available SEL protection relays.
- Produce documentation that details the processes required to design, program and operate simulations that demonstrate desired functionalities.

2. Protection Relays

2.1 Purpose

The protection of power distribution systems is and always has been a critical element in maintaining a stable network for power generation, transmission and consumption. Protection Relays allow the integrity of the distribution equipment, such as transformers, generators and transmission lines to be maintained to a high operational standard, improving supply and reliability and achieving almost 100% availability of electrical power to consumers. Protective Relays provide protection from fault events by opening circuit breakers, which isolate the equipment from the fault; the relay will also trip the circuit breakers if the equipment is the cause of the fault thereby protecting the network from damage. The relays constantly monitor the necessary network elements, including Current and Voltage, and occasionally temperature or harmonics among others. The implementation of these relays depends upon the protection function and the equipment that needs to be protected. The relays measure the network elements (current and voltage) through step-down CT's and VT's and their operations are based upon the secondary magnitude, which allows the relays to be of a manageable size and achieve the quickest possible operating time. The relays will trip the circuit breakers when the monitored elements reach a pre-set value indicative of a potential fault event, thus protecting the equipment from the damages that could result if the fault persists.

2.2 Analog Relays

2.2.1 Electromechanical

Traditionally Protective relays are an analog type electromechanical device designed to measure and calculate network nominal operation conditions and to trip circuit breakers, thereby disconnecting the network, when a fault is detected. These electromechanical relays have well defined and selectable operation parameters based upon the protection function to which the relay belongs. These relays operate directly from the current and voltage signals being supplied and converting these into electric or magnetic forces/torques, via electromagnetic coils, which acts against internal springs to open the relays. The configuration of these relays is conducted by adjusting the tension of the spring and/or taping of the electromagnetic coils thus changing the trip characteristic of the relay. Mechanical relays in general have developed a reputation of being highly accurate, dependable and reliable [2]. Figure 3 shows an example of a traditional electromechanical protection relay as installed in its electrical cabinet; this particular relay is an overcurrent protection relay (type 50), used in this instance to protect local generators. The black blocks below and above the relays are test points that allow isolation of the relays from the equipment for testing. This prevents the test from interrupting supply to the consumers.

Figure 3 - Overcurrent Protection Relay [3]

The vast majority of available electromechanical relays available can be classified under the following types, based upon the mechanism responsible for opening/closing the relay contactors:

- Attracted Armature
- Induction
- Moving Coil
- Motor Operated
- Thermal

All of these types have their advantages and disadvantages such as inherent operation delays or simple and accurate configuration and operation. The type selection generally is based on needs of the application. The type depicted in Figure 3 is an induction disc, where current flowing through a set of electromagnetic coils induces a current on the rotatable disc. When this induced current produces a force exceeding that applied by the opposing spring tension, the disc will rotate, causing the relay contactors to open. One advantage of the induction disc mechanism is that a higher fault level results in a higher coil current thus causing faster disc rotation. In this instance, as with most of the other types of electromechanical relays, the relay switching would be driven by the signals being supplied from the CT or VT. The induction disc relay type is one of the most popular and widely used electromechanical relays because of its short operating time, reliability and ability to be applied in almost any form of protective function (voltage, current, frequency, power etc.) [2].

Electromechanical relays are generally limited in functionality and operational scope, and are designed specifically for the protection function desired. This means that to monitor more than one function on one component of the network, multiple relay units are required to achieve the desired suite of protective functionality. Figure 3 offers an example where each phase and neutral requires its own individual electromechanical relay for protection. This often means that the protection relays are housed in large standalone cabinets dedicated specifically for each relay, or set of relays for the application.

2.2.2 Solid State

Solid State protection relays are an alternative analog based system that has recently seen some increased implementation [2]. These relays are just as capable as the electromechanical equivalents with a fraction of the footprint and an ability to be more than single phase/single contact relays. SSR's utilize the electric principles of MOSFETs to operate and thus have no moving parts, yielding some fairly significant advantages including: faster operation time, lower burden, longer lifespan, bounce less operation, lower electrical noise and improved sensitivity to operational environment impacts (vibration, humidity etc.). However the following disadvantages also exist, which prevents their widespread adoption: influenced by transient events causing undesired operation, and having a high resistance when closed, which generates heat and results in a non-linear voltage/current characteristic, which impacts performance. Figure 4 below is an example of a Solid-State protective relay, available as part of the Lab-Volt Protective relaying system. The three CT inputs are shown at the top, potentiometers for setting trip level and time delay are in the middle, and at the bottom are the relay contactor outputs with the auxiliary power supply connections.

Figure 4 - Three-Phase Overcurrent Relay

2.3 Digital Relays

Digital relays, unlike mechanical relays, use microprocessor technology to detect and respond to trip conditions. Like other forms of protection relays, digital relays measure the secondary elements but convert these to a digital form for the microcontroller to process and respond in the event of a fault.

Being a digital based fault calculation process digital relays emulate the protection functionality and are thus able to emulate multiple protection functions through the one unit. As an example a base overcurrent protection digital relay with only CT inputs could also be used to emulate negative sequence protection, earth fault protection, breaker failure protection and thermal overload, through appropriate programing. This means that one digital relay has the potential to replace any number of electromechanical relays, saving space and cost. Because of this the digital relays are designed or created to meet the needs of a certain application (e.g. transformer protection, feeder protection) and not the protective function type required.

The transition from electromechanical to microcontroller technology has allowed for the inclusion of modern communications related technologies, thereby improving the monitoring, operability, and control and network integration of protection relays. Some of the extra features include:

- The introduction of communications and SCADA – the primary source for most of the following features, allowing remote and local interactions of other relays, users and control systems.
- GPS integration – allowing accurate timekeeping
- Synchronized Measurements (Synchrophasor) – synchronized measurements based on the GPS clock, which improves fault event monitoring and reporting.
- Automation – the ability to automate functions within the relay and other devices as part of the protection system; for example to signal other protection relays to open respective breakers.
- HMI – allows for remote and local monitoring of relay specific values, statuses and events history along with providing a means of manual control over the relay controls.
- Reporting – event report generation containing critical event data, measurements, statuses etc.
- Self-testing – internal checks for failure of relay systems from internal memory to I/O contacts in element inputs.
- Alarming – automated alerts to faults, relay failures or undesirable operation conditions.

Besides the improvements in functional operation and availability the microcontroller systems provide more generalized advantages to digital relays including:

- Increased accuracy, reliability and a reduced expense per functionality [4].
- Smaller size and significant reduction in cabinet space per protection function.

- Modular layout and upgradability that allow for easy replacement or expansion as functional demand increases or changes over time.
- Software interactions providing a gateway for programing, monitoring and control.
- Smaller burden on the CT's or VT's when compared to electromechanical relays, as digital relays do not use the signal from the signal transformer secondary to drive the internal tripping circuits, thus reducing the applied load.

However, as with many technological advances there are some disadvantages that need to be noted:

- Increased configuration complexity – the transition from analog to digital combined with the consolidation of protective functions and addition of microcontroller functionality adds to the programing configuration and development requirements compared to the adjustment of dials or relay selection for the protection function.
- Relays require their own dedicated power source. The microcontrollers require a dedicated power supply to maintain monitoring and protective functionality. If the relay loses power their operational protection is lost.
- Significant transition process – significant time and cost is required to successfully migrate from analog to digital relays, inclusive of relay cabinet refitting, updating required drawings and configuration time.
- Inability to operate effectively or accurately as designed in harsh conditions, such as: high temperatures, severe environmental conditions and in high EMI or RFI prone areas.

Some of these disadvantages are the main driving forces behind old mechanical relays being replaced by newer non-digital models simply because there is not enough knowledge of digital relays to install, configure and operate, or the installation environment won't permit the installation of digital relays. Evidence of this can be seen through the new installations of GE designed protection relays in Canada, where 40% of these were still electromechanical based systems [4]. Figure 5 is an example of a digital protection relay developed by an alternative competing company to SEL, as a point of comparison to illustrate visually the differences in relay design and implementation and device operations.

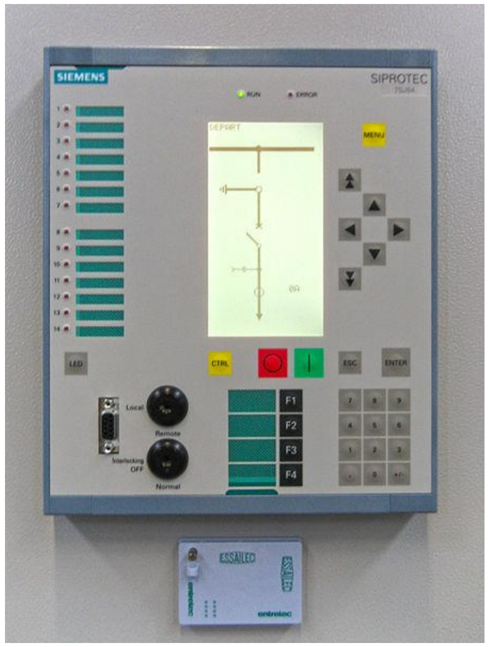

Figure 5 - Alternative Digital Protection Relay

2.4 Schweitzer Engineering Laboratories, Inc.

Schweitzer Engineering Laboratories (SEL) is a company founded by Edmund O. Schweitzer in 1982; it is based in Pullman Washington and was the first company to develop and manufacture digital protection relays in 1984 [5]. To this date the company continues to develop embedded systems for control, metering, monitoring and protection of power systems and remains one of the leaders in digital protection relays as ranked by national (USA) and international utility companies [6]. SEL remains at the forefront of innovation, as highlighted by the recent introductions of load-encroachment protection, the standardization of Synchrophasor measurements in all digital relays, and the development of a secure and highly reliable relay-to-relay communications protocol (SEL Mirrored Bits). As the title of this thesis may suggest, SEL manufacture the digital protection relays that comprise the SEL Protection and Monitoring System.

3. Relay Functionality

The SEL Protection Relays provide a variety of protective functions with a specific means of identifying said functionality. The protection function for all protection relays can identifiable by a number, which indicates the function of the device and adheres to the ANSI Standard Device Numbers defined in the ANSI/IEEE Standard C37.2 [7]. The use of letters allows quick identification of available protection functions and provides a method for easy identification of the device and/or its function in physical installations and any related single line diagrams, electrical wiring diagrams or even cable schedules. The IEC document IEC 60617 *Graphical Symbols for Diagrams* defines the graphical symbol for each particular function, which improves relay identification in any technical drawings [8].

3.1 Protection Functionality

The SEL Protection and Monitoring System Provides a variety of protective functionality and in some cases requires specific functional interactions to properly operate and protect electric distribution elements. Table 1 contains a list of all the ANSI/IEEE defined protection functions [9] that the SEL Protection and Monitoring System currently provides, while Table 2 details the lettering variations where the usage will indicate which specific measurement component the function will monitor for fault detection, e.g. phase, negative-sequence, neutral etc.

Table 1 - Available ANSI/IEEE Protection Functions

ID	Variants	Name	Description
21		Distance Relay	Distance protection based on Line Impedances (mho relay zoned protection)
24		Volts Per Hertz Relay	Protection from over excitation of a transformer, based upon nominal voltages and frequency
25		Synchronism Check	Internal checks for synchronism of relay components
27	S	Under voltage Relay	Protection against voltage sag or dropping network voltages within present bounds
32		Directional Power Relay	Two way protection against overload or reverse power
49		Thermal Relay	Protection against abnormal temperatures
50	P,G,Q,N	Overcurrent Relay	Protection against abnormal high currents or fault conditions
51	P,G,Q,N	Time Overcurrent Relay	Time overcurrent protection, coordinated relays, TOC curve
52		AC Circuit Breaker	AC circuit breaker opening contactors in a network.

55		Power Factor Relay	Protection against undesired power factor conditions
59	S,Q	Overvoltage Relay	Protection against high network voltages
67		AC Directional Overcurrent Relay	Protection against phase-to-phase short-circuits through comparison to voltage waveform patterns.
68		Blocking Relay	Prevents tripping under certain conditions (e.g. Out-of-Step)
79		AC Reclosing Relay	Auto reclosing relay for purposes of automatic reconnection of network if fault clears, limitation of downtime
81	R,RF	Frequency Relay	Protection against undesirable frequencies
86		Lockout Relay	Latching type relay, meaning constant control signals not required
87		Differential Protective Relay	Protection against a differing current between to measurement points
50BF		Circuit Breaker Failure	Protection against breaker failure by signalling upstream breakers to trip if main failure occurs
60LOP		Loss of Potential	Protection in the event of a dropout of local AC voltage inputs where there is no corresponding changes in current signals
REF		Restricted Earth Fault	Protection against internal ground faults in wye transformers.
AFD		Arc-Flash Detector	Fault protection against internal switchgear arcing

Table 2 - Letter Variations

Variant	Definition	Extra details
P	Phase	Phase based protection
G	Ground/Residual	Type dependent upon CT/VT availability
Q	Negative-Sequence	Reverse Phase Rotation protection
N	Neutral	Neutral Current Detection, Similar to RCD protection principles
R	Rate-of-change	protection against frequency instability by initiating load shedding
RF	Aurora Mitigation	frequency based protection in detecting islanding
S	Synchronism	localized application of function 25

3.2 Monitoring Functionality

There is an assortment of various monitoring, metering and relay protective functionality which are common to all the relays available in the SEL Protection and Monitoring System. Table 3 lists the common or standardised functions. All of these and others which are unique to specific relays are configurable through the AcSELerator Quickset software package, from the relay's front panel, or through remote network communications based commands.

Table 3 - SEL non-ANSI/IEEE features

Name	**Details**
Password Protection	Prevention of unwanted operation or Configuration changes
Sequential Events Recorder	Recording of operations of relay through internal word bit assertion/desertion monitoring.
Various Communication Protocol Support	Ability to communicate to a variety of varying devices (Modbus, DNP3, TCP/IP etc.)
Mirrored Bits	SEL Proprietary relay-to-relay communications protocol
Synchrophasor (PMU)	Time synchronized measurements/monitoring
Remote and Local control switches	Local and remote control of relay elements
Event Reports	Reports detailing fault event specifics
Metering	Real-time display of metered values with CT/VT compensation
HMI	PC based control and monitoring of relay functionality
Front Panel Interface	Local Relay control and Status Monitoring

4. SEL Units Overview

During the initial stages of the project it was found that amongst the relays there were units that shared several functional capabilities, were easily replicated through appropriate programing or required additional hardware to be effectively utilized. As a result the thesis focused on the following relays: 421, 751A and 787. All the relays have different power supply requirements, nominal CT ratings and I/O switching characteristics, which are detailed in Appendix 12.4, product number and FID to allow establishment of settings without reading directly from the relay, this process is detailed in Appendix 12.1. All the monitoring functions detailed in Table 3 in section 3.2 Monitoring Functionality are as already stated common to all the relays featured, both Primary and Secondary. The entirety of this chapter contains details into the design of the relays and their associated functionalities.

4.1 Primary Relays

Figure 6 - Primary Relays

4.1.1 SEL-421: Protection Automation Control

The SEL-421 Protection Automation Control Relay is a three-slot rack mountable protection relay designed for high speed transmission line protection; it is the top most relay shown in Figure 6 above. This relay features single and three pole tripping with reclosing control, circuit breaker monitoring and failure protection, series compensation logic and automation programing logic. The relay is capable of providing the following functions: 21, 25, 49, 50, 50BF, 51, 67, 68 and 79. To achieve this the relay features two sets of three phase CT and VT inputs, 16 digital outputs and 15 digital inputs, and communications is supplied via three 9 pin D-sub connectors, two fibre optic ports and an IRIG-B BNC connector.

From the available digital I/O, 8 of the digital outputs (available in slot 1) offer NO or NC contacts while the remaining 8 (available on slot 2) provide NO high speed interrupting outputs. The appropriate configuration of the available inputs and outputs allow control and monitoring of attached circuit breakers. The SEL-421 can be programed with two outputs, one to signal open commands and the other to send close commands, while one input is used to monitor the status of the circuit breaker.

Monitoring functionality that is unique to the SEL-421 includes dual circuit breaker condition monitoring, station battery monitoring, fault locator, transient overreach, load encroachment monitoring, oscilloscope type monitoring and metering capabilities, and extensive user programed automation logic. The automation logic is programed using SELogic equations to allow user required functionality to be automatically enforced under the required conditions. This can include the communications based tripping of other upstream relays, automatic report generation and transmission to a local database, or the activation of external alarm outputs not normally tied to fault event conditions within the standard relay configuration. With the use of SELogic to program the automation functions, the user can define any number of conditions that would be required before the automation function can be activated. This can include specific pickup levels and the current status of relay I/O or internal target or the contents of communications from upstream/downstream relays (metering information, fault data or the status of relay targets).

4.1.2 SEL-751A: Feeder Protection Relay

The SEL-751A Feeder Protection Relay is a six-slot I/O expandable protection relay, shown in the bottom right of Figure 6. It is designed to provide current protection to distribution feeders and localized power equipment. The relay provides the following functionality by default: 50, 51 and 81; while the following is available through the installation of additional I/O cards: 25, 27, 32, 59, 60, 79, Arc Flash Detection and RTD based protection. The default relay configuration provides 4 CT inputs, 2 inputs and 3 type C outputs (NO/NC), two RJ45 connectors, one fibre optic port and two serial RS-232 connectors. There are two expansion I/O cards installed providing 4 digital inputs, 4 digital outputs, 4 analog inputs and 4 analog outputs, which results in a majority of the optional protective functions becoming available. The main functional advantage of the 751A relay, within the three primary relays, is the existence of the Neutral CT connection that allows direct measurement of neutral currents, thereby optimizing residual current protection and detection of faults.

4.1.3 SEL-787: Transformer Protection Relay

The SEL-787 Transformer Protection Relay is a six-slot I/O expandable protection relay, that is visible in the bottom left of Figure 6. This relay offers current protection functionality targeted specifically for transformers. The relay provides the following functionality by default: 50, 51, 87; and breaker failure protection with the following available through the installation of expansion I/O cards: 50/51N, 24, 27, 32, 59, 60LOP, 81 and REF protection. The 787 that is available in the project room only offers the basic default suite of protection as there are no expansion I/O cards installed.

The unique feature of the SEL-787 is the Transformer Through-Fault event monitor, which analyses the network conditions during a fault ride-through event and reports back on the thermal operation of the transformer during that fault, allowing ride-through damage mitigation procedures to occur. The configuration for this is user definable by setting alarms and the transformers nominal impedance. The monitor will activate for all non-internal faults, and monitor internal conditions using the measured line currents and calculates thermal characteristics using the configured line-to-line voltage, transformer MVA rating, CT ratios and the measured primary current to develop a thermal curve and check that the transformer is not operating beyond the defined limits. The report would indicate if this is the case and thus pickup levels would then need to be reduced to prevent thermal overload of the transformer.

The control of the attached circuit breakers operates similar to the other relays, the difference being the control interaction of a Lockout Relay (86), a requirement of the application of transformer protection. A Lockout Relay is similar in operation to a latching relay where a manual reset is required to reclose the contactors. This is to prevent reconnection of the transformer in the even the transformer is internally faulted or to protect against consecutive reconnection transients damaging the transformer if the fault is still present. The manual reset enforces inspection and fault analysis before circuit breaker closure is attempted, thereby ensuring it is safe to proceed with re-energizing the transformer.

4.2 Secondary Relays

Figure 7 - Secondary Relays

4.2.1 SEL-311L: Line Current Differential Protection and Automation

The SEL-311L Line Current Differential Protection and Automation Relay is a three-slot rack mountable protection relay designed for current differential protection of long distance transmission lines. This is achieved through the integration of fibre optic communications to allow coordination and interaction with another SEL-311L monitoring the breakers at the opposite end of the transmission line. Specific protection functions provided include; 21, 25, 50, 51, 67, 79, 81 and 87L; and monitoring functionality include: Breaker Wear monitoring, Battery monitor, Oscilloscope event recording and Fault Locator capabilities. The majority of functionality available within the SEL-311L is also available through the three primary relays to some extent. The exception is the communications based differential protection capabilities. However a secondary unit would be required to properly demonstrate this functionality. The SEL-311L is the second relay from the top shown in Figure 7.

4.2.2 SEL-351: Directional Overcurrent Relay

The SEL-351 Directional Overcurrent Relay, which is the top most relay shown in Figure 7, is a two-slot rack mountable protection relay designed to protect against forward and reverse direction overcurrent. This is achievable through monitoring the phase relationships of the sequence components of the AC system [10]. The main protective functionality provided by the SEL-351 relay includes; 25, 27, 32, 50, 50BF, 51, 59, 67, 79 and 81. Also available is a collection of monitoring functionality similar to that available from the other relays. Again the majority of functionality available can be demonstrated using the three primary relays.

4.2.3 SEL-387E: Current Differential and Voltage Protection Relay

The SEL-387E Current Differential and Voltage Protection Relay is a three-slot rack mountable protection relay, the third relay shown in Figure 7, which provides localized current differential protection and a variety of voltage based protection including over/under voltage and frequency monitoring. The relay contains three sets of three-phase CT inputs to provide differential protection for 2 or 3-winding transformers or other local network elements. There are 3 VT inputs and one neutral connector available to enable the voltage based protection functions. The specific protection functions provided by the 387E relay include; 24, 27, 50, 51, 59, 67G and 87, along with a variety of metering and monitoring functionality and additional I/O to meet other application requirements. The majority of protective functionality on offer is also provided in some form by the three primary relays with the exception of the 3-winding transformer current protection.

4.2.4 SEL-3351: System Computing Platform

The SEL-3351 System Computing Platform is an Embedded PC running Windows XP that provides a variety of monitoring advantages. It is the bottom most device shown in Figure 7. The 3351 relay has the following features:

- 16 9-pin D-sub connectors permitting up to 16 SEL relays to be simultaneously interconnected, providing a common access point interface to each relay.
- The 3351 has its own display, keyboard and mouse connectors to locally monitor, configure or control any relay connected on a local network or directly to the D-sub connectors.
- RJ45 Megabit network port allowing internet connectivity that permits a remote connection to the device's windows environment and thus to any connected relays.
- Two fibre optic ports for long distance system communications
- 4 USB ports for connecting of external storage drives, keyboard and mouse.

These features benefit the system user, both local and remote, by providing a single point of access to all the features and functionality of the connected relays within the protection system.

4.3 Modularity

All relays available are rack mountable (with the technical exception of the 751A and 787 relays). Expandable and/or modular layout allows easy replacement of devices, easy addition/removal of optional functionality and devices can be upgraded when new functional sets or inputs are required. This is achieved by the slot I/O card structure implemented by all the relays and is similar in concept and operation to the expansion cards (graphics, networking etc.) found in the modern desktop PC. Figure 8, as an example, shows the 751A relay with its I/O interconnects, with the rear panel removed showing the internal slot card structure and internal connections.

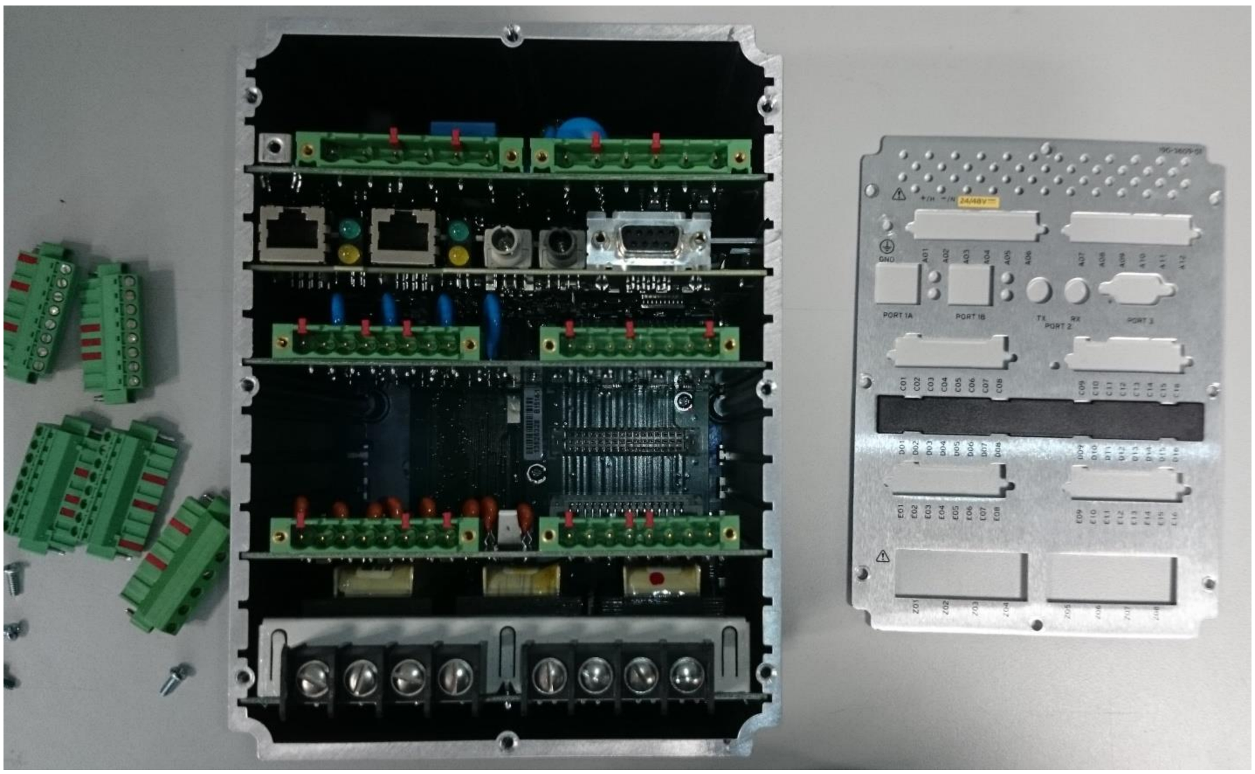

Figure 8 - 751A Relay Expandable Slot I/O

The components in this particular relay include:

Slot A. Power supply and base digital I/O
Slot B. CPU and external communications interconnectors (serial, Ethernet, fibre optic)
Slot C. Digital I/O expansion, 4 inputs and 4 outputs
Slot D. Empty
Slot E. Analog I/O expansion, 4 inputs and 4 outputs
Slot Z. CT inputs, one for each phase and neutral measurement.

The expansion I/O cards allow for additional functionality such as voltage monitoring, RTD monitoring, expanded external alarming and control to become available to the relay. As a point of comparison the 787 relay uses the same I/O slot structure as the 751A relay, however, the available unit only has slots A, B and Z occupied, meaning that only the basic current protection functionality and circuit breaker control are available.

Figure 9 shows the Expandable I/O of the SEL-311L relay to provide a comparison between the two different slot I/O systems. Like the 751A and 787, the I/O terminals can be removed and the relay enclosure opened to allow removal and replacement of individual slot I/O cards. However, with this system there is no room to install extra or optional functionality without sacrificing the default capabilities.

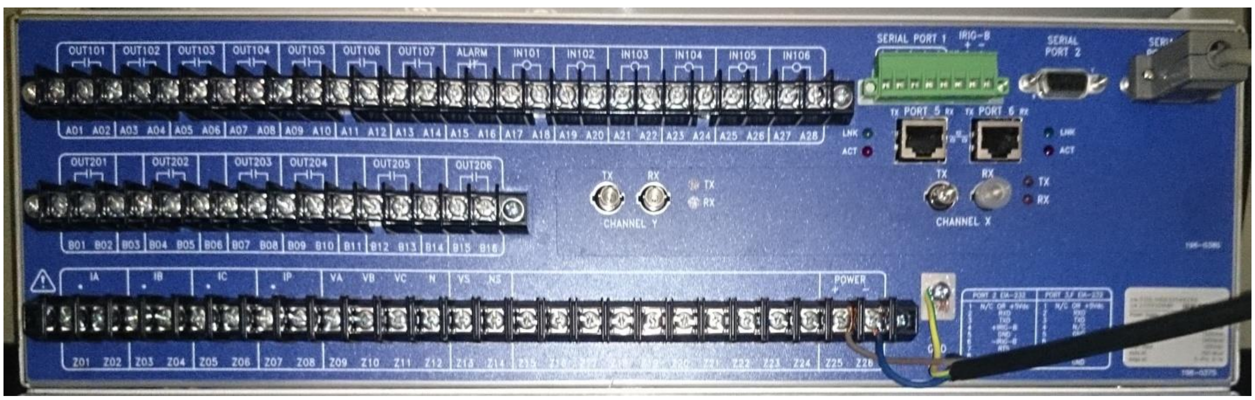

Figure 9 - 311L Relay I/O

5. AcSELerator Quickset

Chapter 5 address the AcSELerator Quickset PC application including its features capabilities and importance in programing the SEL relays.

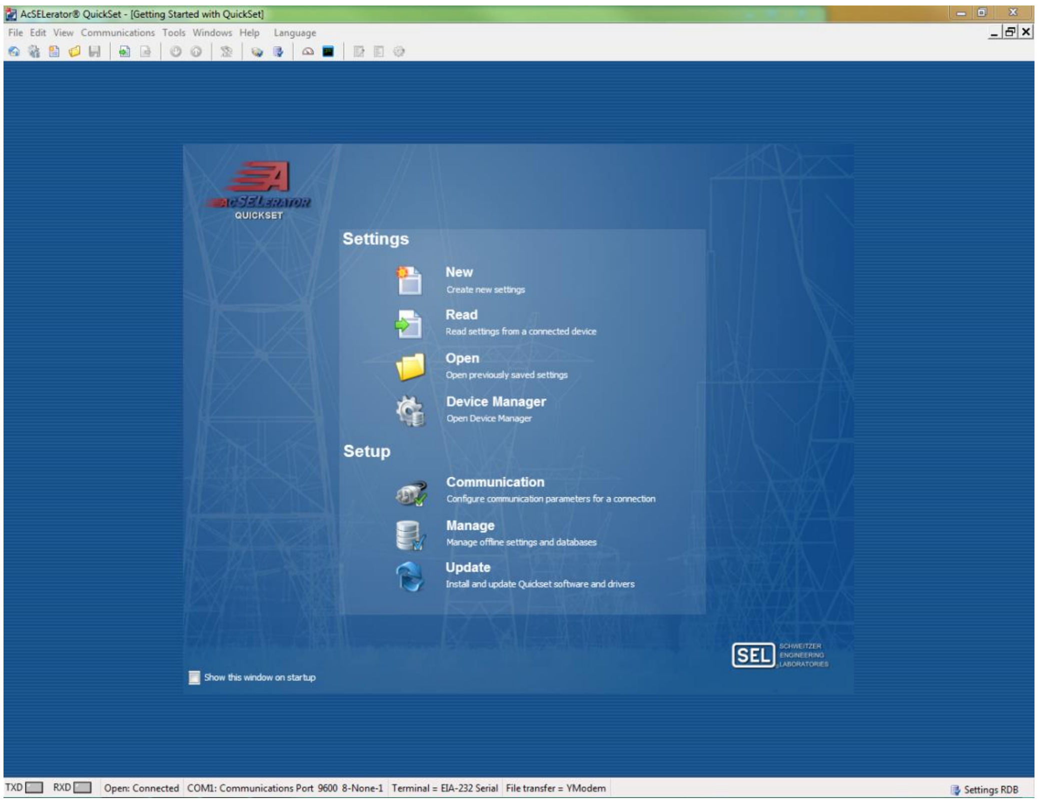

Figure 10 - AcSELerator Quickset Home

The software package AcSELerator Quickset is the primary mechanism for communication, programing, monitoring, remote control and metering of the SEL relays as part of the Protection and Monitoring System. The program is currently installed on the associated Windows 7 PC and on a USB Flash Drive connected to the SEL-3351 to allow the device to communicate with the relays. Figure 10 illustrates the initial start-up window where a new settings file can be created. Settings can be read from the connected relays. Previously saved settings files can be opened from the local database. Any connected devices can be managed (using port addresses, unique names, remote connection settings etc.) or communications parameters can be modified by selecting any of the available options. All settings, control or communications operations require an elevated operation security level, often level 2; this can either be entered into the communications parameters, through the tools drop down menu, or entered upon each initialisation of communications. The current common requisite passwords are included in Appendix 12.1.

5.1 Command Window

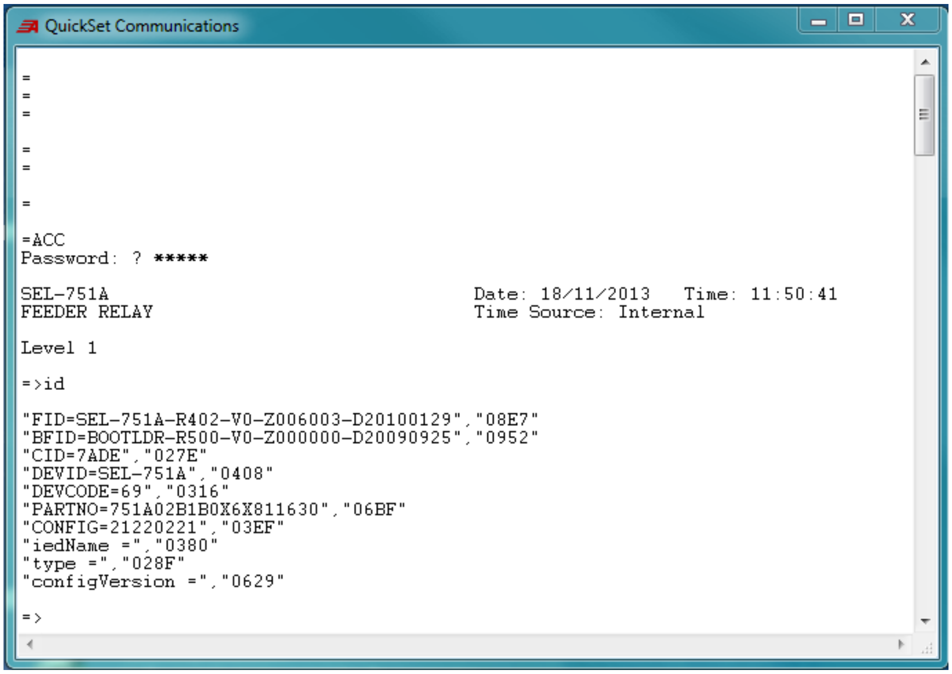

Figure 11 - Communications Window

The command window is a terminal emulator allowing serial based text communications to occur between the relay and PC. It provides mechanisms to modify specific settings, poll for relay metering/event data, relay control and status monitoring. The command window will also display live communications when other parts of the package are communicating with the relay (settings download, HMI etc.) Figure 11 illustrates the appearance of the communications window, showing the initial processes of connecting to the SEL-751A relay by entering the appropriate access level and then gathering specific relay version details to allow the settings editor to display the available functionality configurations.

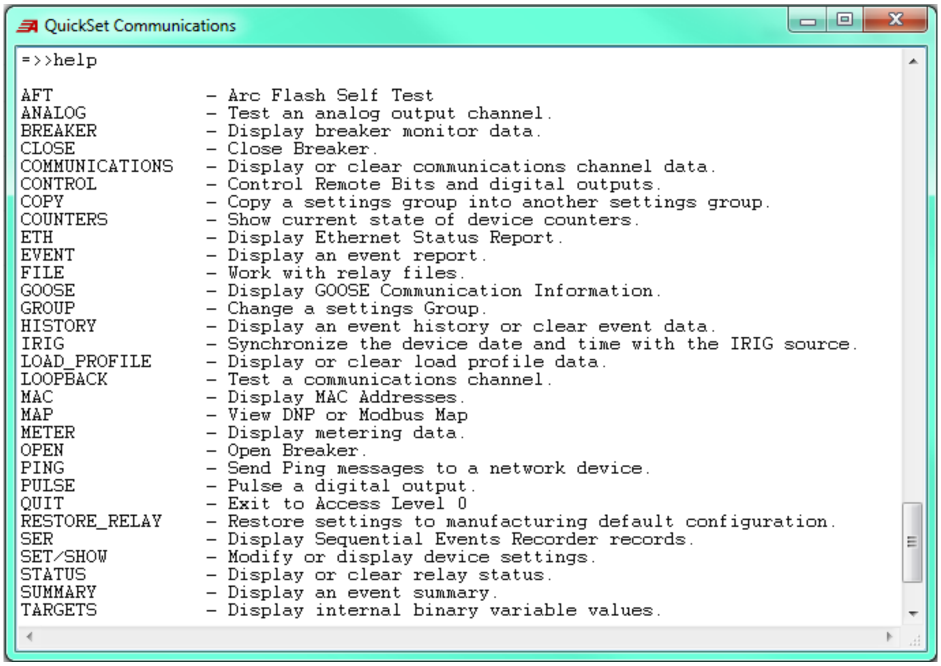

Figure 12 - Terminal Commands Overview (751A)

Figure 12 illustrates the command window after the input of the help command. Not shown is the requisite procedure to reach level 2 access to enable usage of the visible commands among others available. This shows the particular commands available to the SEL-751A relay that enables control, monitoring or event report requests. The operations available through the communications window can be utilised with another third party terminal or serial communications program. However the usage of such programs would require extra background knowledge to establish communication and effectively communicate with the relay.

One of the more useful commands, common to all relays, is the Summary command, which will display the required data of the most recent fault recorded in the relays event history. This command provides the ability to display the metering data at time of fault, indicating the system conditions and fault type that has occurred. This command can also call older fault event data by using numeric numbers following the summary command, e.g. summary 8 will display the 8th fault event summary recorded by the relay. For a complete list of available commands, see the associated relay instruction manual, accessible through the university or within the AcSELerator Quickset settings editor environment through the help tab.

5.2 SELogic

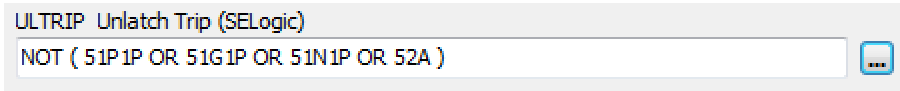

Figure 13 - SELogic Equation Field

SELogic is the name given to the equation logic used to develop a large portion of the programing of the SEL relays within the AcSELerator Quickset software package. It is a collection of programing functions including Boolean logic, mathematical operations and triggering functions, which combine to allow a simple and effective mechanism to program specific functional elements of the relays. The SELogic equations can be directly entered into the field within the Settings editor (Figure 13) or through the dedicated SELogic editor window (Figure 14), accessible by using the button to the right of the field.

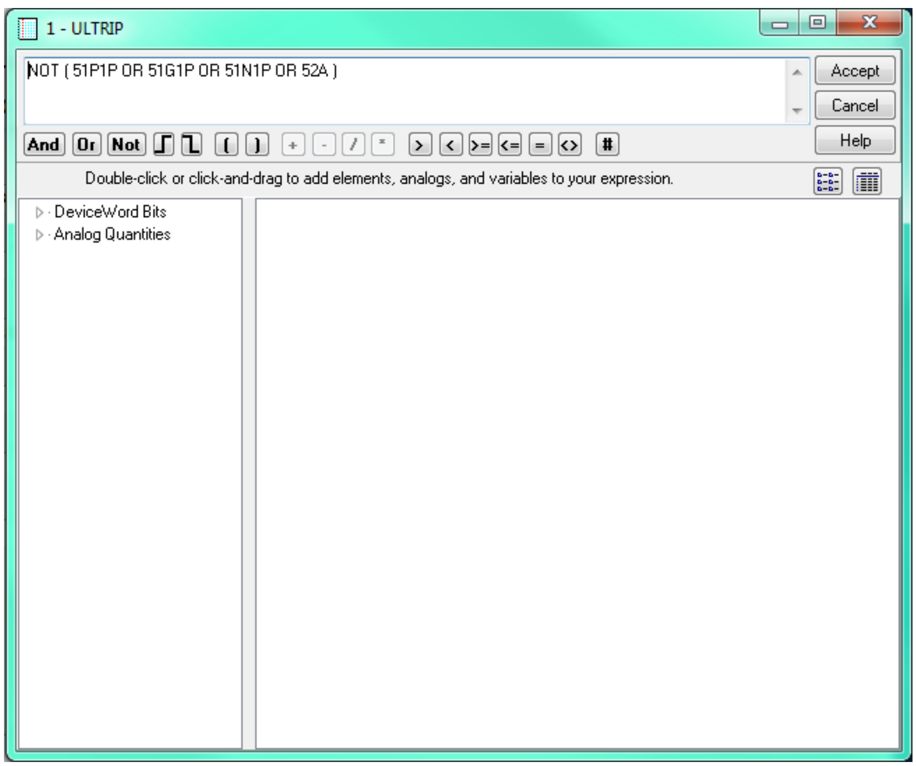

Figure 14 - SELogic Editor Window

Both Figure 13 and Figure 14 illustrate the SELogic equation for the Unlatch Trip relay word (ULTRIP) target of the SEL-751A relay, where the SELogic equation will remain true as long as the targets for function 51 time overcurrent protection elements remain false and the status of the breaker remains closed (52A). The moment either one of those relay word targets becomes true the Unlatch Trip target will become false while the related Trip target should become true, indicative of the presence of a fault.

5.3 Settings Editor

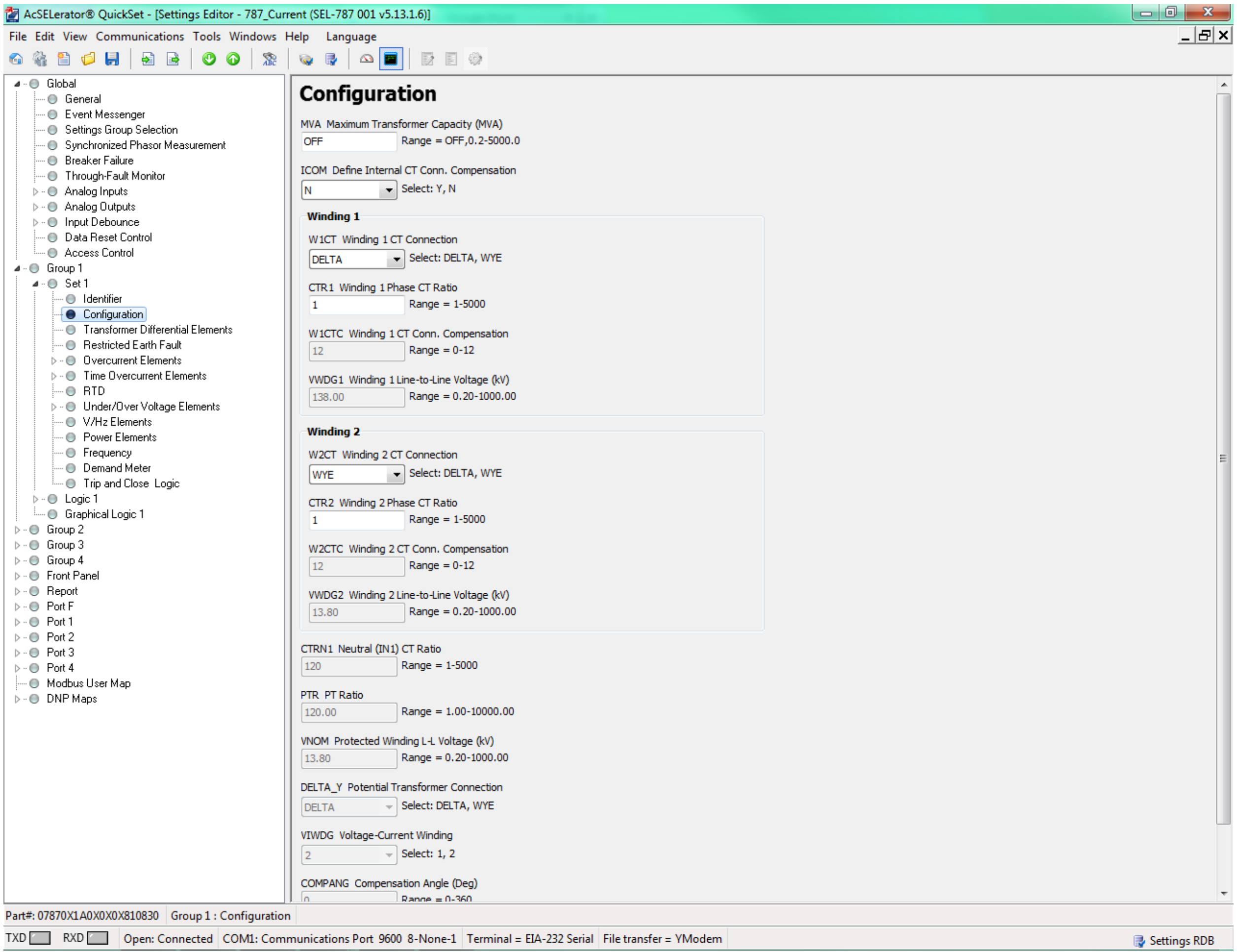

Figure 15 - Settings Editor (787)

The Settings editor is the most important component of the AcSELerator Quickset software package as it provides the mechanism to allow easy programing and configuration of the connected relay. Once the connection has been established to the relay the settings editor will open and allow configuration of relay words that relate to available functionality. Figure 15 illustrates the settings editor for the SEL-787 relay with the group 1 set 1 configuration collection of relay settings open. This window configures the CT, transformer configuration and MVA and nominal line-to-line settings for the primary and secondary of the connected transformer. The settings editor will display the available setting ranges or options next to the field to allow for easy identification and programing of the field and the associated configuration restraints. An example is the CTR1 field in Figure 15, where the indication suggests that the possible setting for the CT ratio is between 1 and 5000. Also visible is the inability to modify some relay word elements, e.g. CTRN1 (Neutral CT ratio), as the functionality that the relay word refers to is unavailable with the current version of the 787 relay. The settings editor will have a different overall left column structure based upon the connected relay and associated available functionality and configuration options.

5.4 HMI

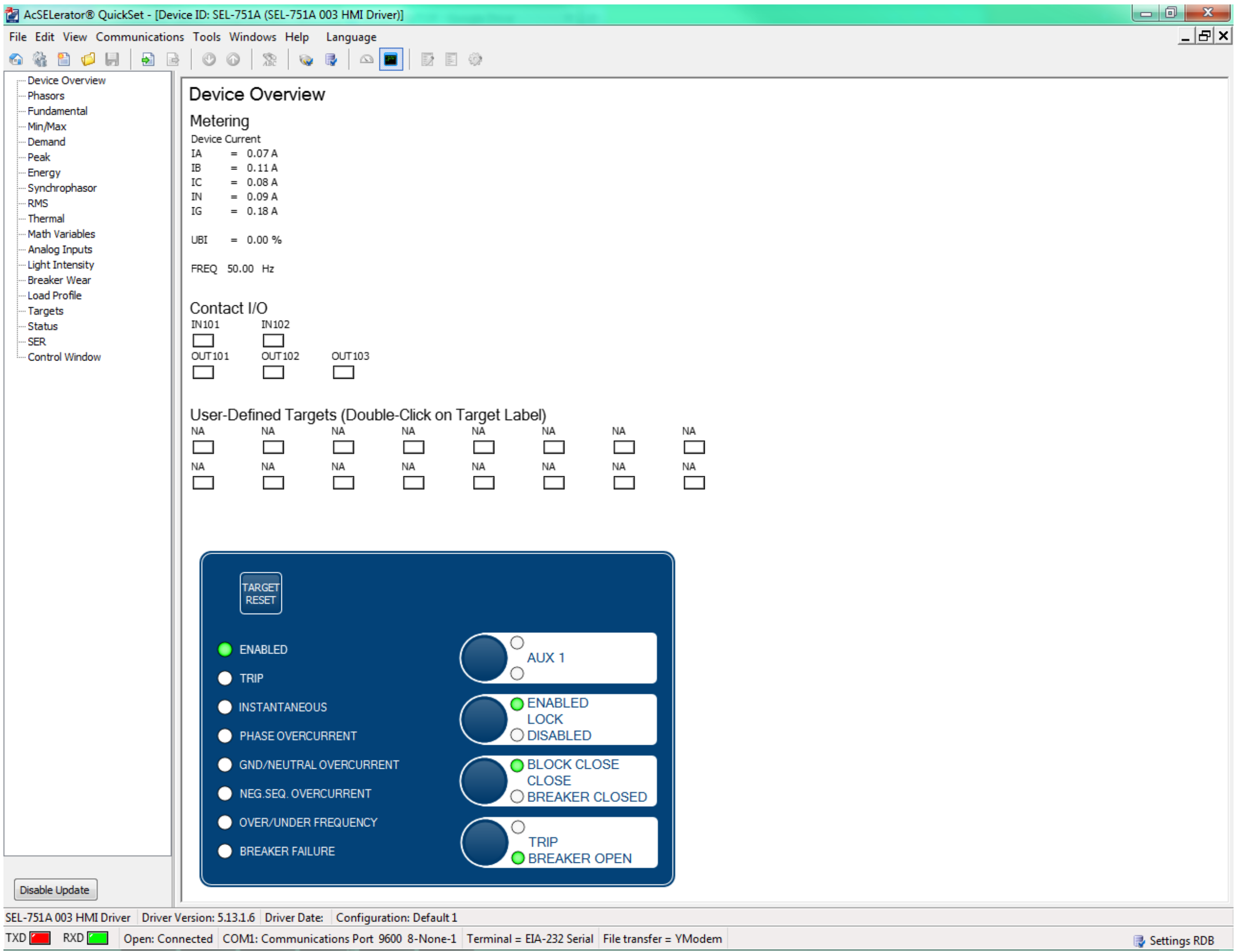

Figure 16 - HMI (751A Device Overview)

AcSELerator Quickset also offers a HMI window allowing display of all necessary relay elements and variables as well as allowing control of the relays I/O and functionality. The example illustrated in Figure 16 contains the device overview window for the SEL-751A relay. The HMI can be accessed as long as the relay remains connected and can be accessed via a locally connected PC or remote connection. However operation of the HMI will consume the communication resource, which will cause any automated communications to be impossible. Figure 17 contains a command window snapshot illustrating the continual serial communications during HMI operations. The screen shot shows the data transmission of metering data to operate the HMI Phasors Window.

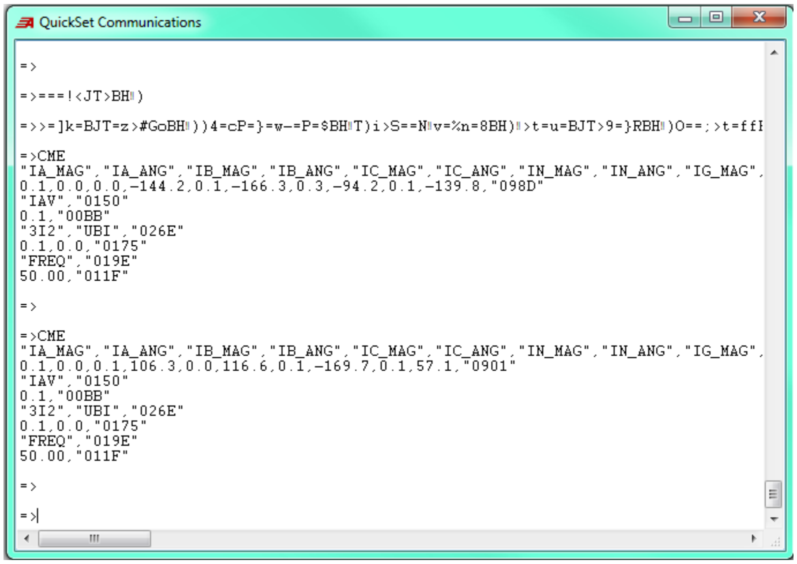

Figure 17 - HMI Communications Impact

6. Relay Investigation

The relay investigation process was a significant component of the overall thesis as was the achievement of the final simulation outcomes. This process yielded all the necessary details regarding the relays, the means to program and the capabilities available through accurate configuration, the details of which have been covered previously. However this process also yielded some significant discoveries, some which prevent many of the functionalities being demonstrated, while one in particular changed the direction of the project, most notably the change from a full Lab View, cDAQ based simulation to a completely hardware based simulation.

6.1 Familiarization

The first component of the investigation was familiarisation. This involved simply exploring the system and attempting to replicate and understand the previous works conducted.

One significant aspect to this was recreating the LabView program previously developed, which was the direct result of the program utilising an additional toolkit, the Electrical Power Design suite, as a trial version. The initial program was working towards simulating the network shown in Figure 1, featuring a HMI window detailing the relay connections and their metering data as simulated by the cDAQ. This program was designed to simulate the network elements and replicate the circuit breaker status. However the attached relay (SEL-421) had not been programed to respond to faults and the LabView program was not configured to introduce network faults. This investigation yielded significant inroads into how the relays monitor the network elements and allow control of the associated circuit breakers. At this stage the program would simulate network conditions and simulate the operation of the circuit breakers. This simulation was to be removed from the final simulation platform following the significant discovery detailed in section 6.2 Significant Findings.

The remaining aspect of this stage of the project involved the detailed study of the relays and software manuals in conjunction with the appropriate relay/software exploration, which determined a majority of the power, wiring and programing requirements and procedures to allow development of a successful protection simulation.

6.2 Significant Findings

6.2.1 Compaq DAQ

The first and most significant finding is that the minimum CT pickup setting within the available relays is 0.1A or higher, a significant increase on the maximum possible current output by the cDAQ card of 20mA. This discovery caused the cDAQ LAbView based simulation to becoming infeasible as a means to demonstrate the protective functionality of the relays, given that the majority of protective functionality provided is based upon the CT secondary current being measured. This had a significant impact on the project due to the significant amount of time that had elapsed before this fact was confirmed through careful analysis of all the relays documentation and configuration settings. This discovery lead to a significant change in the direction of the project, resulting in the need to acquire and develop a hardware based simulation. The resulting hardware investigations would uncover the existence of the Protective Relaying Lab-Volt Training system and the associated available components within the University. The details of this system are identified and explored in Section 7 Simulation Development.

Later investigations have identified a potential application for the cDAQ system, this being alarming and remote control functionality, where the relay has additional digital, or even analog, I/O that is able to being programmatically tied to an alarm, Relay Word or target to externally indicate the status of relay conditions, elements or protection functions which aren't displayed on the front panel.

6.2.2 Distance Protection

There is a collection of functionality that requires specific hardware to enable proper and effective simulation development. The notable function is the distance protection offered by the SEL-421 relay. The protection function utilises the known impedances of the source, line and load in order to determine which zone of protection the fault occurs and apply the required tripping response. This function uses the impedance as a secondary value to determine the zone of operation for protection. The secondary impedances are calculated through the following equations: Equation 1 will determine the impedance ratio then Equation 2 will convert the known primary impedance into the equivalent secondary impedance.

Equation 1 - Secondary Impedance Ratio [11]

$$K = \frac{CTR}{PTR}$$

Where:

- CTR = Current Transformer Ratio
- PTR = Potential Transformer Ratio (Voltage)

Equation 2 - Secondary Impedance Calculation [11]

$$Z_{l,secondary} = K \times Z_{l,Primary}$$

The zones can then be configured through multiplying the secondary impedance by the desired distance percentage (reach). The reach determines which tripping scheme and operation mode will operate based upon the measured impedance at the time of the fault.

One other calculation that needs to be made for distance protection is that of the Source Impedance Ratio (SIR), which will determine if CVT transient detection is required. This is to prevent the instantaneous or underreaching protection zone being tripped through an external fault. Equation 3 illustrates the calculation to determine the SIR; if this calculation results in a value less than five then the CVT detection can be disabled.

Equation 3 - Source Impedance Ratio [11]

$$SIR = \frac{|Z_{source}|}{Reach \times |Z_{line}|}$$

More details about these calculations and configuration options can be obtained from the SEL-421 Applications Handbook as supplied with the relay. The Applications Handbook contains a variety of example configuration steps to develop a variety of different protection functions that the SEL-421 is capable of providing. The examples provided can be used to assist the development of simulations using the SEL-421 relay or similar protection functionality provided by the other available relays within the SEL Protection and Monitoring system.

6.2.3 Differential Protection

The configuration of the differential protection elements of the SEL-787 relay can be both a pain free or painful process, depending on the network components. The relay has input fields for the transformer rated MVA, primary and secondary winding configuration, CT ratio and nominal voltages which are used to calculate the current in terms of Current Tap (TAPn), as shown in Equation 4 and utilised in the configuration for transformer differential current protection.

Equation 4 - Differential Element Configuration Equation [12]

$$TAPn = \frac{MVA \times 1000}{\sqrt{3} \times VWDG \times CTR} \times C$$

Where:

- C=1 (for wye) or $\sqrt{3}$ (for Delta)
- MVA=Maximum transformer power Rating
- VWDG=Line-to-line winding voltage (kV)
- $and, CTR = CT\ ratio\ setting$

If these elements are correctly entered in the configuration window then this equation is automatically calculated, accounting for any current imbalance that would occur from a phase shift within the transformer, thus allowing pickup levels and other configuration elements to be entered without the development of errors, which can make this process pain free assuming these values are realistic.

Problems with this process arise when these configuration elements are set to abnormally low MVA, line voltages and CT ratios, causing large configuration errors for the differential elements so that the nominal voltage input fields become inaccessible and the MVA field reverts to its off state. If the MVA field is set to off, this calculation can be done manually and the differential element configuration process will then need to be completed by the user adjusting each field to satisfy the various limitations imposed by the relay. If this process is completed correctly then the differential protection elements can be enabled without causing undesirable trip conditions. This process has pickup elements which are set in multiples of TAP, which if the system is ideally configured (balance CT ratios) then this pickup level could remain at the lower end of the configuration range improving operation response times.

6.2.4 The Relays

Some specific aspects of the relays suggest that the system is composed of a collection of spares or outdated devices. Facts such as the varying power supply requirements, the apparent manufacturing dates and the indication that some devices have been replaced, updated or superseded, support this theory. The serial numbers of the relays tend to indicate the date of manufacture with the oldest relay originating from 2007. The datasheets available from the SEL website and list of available relays suggest that a couple of the older relays have undergone significant updates: notably the SEL-351 is now referred to as a Protection System [13], while others, such as the SEL-3351 no longer exist in the product catalogue, although this could be attributed to the impending phase-out of Windows XP via Microsoft [14].

6.2.5 Switching Requirements

For some of the relays the I/O switching pickup levels can be configured within AcSELerator Quickset to suit the magnitude of the voltage source being supplied to the relay or to meet the requirements of the device receiving the outputs. The SEL-421 is an example of this where the cDAQ was capable of reading and driving the digital I/O, in the initial simulation system, and can be used to interface the external control or alarming capabilities as addressed in section 6.2.1 Compaq DAQ. Other relays such as the SEL-787 and SEL-751A, where these switching pickup levels are indicated on the relay I/O tag and related to the power supply; the 787 has 110 V AC power supply with 125 V DC switching specs, while the 751A has a 24V DC supply with 24V specs. The on/off levels of both of these specs can be seen in Appendix 12.4, which contains the important relay specifications. This means that for both these systems the digital inputs can't be triggered by the low voltage output that the cDAQ currently provides.

6.2.6 Communications Functionality

There are communication functionalities that either cannot be demonstrated due to lacking necessary hardware. The biggest impact of this is seen in the SEL-311L which uses communications to allow operation of the line current differential protection functionality. This requires fibre optic hardware and an identical 311L relay to communicate with and allow the protective functionality to be demonstrated in the context of long distance transmission line protection. There are target elements within the relay that become true in the absence of a paired 311L relay, impacting the behaviour of the relay often resulting in false trip events due to the lacking incoming differential metering communications.

The disappearance of the required relay-to-relay 9 pin D-sub cable and time constraints prevented the testing of the Mirrored Bits communications integration of the SEL-3351 and other relay-to-relay communications, a functionality that would be highly beneficial in integration of a variety of local substation based relays for total protection and automated tripping protection. Again the absence of fibre optics prevents the high speed operation capabilities that some of the relays can provide through communications.

6.2.7 Configuration Capabilities

Besides the ability to configure the protection elements of the relays there are other beneficial configurable components of the relays.

6.2.7.1 Front Panel

On the SEL-421, 751A and 787, the front panel items (buttons, indicators and controls) are user configurable, allowing the buttons to control whatever relay functionality the user requires while the indicators can be changed to indicate the status of any required elements (targets). As an example the Open (Trip) button on any for the relays could be re-configured to directly control the status of the Trip target element rather than control the status of the circuit breakers. Of these three relays, the SEL-421 and 787 allow the labelling of the buttons and indicators to be changed to reflect the function or element being controlled or monitored, while the SEL-751A labels are not removable or changeable.

For the remaining relays (351, 311L and 387E) only the indicators are changeable, the pushbuttons available provide a mechanism to navigate the operations available through the front panel display, where various relay functionality can be controlled, modified or monitored.

6.2.7.2 Automation

The automation logic is a separate set of logic equations, up to 1000 lines of code, fully user programmable and not functionally tied to any particular function within the relays. The automation logic also exists separately to any variables and math functions available within the relay. The programing of the automation logic is entirely up to the user with respect to the interfacing of relay words, metering data, the status of I/O words and any communications received. The programming is free-form, where the intended target of the equation or function is user definable and can be a math variable or operable relay target. The relay uses Aliases to allow this free form logic to be associated directly to relay word bits without modifying the traditional functionality of the associated relay word bit. Figure 18 illustrates an example of the free-form programing which is typical of that used to program the automation logic. The example shows the configuration for the interlocking of the functionality associated with several of the front panel pushbuttons.

Protection Free-Form Logic Settings: PROTSEL1 - PROTSEL250

```
PLT02S := PB2_PUL AND NOT PLT02 # COMM SCHEME ENABLED
PLT02R := PB2_PUL AND PLT02
PLT04S := PB4_PUL AND NOT PLT04 # RELAY TEST MODE
PLT04R := PB4_PUL AND PLT04
PLT05S := PB5_PUL AND NOT PLT05 # MANUAL CLOSE ENABLED
PLT05R := PB5_PUL AND PLT05
PLT06S := PB6_PUL AND NOT PLT06 # RECLOSE ENABLED
PLT06R := PB6_PUL AND PLT06
```

Figure 18 - Free-Form Setting Example

6.2.7.3 Variables

All the relays without automation (free-form based) logic have the ability to configure a selection of variables and other functional logic bits and equations for various purposes including metering data communications, alarming and functional interlocking. These variables include latching bits, counters, timers and variables and math variables.

- Latching bits, as the name suggests is a collection of bit set and reset logic which can be configured to latch the associated bit when the configured SELogic equation is true. An example is the indication of momentary alarm conditions having existed and requiring interaction to reset without impacting the status original alarm relay word.
- The timers and variables can be programed to be time based from a given input trigger, where pickup time and dropout time can be configured.
- The counters can be used to develop user defined count events where the user can program the count up and count down triggers, reset trigger, initial value and value output location. An example where counters are utilised is the breaker wear monitor functionality, where the operation of the breaker will trigger a count up event. This number can then be compared to operation limit variable to alert to when the life cycle of the breaker has been reached. The counters can be programed to monitor a wide variety of relay words/targets to indicate the occurrences of status changes.
- Math variables allow for the storage of real non-Boolean type data, mostly required for metering data. This can be utilised to allow metering data to be communicated over networking or to display data that the HMI or communications reports wouldn't normally generate.

7. Simulation Development

The simulation development phase of the project where hardware was compiled and designed to demonstrate the available functionalities of the SEL protection Relays. This chapter focuses on the significant pieces of hardware and the uncovered design considerations necessary to produce the final simulation platform.

The final simulation platform was restricted to transformer protection using the SEL-787 Transformer Protection Relay. This restriction was the result of limited hardware availability and time restrictions caused by the early cDAQ simulation focus. Original simulation design considerations included the acquisition and construction of a custom made set of components to allow a suitable simulation to be developed. To fulfil this task, a three-phase variac, single phase variac and a 1kW rated resistor were acquired from within the university for initial testing purposes. However shortly after this, the testing process was simplified through the acquisition of a collection of various pieces of Lab-Volt equipment.

7.1 Lab-Volt

The process of simulation development was streamlined with the discovery of the Lab-Volt Protective Relaying Training system available within the university. The units available include the Universal Fault Module, Faultable Transformers, Transmission Grid A, Control Relays and a collection of CT and VT modules along with two interconnection modules, their associated patch cables and essential power supply units.

The use of this Lab-Volt equipment had not been explored in any of the previous units, resulting in a small period of operational investigation to ascertain correct limits, procedures and capabilities each module required/provided. This process proved fairly straight forward through front panel, interior and specification analysis, leading to a period of operational guess and check testing to ensure that total operational functionality had been acquired. The majority of the process was conducted with a multimeter to check for continuity, voltage or resistance to confirm operational understandings.

7.1.1 Faultable Transformer Module

The Faultable Transformer Module, shown in Figure 19, contains three isolation transformers, one per phase, with a variety of input and output terminals, current measurement terminals, and a collection of fault inducing switches or input connectors to induce a variety of faults. The input terminals in the fault section of the module allow the second transformer (T2) to being faulted by an external source to allow introduction of short-circuits with a resistive element included.

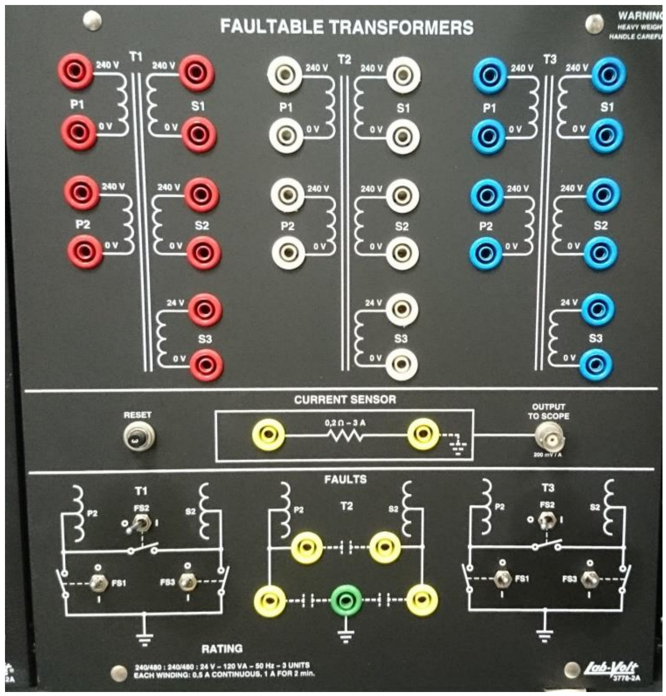

Figure 19 - Faultable Transformer Module

7.1.2 Transmission Grid

The Transmission Grid Module offers a collection of three-phase contactors which can be controlled remotely via the available control relays or through the on board switches. The three phase contactors provide a simulation mechanism for representing the circuit breakers that would usually be controlled by the protection relay. Figure 20 shows the module that is currently available, where the control relay interface visible in the bottom left corner. The control relays are able to control the status of the three phase contactors through these inputs by energising the individual contactor coils.

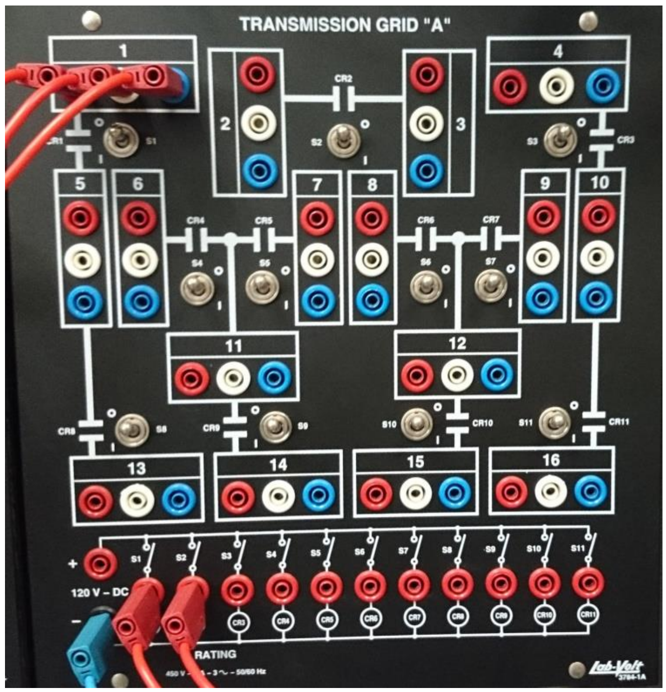

Figure 20 - Transmission Grid Module

7.1.3 Universal Fault Module

The Universal fault module contains an AC powered Pushbutton which activates a collection of internal contacts and time delayed contacts which enable the introduction of various fault elements dependent upon the usage of the output connectors. Figure 21 illustrates the universal fault module which consists of three sections. The first is the powered switch and the associated activated contact coils and time-delayed coils. The second is the collection of control relay contactors and power relay contactors. The third section contains a collection of resistive outputs to provide a variety of short circuit current conditions. This module allows the introduction of various network level (external) faults which can be applied to any component of the simulation network.

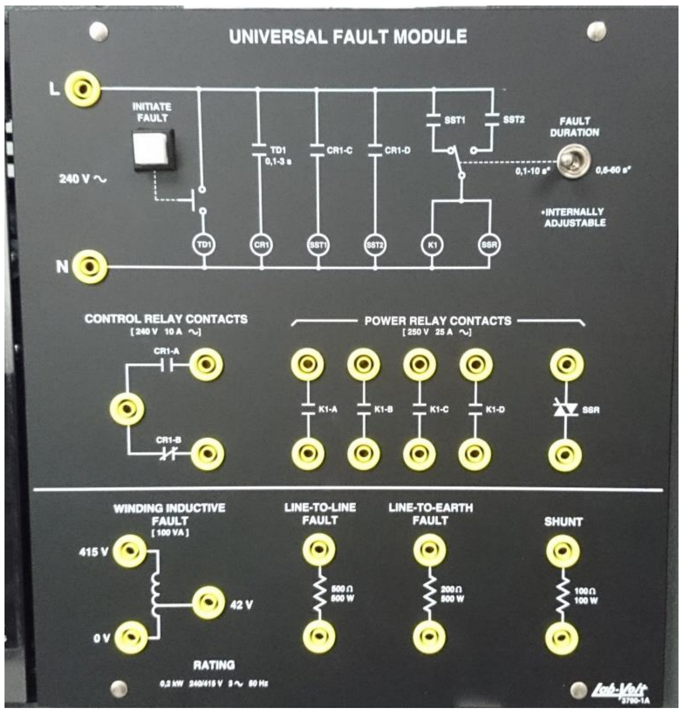

Figure 21 - Universal Fault Module

7.1.4 Control Relays

The control relay modules are a collection of latching, non-latching and time-delayed SPDT and DPDT relays with interconnectors to drive the coil and interface with the contact outputs. All of the available control relays are of type C with NO and NC switching terminals. Also included is a dedicated DC power supply to provide sufficient voltage to energise or de-energise the relay coils through a switching external interface such as the output contacts of the protective relays or suitably rated switches.

7.2 Design

Once the operational functionality of the Lab-Volt modules was established and the requirements of each component were established, the development of the final simulation system became a simple process. There is an experiment manual supplied with the protective relaying training system which describes a collection of example experiments. These provide a structured process for development, implementation and operable testing of the included experiments, which helped in the development of the final transformer protection simulation. Figure 22 illustrates the final developed simulation layout as adapted from the transformer differential protection example experiment from the experiment's student manual [15]. The major modifications include the introduction of a secondary side three-phase contactor and the removal of the associated Lab-Volt supplied SSR protective relays. The SSR Relays are replaced by the SEL-787 and interfaced to the three phase contactors through the latching control relays. The interface of the control relays and CTs with the SEL-787 is achieved through the use of the interconnection panel modules and the associated patch cables. This minimised clustering cables running between the Lab-Volt system and the 787 relay connections. The process and methods for this simulation development and operation can be viewed in the user manual available in Appendix 12.2.

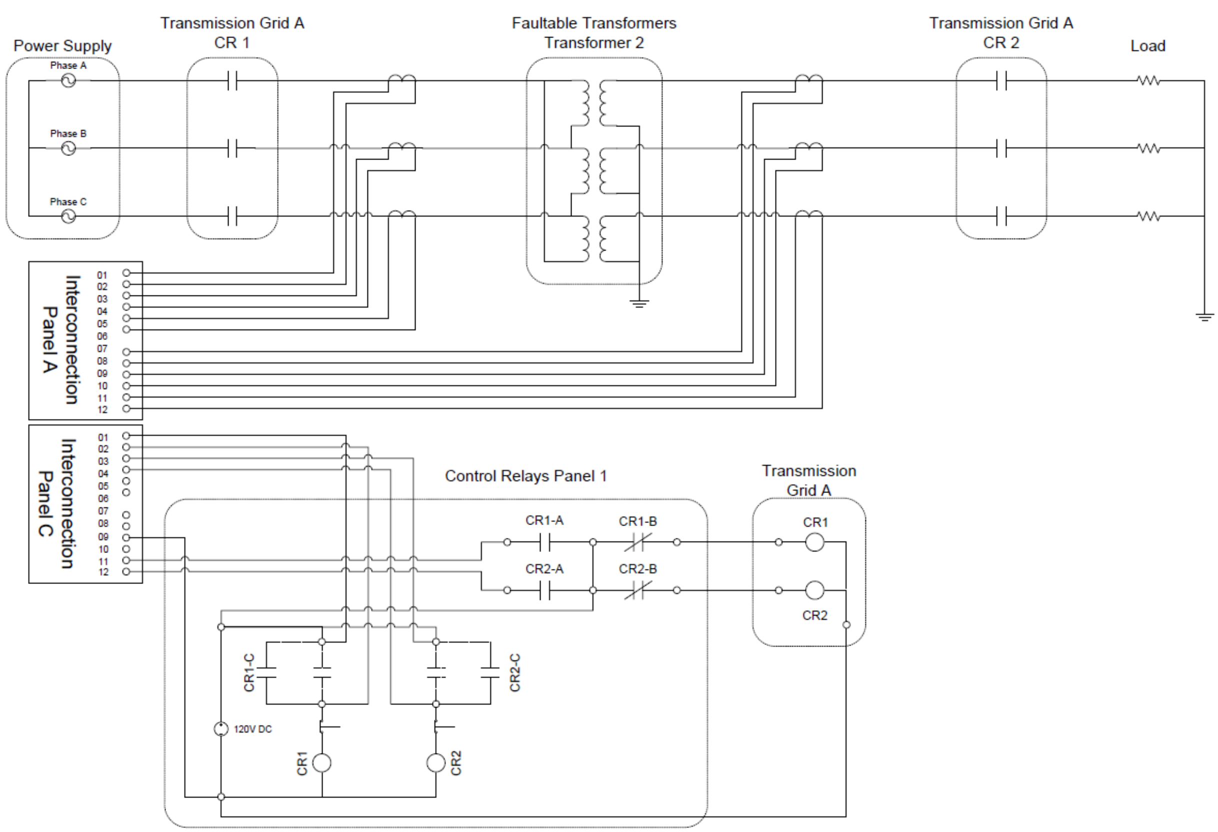

Figure 22 - Transformer Protection Simulation Line Diagram

The interconnection diagram shown in the bottom half of Figure 22 illustrates the connection of the SEL-787 relay to the control relays through the interconnection panel, which in term interfaces to the transmission grid three-phase contactors. The layout of the control relays is directly indicative of that required to properly establish the latching functionality. The physical connection of the single line diagram can be seen in Figure 23 below, where the output of the relay contactors (connection across interconnectors A and B) will momentarily energise the relay coil causing CRn-C to close resulting in the coil staying energised (the result of directly connecting A to C) until the reset button is triggered. CRn-A and CRn-B provide the normal relay contact outputs to control the status of the three-phase contactors and report the status back to the SEL-787 inputs for monitoring.

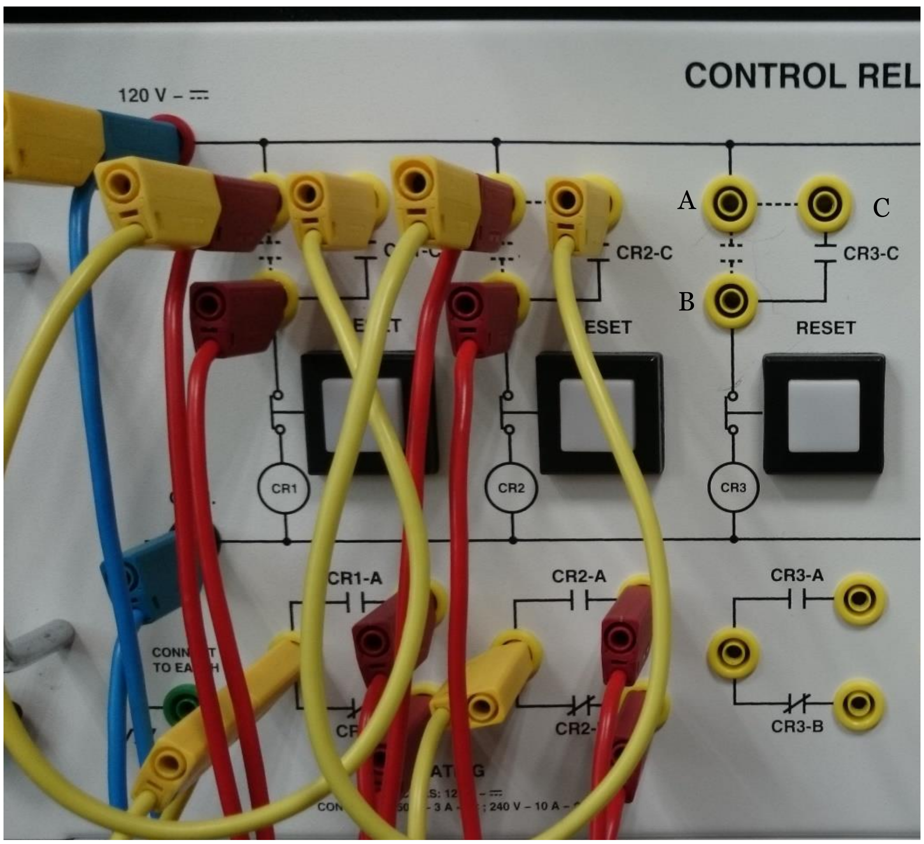

Figure 23 - Physical Control Relay Connection

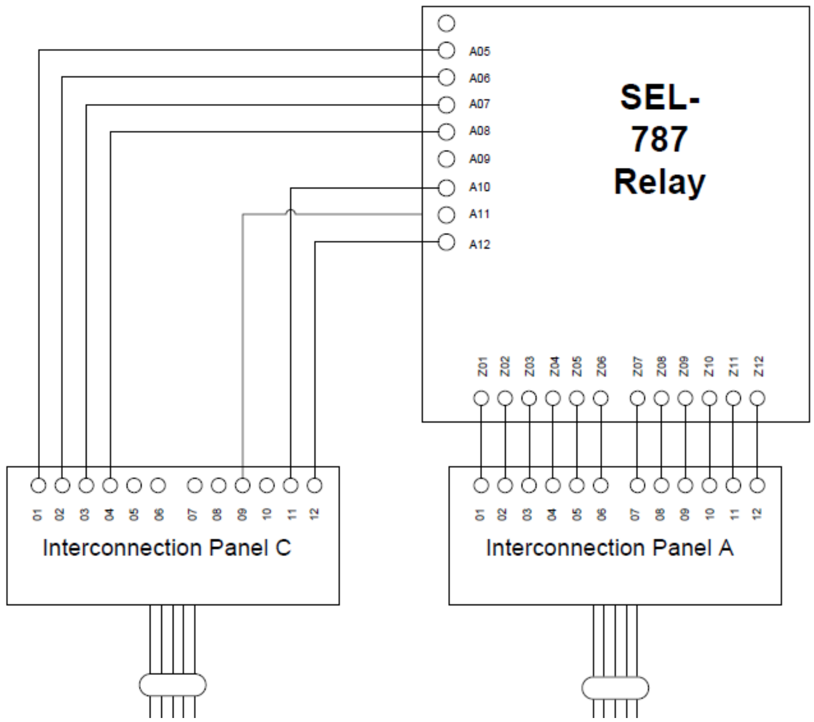

Figure 24 - SEL-787 I/O Connection Diagram

Figure 24 illustrates the connections via the interconnection panel to the SEL-787 relay I/O connectors, where connections A05 to A08 are the output terminals, responsible for latching the control relays, and A9 to A12 provide the inputs for status monitoring. Figure 25 displays the complete Transformer Protection Simulation as developed using the Lab-Volt equipment, visually identifying the configuration and connections, including the interfacing of the control relays and eventual connection to the SEL-787 relay through the interconnection panel.

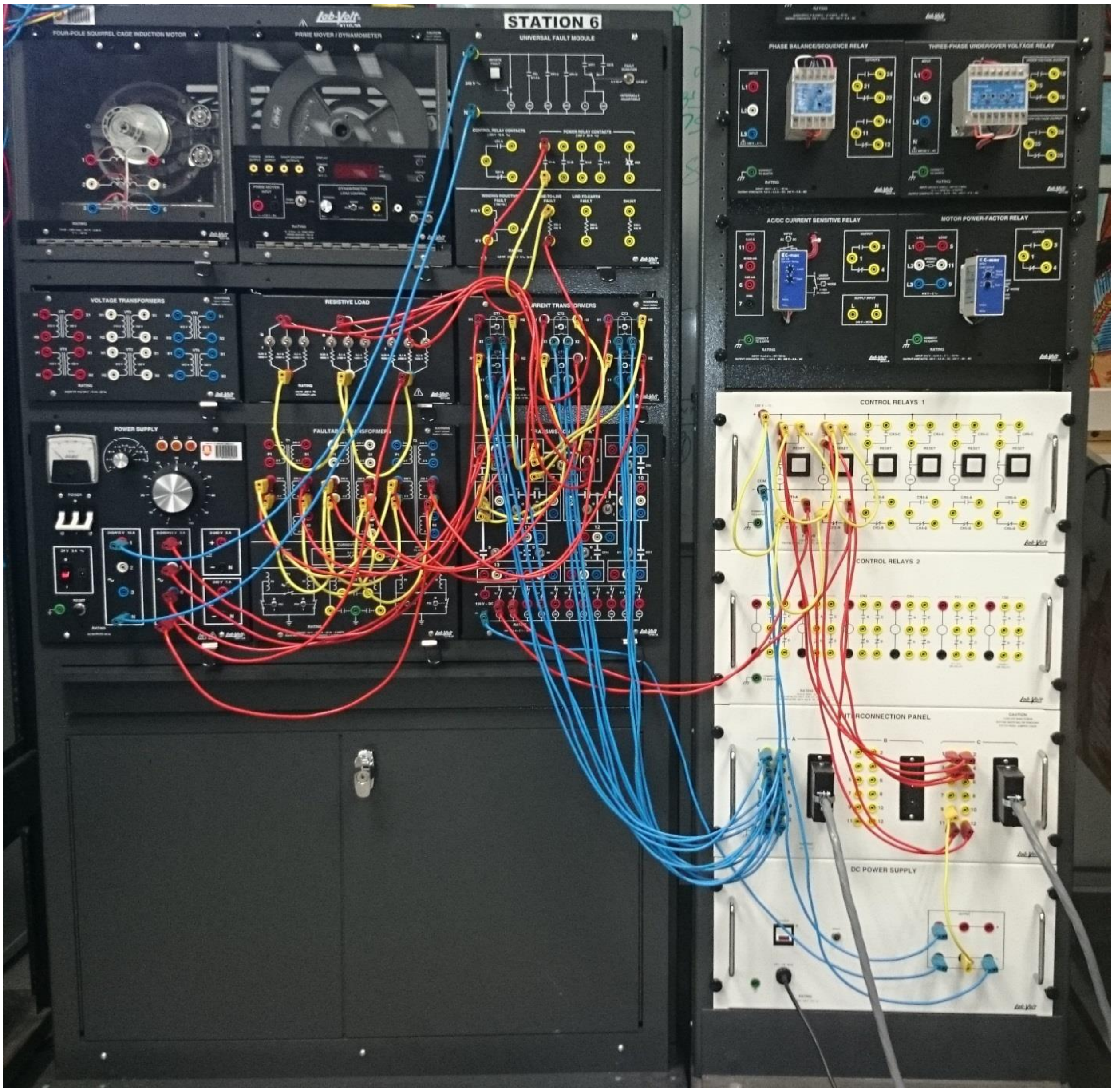

Figure 25 - Physical Transformer Protection Simulation System

7.3 Design Considerations

Throughout the design and testing of the transmission protection simulation system there were several issues that needed to be considered, that could limit the operational levels of the simulation and the variety of testing that could be conducted.

7.3.1 Nominal CT Current

The first consideration was that the nominal CT input of the SEL-787 relay is only 1A. From the specifications this meant that the steady state current signals being measured could not exceed 19.2A and would be unmeasurable below 0.02A (assuming a X/R ratio equal to 40), while the continuous current could be no larger than 15A to prevent thermal impacts upon the relay and the maximum current rating under momentary fault conditions is 100A. It is common practise to select the CT ratios that will result in a secondary current that is as close as possible to the nominal rating of the relay [12], which provides a suitable overhead in the event of severe fault. With the low simulation current and the selection of CTs available through Lab-Volt, none of these limitations would be exceeded. However, this did contribute to the simulation being run at 50% of the total possible Voltage to keep nominal currents as close as possible to 1A secondary. The limitations imposed by the nominal CT input will need to be further considered during development of the standalone system, particularly if the power delivery of the standalone system is significantly higher than that of the current Lab-Volt system.

7.3.2 Mismatched CT Ratios

The Lab-Volt protective relaying training system provides two Current Transformer modules, one which contains 6 0.5:5 ratio CTs (designated Module A) while the second contains 3 1:5 ratio CTs and 3 2.5:5 CTs (designated Module B). Initial operative testing with the Module a CTs yielded some unexpected results: one of the CTs was failing to scale the input current according to the rated ratio, unlike the remaining 5 CTs. Upon further investigation it was found that that particular CT was internally shorted causing the undesirable measurement results. As result of this the CT module B was to be used for all remaining tests while a replacement CT for Module A was acquired. The use of Module B would cause a mismatch in CT ratios for the application of differential protection. The mismatch would be partially reduced by the use of a Delta-Wye three-phase transformer configuration however slight this improvement may become. The configuration procedure for the differential protection elements would help to account for this difference and allow differential protection to be appropriately simulated. The mismatch in CT ratios between primary and secondary would not have a significant impact upon overcurrent protection elements as each is configurable separately.

One issue associated with the step-up CT ratios results from a programing limitation in the SEL-787 relay configuration, where the lowest CT ratio configurable is 1:1, meaning that the relay is incapable of scaling the measured currents to the precise Lab-Volt system currents. There is an advantage with this configuration which is the fault currents of the simulation are exaggerated permitting the relay to easily detect the smaller fault currents that the Lab-Volt system generates in the current configuration.

7.3.3 Lab-Volt Ratings

The second consideration was the current ratings of the Lab-Volt equipment, particularly the resistive load modules used. Where 0.35A was the maximum possible measured from the primary side of the transformer. During initial system testing a multimeter was connected in series with one phase of the load to monitor and ensure safe operation conditions. This resulted in the simulation being operated at 50% max voltage, which would keep the load current below the limit imposed by the resistive load. The current ratings of the other lab-Volt modules were also monitored, but at this operating limit there were no associated overcurrent issues.

In an attempt to overcome the limitations imposed by the resistive load, a three-phase four-pole squirrel-cage induction motor already installed in the Lab-Volt rack was connected in place of the resistors, which resulted in a new current limit of 0.46A. Despite this increased current limit there was a noticeable drawback in the overall protective operation. While normal overcurrent protection functionality would operate normally after reconfiguration, the same could not be established for the differential current protection elements. With differential protection enabled and appropriate configuration of the higher operation current available, both primary and secondary caused undesirable differential trip events under nominal system operational conditions, which were caused by the non-ideal CTs and natural current differential of the Delta-Wye transformer used. The higher operational current available through using the motor causes a greater current differential across the transformer which is further exaggerated by the CTs, preventing easy configuration of the differential protection element. With the knowledge that the resistive load provides a more suitable operating condition resulted in the motor being removed as an alternative solution.

7.3.4 Type 68 Lockout Relay

The absence of a required type 68 lockout relay for the SEL-787 was another design consideration. To account for this absence, the latching relays were utilised whereby the pushbutton provided would replace the reset operations the SEL-787 would normally control. The main reason this was the case was the pulse output nature of the 787, where the relay would not maintain a constant output throughout the occurrence of a fault/trip condition.

7.3.5 Earth Leakage Circuit Breaker

The existence of the earth leakage circuit breaker on the three phase power supply within the room was a significant operations consideration. The presence of this circuit breaker would prevent ground fault simulations from being conducted, due to the low pickup current of 30mA. The existence of this device was confirmed by initiating a ground fault on the Faultable Transformer module, which caused the three phase power supply to trip off by tripping the earth leakage circuit breaker. The low operating pickup current of this circuit breaker prevents the 787 relay from detecting any kind of fault where reasonable pickup settings are configured.

7.4 SEL-787 Configuration

The configuration process for the SEL-787 relay included the following steps (full details of this process can be found in Appendix 12.2, Transformer Protection Simulation Manual):

- Disabling all conflicting or unnecessary functionality, including most monitoring including the Through Fault feature.
- Configuring the primary and secondary CT connections and CT ratios
- Running a normal non-relay protected simulation to obtain the nominal current and differential element data, to develop appropriate pickup levels and configuring the elements and enabling the protection functionality.
- Associating the outputs and inputs to control and monitor the individual control relay/three-phase contactor status.
- Modifying the trip and close logic to respond to the protection targets (e.g. 51P1 phase overcurrent, 51Q1 negative-sequence overcurrent).

7.5 Simulation Results

For the purposes of testing the simulation, a variety of faults were introduced, including internal transformer winding short-circuits, external short-circuits, line-to-line faults (at the transformer terminals, load and power supply), single phase load removal and power supply control variations to induce a differential fault. And for each different configuration, settings for pickup levels, detection modes (phase, residual and negative-sequence), time-overcurrent protection and programmed time delays were all configured, both individually and as a combination, to observe any functional differences or benefits in the responses of the relay. For all the simulations, operations under nominal conditions were first carried out. This involved enabling the relay without any entangled protection functions and using the HMI and command window to read the nominal current metered variables. The configuration of the CTs being 1:1 in the relay meant that the displayed metering data was identical to the currents being measured, slightly simplifying the configuration process.

For the purposes of testing a couple of ground fault tests were conducted to confirm that it would be impossible for the relay to properly respond due to the existence of the earth leakage circuit breaker on the three-phase power supply. This fault was initiated first on the transformer to ground and then using the Universal fault module, while the relay was configured to respond as quickly as by through minimising any response delay elements. In both cases the three-phase power was disconnected before the relay had a chance to respond, and the breaker required resetting before simulations could resume.

7.5.1 Overcurrent Protection

7.5.1.1 Phase

For the Phase overcurrent protection simulations, the associated elements were the only ones to be enabled and were configured for instantaneous operation (type 50). For these simulations the pickup settings were set to 10% higher than the nominal current for both the primary and secondary to ensure Lab-Volt equipment (resistive load module) wasn't exposed to high currents for a prolonged period. The low fault levels produced during testing also justified the use of a small margin. However, ideally margins in the range of 50% are often desirable to prevent low level tripping due to network fluctuations.

For the majority of the faults induced (line-to-line, winding short circuit, phase load removal) the response resulted in the primary side contactors being tripped. This is evident by the front panel display of the SEL-787, as shown in Figure 26, after a transformer winding short-circuit fault event was introduced. The one exception to this was the introduction of an overcurrent event through an increase in the power supply voltage, where despite the relay response indicating initial fault being detected on the primary winding CTs, both contactors were tripped as analysis of the fault event summary showed both primary and secondary currents had exceeded pickup levels causing the relay to trip both primary and secondary contactors.

Figure 26 – Fault event SEL-787 Front Panel

Figure 27 contains the fault event summary as displayed through the Communications window after the use of the sum command showing that only one phase metering element has exceeded pickup settings enough to generate a trip condition. The use of the summary command produces specific fault information, which includes: the target relay ID; time and date; the type of fault event; responding relay targets (I/O); and the metering data at the time of fault. It should be noted that this report indicates the network frequency; however, without the ability to measure the network voltages at the time of the fault, this is only an indication of the expected frequency. There is an alternative command called EVENT, which will provide various snapshots of metering data and control status leading up to and following the fault event. Further examples can be observed in Appendix 12.3.

```
SEL-787                            Date: 30/10/2013   Time: 11:19:32.088
TRNSFRMR RELAY

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  EVENT LOGS = 11

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

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)       1.4           1.0           1.0          0.00

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       1.4           1.4           1.4          0.04
```

Figure 27 - Fault Event Summary

7.5.1.2 Residual

For the application of the residual overcurrent protection function, only winding two was configurable, the use of a delta configuration on the primary side prevents the detection of any residual currents available. This residual current protection function is derived directly from the three phase current metering data due to the absence of a neutral CT metering input on the relay. Analysing the IGW2 metering element at nominal current yielded a residual current of less than the minimum configurable setting (0.1A), thus the residual pickup setting was set to this value. Throughout simulations the phase overcurrent elements remained configured to replicate normal operational configurations. Figure 27 illustrates that in phase overcurrent trip events, the residual element (IGW2) is still below the minimum pickup setting.

During simulation, testing the residual element only responded to the removal of one phase of the load. This is because under these circumstances there was no introduction of overcurrent conditions on both the primary and secondary windings. Figure 28 contains the event summary for the residual fault trip event, showing that the residual metering element IGW2 has exceeded the configured pickup setting while not causing phase overcurrent conditions to result due to the removal of a single phase of the load.

```
=>>sum

SEL-787                                    Date: 26/11/2013   Time: 09:36:25.556
TRNSFRMR RELAY

Serial No = 2009300461        FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                    EVENT LOGS = 26

Event:     Wdg2 Gnd 50 Trip
Targets    11010000
Freq (Hz)  50.0

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)       0.7           1.0           0.8          0.00

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       0.6           1.4           1.4          0.82
```

Figure 28 - Residual Trip Event Summary

7.5.1.3 Negative Sequence Overcurrent Protection

The relay provides negative-sequence overcurrent protection, which is best suited in the detection of and protection from line-to-line faults. "*Because negative-sequence overcurrent elements do not respond to balanced loads, they can be set to operate faster and more sensitively than phase overcurrent elements for phase-to-phase faults on distribution systems. Like ground overcurrent elements, negative-sequence overcurrent elements can be set below load levels* [16]." To test and confirm this, phase overcurrent elements remained configured as previously while the pickup settings for the negative-sequence elements were set to the minimum possible 0.1A. The usage of this is justified after analysis of the phasor overview HMI window, confirmed negative sequence elements to be 0A (or below minimum pickup) during nominal conditions.

During simulation, testing the negative-sequence overcurrent protection elements responded to the introduction of line-to-line and phase load removal faults while the phase overcurrent element responded to the transformer winding short-circuit fault event, confirming the ideas presented by Edmund Schweitzer [16] as mentioned previously and confirming a successful simulation configuration. Figure 29 illustrates the event summary for the negative-sequence (50Q) trip event and provides verification (the event being identified as Wdg1 50Q Trip) that the desired response was obtained during a line-to-line fault. This summary doesn't contain the metered negative-sequence component; however it does give an indication that both contactors would be tripped and shows the variations in primary and secondary phase currents at the time of the fault.

```
=>>sum

SEL-787                              Date: 26/11/2013   Time: 09:29:34.406
TRNSFRMR RELAY

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  EVENT LOGS = 20

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

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)       1.6           2.9           1.7           0.00

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       1.4           3.7           3.6           0.02

=>>
```

Figure 29 - Negative-Sequence Trip Event Summary

The negative-sequence protection response to phase load removal prevents the residual current protection elements from responding. This has been tested and confirmed by configuring the residual component during the previous negative-sequence fault simulations.

7.5.2 Differential Protection

The simulation of differential protection required some "cheating" to allow for the configuration elements to be configured without generating errors. The calculation of the TAPn (Per-Unit value) element was required to be completed manually as described in section 6.2.3 Differential Protection. However with the variables entered to identically match those of the simulation the results were significantly outside the permissible configuration range (0.1-6.20 TAP). To overcome this issue the CT ratios used in the calculations were increased (by a factor of 10) to reduce the final calculation of TAPn to an acceptable level. At this point the O87P element (Restrained Element Operating Current PU as a multiple of TAP) was set to the maximum and the differential protection functionality was disabled to allow operation and obtain the nominal differential metering data through the Differential HMI window. At this point it was found that even with the modified calculations the differential metering values showed that the system was operating beyond a configurable level; the O87P element has a configuration range of 0.1-1 PU while the measured data reported 1.32 or higher PU, as shown in Figure 30.

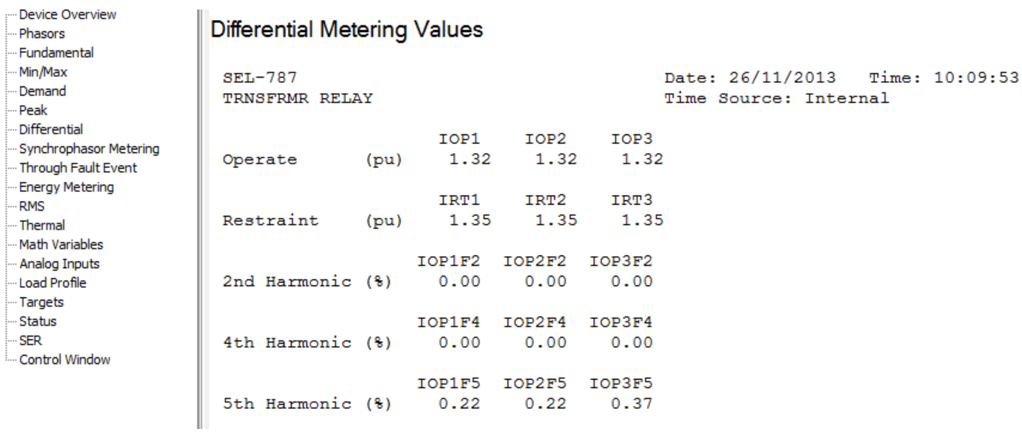

Figure 30 - Initial Differential Metering HMI

To account for this, the TAPn values were doubled (keeping the result within permissible bounds) and this resulted in both operate and restraint metered values being within protective configurable bounds, reducing these values below 0.68. As such, the O87P element was thus configured to 0.7 and the differential protection elements were enabled. Table 4 - TAPn Calculations shows the TAPn calculations and adjusted calculations that were made to reach the successful configuration of the Differential protection elements. The left most section contains the calculations with the real settings for the CT ratios while the middle contains the increased CT ratio calculation and the final section shows the resultant doubling of the configuration to allow operable configuration.

Table 4 - TAPn Calculations

Original Calculation			CT Correction Calculation		Final Adjustments	
Variable	Primary D	Secondary Y	Primary D	Secondary Y	Primary D	Secondary Y
TAPn	**23.80952381**	**15.19342814**	**2.380952381**	**1.519342814**	**4.761904762**	**3.038685627**
MVA	0.005	0.005	0.005	0.005		
VWDG	0.21	0.19	0.21	0.19		
CTRn	1	1	10	10		
C	1.732050808	1	1.732050808	1		

Throughout the initial tests the phase overcurrent elements remained enabled and configured from previous simulations, to again provide a realistic operating simulation, despite reducing the means to allow development of differential trip event. Under these conditions the differential elements would assert when the power supply was increased and the transformer windings were shorted. The remaining faults resulted in phase overcurrent faults. Figure 31 contains the event summary for the increase in power supply induced fault, showing both the primary and secondary currents increasing, which caused an increase in the differential elements being measured. This change can be observed in the event report generated through the use of the command EVE DIFn (n being the required phase 1, 2 or 3), which has the same result as the EVENT but includes the differential metering data for the numbered element set. An example of this output can be observed in Appendix 12.3.

```
=>>sum

SEL-787                          Date: 26/11/2013   Time: 09:54:59.778
TRNSFRMR RELAY

Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  EVENT LOGS = 32

Event:     Diff 87 Trip
Targets    11100000
Freq (Hz)  50.0

Winding One Current Mag
       IAW1          IBW1          ICW1          IGW1
(A)       1.1           1.1           1.1          0.00

Winding Two Current Mag
       IAW2          IBW2          ICW2          IGW2
(A)       1.5           1.5           1.5          0.02

=>>
```

Figure 31 - Differential Event Summary

There were occasions during differential configuration where the initial configuration of the CT ratio alone was enough to generate errors when attempting to download new settings regardless of whether the differential elements are enabled or not. The cause of this is the existence of the automatic calculation function associated with the configuration of the differential elements combined with the relays inability to ignore disabled elements during settings download. Even when the differential functionality is disabled the auto calculation still computes and with the non-ideal simulation configuration the eroded calculation for TAPn is still generated causing the initial errors. The solution is to enable the differential functionality to permit changing of the configuration then reduce the TAPn elements to acceptable bounds and adjust any other elements that will result in the generation of configuration errors. Once that is completed, disable the differential functionality then initiate the download process. This should now complete without error allowing operable testing to begin. The issue with the existence of the auto calculation is that every time changes to the CT configuration are made (CT ratio, nominal voltage (if available) and CT connection) the calculation will compute causing download errors. The errors produced are exaggerated by the inability to change the nominal line voltage settings, which are disabled the moment a change to the MVA setting is made, resulting in auto calculations always being erroneous. Even in the event that manual calculation settings are entered, the nominal line voltage fields are disabled, preventing these from being adjusted for future calculations.

8. Conclusion

The development of a comprehensive understanding of the SEL protective relays available within Murdoch University was the primary focus of this project, as this would enable development of a simulation to demonstrate the capabilities and functionality of associated devices. Throughout of the project various details and knowledge about the various collective relays have been acquired, which includes their scope of operational functionality, their individual requirements and the means and methods to program them. The use of this acquired knowledge was then used to successfully develop an operational simulation for transformer protection through the use of available Lab-Volt equipment and the SEL-787 Transformer Protection Relay. The incorporation of the Lab-Volt equipment in the final simulation allowed for successful demonstration of the SEL-787's current based protection functionality and provides the groundwork necessary to allow further development of Lab-Volt based simulations for voltage, frequency, power and other current based protective functions that the remaining relays are capable of providing.

Despite the development of a successful simulation, further hardware acquisition, investigations and functional testing is required in order to develop appropriate simulations for the remaining relays that comprise the SEL Protection and Monitoring System. The completion of these tasks would allow demonstration of the vast extent of protective functionality and its incorporation into a comprehensive distribution protection simulation.

9. Recommendations

Following completion of this project there are several recommendations that can be made for future project work and overall system improvement.

9.1 Lab-Volt Equipment

1. Acquisition of a Faultable Transmission Line module (not currently available within the university) from Lab-Volt to allow development of a series of simulations for transmission line, feeder, directional, distance and power protection functions. This module simulates the impedance (which is a known value) of a transmission line and provides a means to introduce faults midway along the simulated line. The line and feeder protection functions can be simulated in a similar manner to the transformer protection system already developed. The known impedance of the module combined with an addition of voltage monitoring will allow the simulation of power based protection. And with the addition of the Source Impedance module (already available within the university) distance and direction protection can be effectively simulated. Like the Faultable Transmission Line module, the Source Impedance module has a known value, which when configured correctly can permit the distance and direction protection functions to be configured to produce a suitable simulation platform. By using the Lab-Volt Protective Relaying Training system, a simulation can be constructed to an extent that the understanding of the operational capability of SEL functionalities can be determined and demonstrated, like the Transformer Protection Simulation. One suggestion though is to develop the simulation function by function separately; the conflicts that can arise when combining operational functionality can result in undesirable operations or unexpected results.

9.2 General Hardware

2. Investigate the possible removal of the three-phase power supply earth-leakage circuit breaker or using an alternative power source without this protection. The existence of this circuit breaker prevented the operational analysis of the relay during any form of fault to ground. This limited the ability to completely explore the SEL-787's protective capabilities in a wide range of faults and the configurations required to adequately and simultaneously protect against a variety of different fault conditions. Once this is completed, the transformer protection simulation system can be upgraded to include ground.
3. An improvement to the simulation can result from the acquisition of a more capable, higher rated load bank (resistive and reactive) providing a greater operational capability. Doing so will allow for higher fault levels to be developed during simulations, allowing better demonstration of the operable functionalities that the relays can provide. Currently, the resistive load module available

with the Lab-Volt system resulted in a fairly heavy operating restriction on the final simulation in terms of limiting the variety and magnitude of faults being introduced.

4. Acquire a collection of better rated hardware (transformer, contactors, relays etc.) to develop a higher powered and standalone system which can replicate the functionality provided through the Lab-Volt system whilst doing so at higher power ratings. This will allow a more realistic and self-contained simulation to be developed and improve the overall operation of the simulation and its protection capabilities.
5. Acquire a wider range of CTs with various ratios to help develop a more ideal simulation that is particularly beneficial to differential protection. In differential protection it is desirable to have CTs that result in identical secondary currents to allow easy and ideal configuration and operation of differential protection. The current mismatched CTs result in a differential protection system that under nominal operation has a significant difference in currents between the primary and secondary windings once the relay measures the currents. The calculations account for a variety of factors but can't eliminate the impact of mismatched CT ratios.
6. Acquisition of a non-isolation type faultable transformer will improve simulation relevance an applicable demonstration. The isolation type transformer used in the Faultable Transformer module has a turn's ratio of 1:1, resulting in un-realistic simulation circumstances and preventing a differential current across the transformer under fault conditions. This is why the Delta-wye configuration has been used, so that there is a natural adjustment in voltage and current seen between the primary and secondary windings. The use of a transformer with a non-isolating type turns ratio will help to improve the demonstration of differential protection. The fact that the simulations conducted were at similar voltages primary and secondary added to the complications experienced during the configuration of the differential elements.

9.3 SEL Relays

7. Further investigate the operable functional capabilities and develop appropriate simulations of the SEL-421 and 751A, the completion of which will allow for an understanding of the majority of protective functionality the SEL Protection and Monitoring System provides. Paying particular attention to the voltage and power based protective functionality of the SEL-421, features that haven't been deeply assessed during the transformer protection simulation, resultant of the availability of current based protection only with the relay.
8. Regarding the SEL-787, the acquisition of expansion I/O cards should also be considered. Doing so would expand the protective functionality to the point where neutral CT protection, voltage protection and thermal protection functions can be applied to the transformer protection simulation system. Doing so would allow replication of the necessary protective functionality applied to distribution transformers thereby improving the overall performance of the simulation. This may be solved by simply borrowing the expansion cards currently installed in the SEL-751A

to explore the possibility of the optional functionality. This is possible because both relays are built on the same design platform and the available expansion cards appear to be common in configuration and I/O capabilities between the two relays [12], [17]. The installation of new expansion cards will require proper configuration within the relay and on the I/O card itself, the transition is not quite the same as a plug and play functionality of the expansion system used in modern desktop PCs.

9. Investigate the acquisition of a second SEL-311L to allow development of a Line Current Differential Communications assisted simulation of a long distance transmission line. This relay has integrated communication settings within the line current protection functionality. The addition of this 2nd relay will also allow demonstration of the benefits of relay-to-relay communications provided by the SEL proprietary Mirrored Bits communication protocol.
10. Develop a system that incorporates the SEL-3351 Embedded PC and the monitoring communications it can provide. Investigations need to be made into configurations that allow the device to simultaneously communicate and receive monitoring data from all the relays. If enough of the proper Db-9 type cables are acquired then the 3351 can be used to easily program all relays simultaneously through proper networking configuration via the device manager functionality of the AcSELerator Quickset program. Currently the program is installed on a flash drive connected to the device, but the on board memory is fairly limited, which restricts installation of the program directly. One possibility before commencing this course of action is to investigate the possibility of obtaining a replacement updated model. The current 3351 operates with Windows XP, which encounter the potential security risks when Microsoft drops all support and security updates in the near future. This will be an issue if the monitoring and control/configuration is to be established through a TCP/IP network.

9.4 Protection Functionality

11. Incorporate Time Overcurrent elements into the developed simulations, the benefits of developing a coordinated protection system may be more observable when a larger simulation is developed better demonstrating the protective benefits.

9.5 cDAQ Potential

12. There is a potential for using the cDAQ with the SEL Protection and Monitoring System. the cDAQ has the most potential when used with the SEL-421, which is known to have digital I/O with configurable pickup and dropout levels. This would allow the cDAQ to simulate circuit breaker control and monitoring as part of the original software based simulations. The use of this could be applied to remote control and monitoring simulations. The cDAQ combined with an appropriately developed LabView program could be utilised to simulate a remote HMI panel for manual controls and status monitoring. This is possible because the available I/O can be tied to replicate or control the status of various relay elements (targets and control relay words). This can replicate a physical hardwired I/O panel and alarming equipment that may normally be attached to provide easy control and monitoring of relays elements without diving into the deep front panel display menus.

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11. Glossary

ANSI	American National Standards Institute
BNC	Bayonet Neill–Concelman Connector
cDAQ	Compaq DAQ
CT	Current Transformer
CVT	Capacitive Transformer Voltage
DAQ	Data Acquisition
DMM	Digital Multi-Meter
D-Sub	D-Subminture Connector
ENG454	Industrial Computer Systems Design
GE	General Electric Company
GPS	Global Positioning System
HMI	Human Machine Interface
I/O	Inputs and Outputs
IEC	International Electrotechincal Commission
IEEE	Institute of Electrical and Electronics Engineers
IRIG-B	B type Inter-Range Instrument Group time code
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NI	National Instruments
PMU	Phasor Management Unit
RCD	Residual-Current Device
Relay Word	Labels associating relay functions to the SELogic equations
RJ45	8 position 8 contact Registered Jack
SCADA	Supervisory Control and Data Acquisition
SEL	Schweitzer Engineering Laboratories
SIR	Source Impedance Ratio
SSR	Solid State Relay
Target	The status/indicator of a relay word
TOC	Time Overcurrent
USB	Universal Serial Bus
Variac	Variable Transformer
VT	Voltage Transformer
X/R	Reactance-to-Resistance ratio

12. Appendices

12.1 AcSELerator Quickset Manual

Available via the external document titled “AcSELerator Quickset User Manual” available from the school of Engineering and Information Technology.

12.2 Transformer Protection Simulation Manual

Available via the external document titled “Transformer Protection Simulation User Manual” available from the School of Engineering and Information Technology.

12.3 Simulation Event Data

12.3.1 Phase Overcurrent

Transformer internal short circuit fault EVENT command output

```
=>>event

SEL-787                                   Date: 26/11/2013   Time: 10:04:59.148
TRNSFRMR RELAY

Serial Number=2009300461
FID=SEL-787-R202-V0-Z001001-D20100215   CID=53A1

                                                                 O
                                                               I u
                                                               n t
                      Currents (A Pri)                         1 13
    IAW1    IBW1    ICW1    IGW1    IAW2    IBW2    ICW2    IGW2 2 2
[1]
    1.0    -0.4    -0.7     0.0     1.3    -1.1    -0.3    -0.0  . ..
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0* . ..
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . ..
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0  . ..
[2]
    1.0    -0.4    -0.9     0.0     1.3    -1.1    -0.2    -0.0  . ..
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . ..
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . ..|
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0  . ..
[3]
    1.0    -0.4    -0.8     0.0     1.3    -1.1    -0.2    -0.0  . ..
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . ..
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . ..
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0  . ..
[4]
    1.0    -0.4    -0.8     0.0     1.3    -1.1    -0.2    -0.0  . ..
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . ..
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . ..
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0  . ..
[5]
    1.0    -0.4    -0.8     0.0     1.3    -1.1    -0.2    -0.0  . ..
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . ..
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . ..
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0> . ..
[6]
    1.0    -0.4    -0.8     0.0     1.3    -1.1    -0.2    -0.0  . 2.
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . 2.
   -1.0     0.4     0.8     0.0    -1.3     1.1     0.2     0.0  . 2.
    0.1    -0.9     1.1     0.0    -0.4    -0.9     1.4     0.0  . 2.
[7]
    1.0    -0.4    -0.8     0.0     1.3    -1.1    -0.2    -0.0  . 2.
   -0.1     0.9    -1.1     0.0     0.4     0.9    -1.4    -0.0  . 2.
   -1.0     0.4     0.8     0.0    -1.2     1.1     0.2     0.0  . 2.
    0.2    -0.8     0.7     0.0    -0.2    -0.9     1.1     0.0  . 2.
[8]
    0.5    -0.3    -0.4     0.0     0.7    -0.6    -0.1    -0.0  . 2.
   -0.2     0.3    -0.2     0.0    -0.1     0.4    -0.4    -0.0  . 2.
   -0.1     0.1     0.0     0.0    -0.1     0.1    -0.0    -0.0  . 2.
    0.0    -0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
[9]
    0.0    -0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
   -0.0    -0.0     0.0     0.0     0.0    -0.0     0.0    -0.0  . 2.
   -0.0     0.0    -0.0     0.0     0.0    -0.0     0.0    -0.0  . 2.
    0.0    -0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
[10]
    0.0    -0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
    0.0     0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
   -0.0    -0.0    -0.0     0.0     0.0    -0.0     0.0    -0.0  . 2.
    0.0     0.0    -0.0     0.0     0.0     0.0    -0.0    -0.0  . 2.
[11]
    0.0     0.0     0.0     0.0     0.0     0.0    -0.0    -0.0  . 2.
   -0.0    -0.0     0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
   -0.0    -0.0    -0.0     0.0    -0.0    -0.0     0.0    -0.0  . 2.
    0.0     0.0     0.0     0.0    -0.0    -0.0    -0.0    -0.0  . 2.
```

```
Serial No = 2009300461      FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                  EVENT LOGS = 37

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

Winding One Current Mag
          IAW1          IBW1          ICW1          IGW1
(A)        1.0           1.0           1.4           0.00

Winding Two Current Mag
          IAW2          IBW2          ICW2          IGW2
(A)        1.4           1.4           1.4           0.05
```

Line to line fault SUMMARY command output

```
=>sum

SEL-787                                   Date: 26/11/2013    Time: 09:24:33.486
TRNSFRMR RELAY

Serial No = 2009300461        FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                    EVENT LOGS = 18

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

Winding One Current Mag
        IAW1          IBW1          ICW1          IGW1
(A)       1.7           2.9           1.7           0.00

Winding Two Current Mag
        IAW2          IBW2          ICW2          IGW2
(A)       1.4           3.7           3.7           0.02

=>
```

12.3.2 Negative-Sequence Overcurrent

Line-to-Line fault event SUMMARY command output

```
=>>sum

SEL-787                                   Date: 26/11/2013    Time: 09:29:34.406
TRNSFRMR RELAY

Serial No = 2009300461        FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                    EVENT LOGS = 20

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

Winding One Current Mag
        IAW1          IBW1          ICW1          IGW1
(A)       1.6           2.9           1.7           0.00

Winding Two Current Mag
        IAW2          IBW2          ICW2          IGW2
(A)       1.4           3.7           3.6           0.02

=>>
```

Single Phase Load dropout fault SUMMARY command output

```
=>>sum

SEL-787                                   Date: 26/11/2013    Time: 09:33:18.016
TRNSFRMR RELAY

Serial No = 2009300461        FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                    EVENT LOGS = 22

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

Winding One Current Mag
        IAW1          IBW1          ICW1          IGW1
(A)       0.8           1.0           0.7           0.00

Winding Two Current Mag
        IAW2          IBW2          ICW2          IGW2
(A)       0.6           1.4           1.4           0.84

=>>
```

12.3.3 Residual Overcurrent

Single Phase Load dropout fault SUMMARY command output

```
=>>sum

SEL-787                                   Date: 26/11/2013    Time: 09:36:25.556
TRNSFRMR RELAY

Serial No = 2009300461        FID = SEL-787-R202-V0-Z001001-D20100215
CID = 53A1                    EVENT LOGS = 26

Event:     Wdg2 Gnd 50 Trip
Targets    11010000
Freq (Hz)  50.0

Winding One Current Mag
        IAW1          IBW1          ICW1          IGW1
(A)       0.7           1.0           0.8           0.00

Winding Two Current Mag
        IAW2          IBW2          ICW2          IGW2
(A)       0.6           1.4           1.4           0.82

=>>
```

12.4 Important Relay Specifications

12.4.1 SEL-421

SEL-421	**Protection Automation System**		
P/N	042126152A2AXH35XXXX		
S/N	2008269404		
FID	SEL-421-R128-V0-Z012011-D20090428		
Power Supply		**AC voltage Inputs**	
DC	125/230V	Continuous	300V (L-N)
Range	85-300V	Thermal	600 Vac for 10 seconds
AC	120/230V	**Control Outputs**	
Range	85-240V	Make	30A
Frequency	50/60Hz	Thermal	50A for 1 second
Range	30-120Hz	Protection	250Vac/330Vdc
Burden	35W	Pickup/Dropout Time	6ms
Burden	<120VA	Update Rate	1/8 cycle
AC CT inputs		**Control Inputs**	
Nominal	5A	Direct Coupled	DC use
Continuous	15A	Range	15-265Vdc, independently adjustable
Range	0.25-100A	Accuracy	±5% plus ± 3Vdc
Thermal	500A for 1 second	Max Voltage	300Vdc
Thermal	1250A for 1 cycle	Sample Rate	1/16 cycle
Burden	0.27VA at 5A	Burden	0.24W at 125Vdc
	2.51VA at 15A		

12.4.2 SEL-751A

SEL-751A	**Feeder Protection Relay**		
P/N	751A02B1B0X6X811630		
S/N	2009320380		
FID	SEL-751A-R402-V0-Z006003-D20100129		
Power Supply		**Control Inputs**	Optoisolated
Rated	24-48V DC	Version	24V
Range	19.2-60Vdc	DC ON	15-30Vdc
Burden	<25W	DC OFF	<5Vdc
AC CT Inputs		AC ON	14-30Vac
Nominal	1A	AC OFF	<5Vac
Continuous	15A	Current	10mA
Thermal	500A for 1 second	**Analog Output**	
Burden	<0.01VA	Current	±20mA
AC Voltage Inputs		Voltage	±10V
Rated	100-250Vac	Load (1mA)	0-15kΩ
Continuous	300Vac	Load (20mA)	0-750Ω
Thermal	600 Vac for 10 seconds	Load (10V)	>2000Ω
Burden	<0.1VA	Refresh Rate	100ms
Output Contacts DC		Error	<±0.55%
Rated	250Vdc	**Analog Input**	
Range	19.2-275Vdc	Max Range	±20mA
Make	30A		±10V
Thermal	50A for 1 second	Impedance	200Ω current
Protection	360Vdc		>10kΩ voltage
Output Contacts AC		Error	<0.5% un-calibrated
Max	240Vac		
Protection	270Vac		
Rated Current	3A at 120Vac		
	1.5A at 240Vac		
Thermal	5A		

12.4.3 SEL-787

SEL-787	**Transformer Protection Relay**		
P/N	27870XA0X0X0X810830		
S/N	2009300461		
FID	SEL-787-R202-V0-Z001001-D20100215		
Power Supply		**Output Contacts AC**	
Rated	110-250V DC	Max	240V
	110-240V AC 50/60Hz	Protection	270V
Range	85-275Vdc	Rated Current	3A at 120Vac
	85-264Vac		1.5A at 240Vac
Burden	<20W dc	Thermal	5A
	<40VA ac	**Control Inputs**	Optoisolated
AC CT Inputs		Version	125Vdc
Nominal	1A	DC ON	100-156.2Vdc
Continuous	15A	DC OFF	<75V
Range	0.02-19.2A	AC ON	85-156.2Vac
Thermal	100A for 1 second	AC OFF	<53Vac
Burden	<0.01VA	Current	4mA
Output Contacts DC			
Rated	250V		
Range	19.2-275V		
Make	30A		
Thermal	50A for 1 second		
Protection	360V		

12.4.4 Secondary Relays

SEL-311L	**Line Current Protection and Automation System**	**SEL-351**	**Directional Overcurrent Relay**
P/N	0311L1HDD3254X2X4	P/N	035160H35B4XX1
S/N	2009309181	S/N	2007110113
FID	SEL-311L-1-R410-V0-Z104006-D20100312	FID	SEL-351-6-R403-V0-Z008006-D20091028
Power Supply		**Power Supply**	
	48/125V DC		48/125V DC 50/60Hz
	125V AC 50/60Hz		120V AC
Burden	<25W	Burden	25W
Range	38-200Vdc, 85-140Vac	Range	38-200Vdc, 85-140Vac
SEL-3351	**System Computing Platform**	**SEL-387E**	**Current Differential and Voltage Protection Relay**
P/N	335135741H0004VV7F3	P/N	0387E0Y3X52X4X
S/N	2007214132	S/N	2009131256
FID	NA	FID	SEL-378E-R605-V0-Z003003-D20071025
Power Supply		**Power Supply**	
	48/125V DC	Rated	45/125V DC
	120V AC 50/60Hz		125V AC 50/60Hz
Burden	40W	Burden	<25W
Range	38-140Vdc, 85-140Vac	Range	38-200Vdc, 85-140Vac