WIDE-AREA PROTECTION OF DISTRIBUTION NETWORKS USING DIRECTIONAL AGENTS DERIVED FROM LV POLARISING VOLTAGE SIGNALS AND HV CURRENT MEASUREMENTS

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Abstract

Motivation for this project is to contribute to developing a more sustainable future for humankind by helping to reduce dependency on the burning of fossil fuels. Largely this is expected to be achieved by harnessing energy from renewable resources and converting and supplying it in the form of electricity. The project considers the impact that this will have on existing electrical transmission and distribution networks, and discusses changes needed to transition electrical supply networks to the smart operation that will be required to accommodate increasing amounts of electrical energy generated from renewable resources such as wind and solar.

A proposal, to evolve distribution network protection techniques to adapt them for application to future networks incorporating large amounts of distributed energy resources, is proposed and researched. Specifically, Directional Agents, combining proven measurement techniques with extra information about power system conditions, are proposed as a method of determining directional information about the flow of power flows across networks. A novel approach is introduced, as a low-cost alternative to traditional approaches, for acquiring critical power system signals necessary to compute the directionality of the power flows. Wireless communications are introduced for consideration as a means to inter connect the component parts. The combination is evaluated for suitability to implement selective, cost-effective directional comparison unit protection, for smart, potentially wide-area, distribution networks.

A model of a generic electrical distribution network is created and verified to allow the concept to be evaluated. Simulation models of Directional Agents are designed and validated before being applied to the network model to qualify the protection concepts. The effectiveness of using voltage measurements, acquired from LV locations, to polarise HV/MV protection elements accommodated within Directional Agents located elsewhere on the network at conventional relaying points, is studied. The performance of unit protection schemes formed by interconnection of devices with communications channels is explored. The feasibility of realising the schemes using wireless communications is examined.

Simulation test results, combined with literature review and feasibility studies, provide encouragement to develop the proposal for commercial application, as well as highlighting areas for further concept evaluation.

Declaration

The author declares that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Acknowledgement

Prior to undertaking this PhD study, the author has enjoyed engagement in the discipline of electrical power systems protection for over thirty years.

He obtained his first degree from the University of Bath in the 1980s under the supervision of Allan Johns and Raj Aggarwal, whom he would like to thank for stimulating an interest in the subject.

Shortly after graduating the author completed an Apprenticeship with GEC Measurements in Stafford. Remaining with the Company (in its various incarnations) for over twenty-five years, the author completed a lengthy 'industrial placement'. During this time, he enjoyed working alongside many influencers in the industry. The help and guidance of all is appreciated. In total they are too many to mention, but for their particular part in developing his professional skills, the author specifically acknowledges the help of Wilson Kwong, Miles Redfern, Bob Ball, Adrian Newbould, and David Buckless.

Since returning to study, the author is grateful for the help and advice received from both staff and fellow students at the University of Manchester. This is especially true in the case of the author's supervisors, Dr Qiang Liu and Professor Peter Crossley. The latter of these, however, has provided help and guidance throughout the author's career, and is highlighted for special attention.

Peter Crossley was a post-doctoral engineer at GEC Measurements when the author joined the Company. Peter was one of the driving forces behind the introduction of microcomputer technologies into protection relays and provided early stimulus to the author in this field through involvement in collaborative projects. Collaboration continued as Peter's career progressed researching power systems protection in academia whilst the author pursued a career developing protection equipment in industry. It was through ongoing collaboration that, in 2016, Peter introduced the author to the possibility of undertaking a PhD funded through the EPSRC. It was an opportunity not to be refused and the author acknowledges EPSRC for funding the work[1].

Through his supervisory role Peter has continued to exercise influence over the author's learning. This acknowledgement is, therefore, particularly dedicated to recognising the contribution that Peter has made to the author's (continuing) professional Development.

Thank you Peter.

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[1] *EPSRC (EP/L016141/1)*

Introduction

This thesis is submitted for the award of PhD in Power Networks at the University of Manchester. Its principal focus is on developing the protection of electrical distribution networks to facilitate transitioning towards a Net Zero future [1].

Motivation

Motivation for this project is to contribute to developing a more sustainable future for humankind. A recognised major threat to humankind is global warming linked to increasing levels of carbon-dioxide (CO2) emissions [2].

Much of the increase in CO_2 emissions is attributed to the burning of fossil fuels. According to Denchak [3], "Fossil fuels produce large quantities of carbon dioxide when burned. Carbon emissions trap heat in the atmosphere and contribute to climate change. In the United States, the burning of fossil fuels, particularly for the power and transportation sectors, accounts for about three quarters of our carbon emissions." Whilst converting away from fossil fuel dependency will help combat global warming, alone, it is unlikely to be sufficient. According to the Intergovernmental Panel on Climate Change (IPCC) [4], it is predicted that required adjustments to keep global warming within a 1.5ºC safe limit will not be achieved by conversion alone. Concern over levels of energy usage is endorsed by Woolward [5], but activities to target reductions are not the focus of this work. Rather, the work concerns the efforts to support the transition of satisfying energy demands by supplying them from renewable sources instead of fossil fuel burning. Harnessing energy from renewable resources (such as wind and solar), and converting it into electricity for supply and consumption is expected to drive this transition [6].

Globally, electricity is supplied via vast networks of transmission and distribution components [7]. Changing components (including the sources of generation) that connect, and contribute, to the supply and distribution of electricity, will necessitate change to how electrical transmission and distribution networks are operated [8]. Traditional power supply models feature bulk generation sites which are generally located close to necessary operational resources (fuel and water). Having been generated, the electricity is transported to (usually remote) consumer demand locations via transmission and distribution networks. With such arrangements with generating stations radially supplying the loads, there is an inevitable characteristic that, in the wires and cables that interconnect the components, power flows almost exclusively in the direction of transmission to consumer, from the generating stations to the various, and numerous, loads.

Although electricity generation from naturally occurring 'renewable' energy resources can be concentrated in large-scale generating zones (such as off-shore windfarms), it is generally produced on a smaller scale than that from conventional fossil-fuel burning power stations. Since the resources from which the electricity is generated are less geographically constrained by, for example the locations of coalmines or oil fields, the generators may be more usefully located by embedding them close to load centres. As well as preferentially consuming renewable energy resources, embedded power generation units are usually small-capacity units that can be deployed into the power grid near the load. By doing this, "distributed power generation units ... meet the load demand of specialized users or complement the grid for economic efficiency" [9].

Embedding dispersed sources of generation, particularly in proximity to loads, changes the challenges of balancing supply and demand. Responding to new challenges requires techniques such as demand-side response and storage to be adopted [10]. In part, this is facilitated by integrating Information and Communications Technology (ICT) resources into the existing power networks. The defining terminology 'Smart Grid' is applied to the outcome of this mixing of old and new which delivers computer-controlled dynamic networks [11], be they humble evolutionary hybrids, or applications fully exploiting of the technology advancements [12]. One particular challenge, which motivates this work, is the requirement to protect these smart networks against the effects of faults and abnormal operating conditions. It should be noted that the proposal made in this thesis is not immediately targeted for scenarios such as those currently evolving in the UK where, at distribution level, relatively small amounts of embedded generation may be integrated within a strong (high capacity) grid. Rather, it is expected that the attraction of the proposal will be stronger in alternative scenarios where supply is dominated by the contributions of distributed generation and where grid supply is very weak (or even where it may be non-existent such as in islanded conditions). There may not be a strong compulsion to deploying the techniques in the short-term on evolving network topologies, but in the longer term, or in emergent low-carbon networks, they could present an attractive approach to satisfying operational demands.

Non-directional overcurrent relays are widely used as the main type of protection on traditional radial electrical distribution systems [13]. On a radial network with power flow in only one direction, a fault will generally cause an increase in the current flowing from the source. Since the direction of current flow hasn't changed, the fault will generally correspond to an increase in current magnitude which is easily detected by overcurrent measuring devices. In smart grids where the magnitudes and directions of current flow can dynamically change according to the network topology, even in the absence of faults, a simple overcurrent approach is no longer adequate [14], [15]. An alternative approach that is investigated herein uses information about the directions of current flows across the network to determine whether the network is healthy, or whether the network is faulted. This approach is supported by Razavi et al., who observe that whilst the introduction of distributed generation can make power systems more reliable, secure, and efficient, it brings challenges for protection systems, and voltage regulation issues [16]. Overcurrent protection, they advise, is affected by changes in the magnitude and direction of the fault currents. Amongst alternatives that they discuss to overcome the challenge, they propose the use of directional overcurrent relays.

Directional overcurrent relays employ a reference voltage signal to determine the direction of the fault (current). This requires measurement of both current and voltage using respective sensors and makes directional overcurrent protection more expensive to deploy than non-directional equivalents [13]. A major contributor to the additional ‘expense’ of providing directional protection is the cost and associated footprint size associated with the voltage sensor. It is proposed in this work that a small, low-cost alternative to the conventional protection voltage transformer (VT) could make protection schemes, for evolving distribution networks, based around the proven directional protection principles, economically, as well as technically, attractive.

Research Objective

This project researches the potential for providing unit protection schemes based on directional principles for smart distribution networks, where conventionally determined overcurrent measurements are qualified with directional information derived from using small, low-cost, non-conventional voltage signal acquisition devices.

Providing unit protection requires protection devices to communicate with each other. The increasing reach of wireless communications makes them an attractive candidate for the interconnectivity required by the scheme, and so this suitability is also researched within the scope of the work.

Contributions

Distribution networks are having to change to accommodate a greener agenda. Because the design and operation of these networks are changing, so the way in which they are protected against faults, and abnormal operating conditions, needs to change. Traditionally, distribution networks have relied heavily on the widespread deployment of overcurrent relays to provide protection. Overcurrent relays have many advantages that make them suitable for cost-sensitive applications. As well as the relays themselves being relatively inexpensive, they require connection only to current measuring devices and circuit breakers to provide comprehensive main and back-up protection, and so the whole costs of installation, commissioning, and maintenance are kept low. As distribution networks begin to host resources such as embedded generation powered from renewable resources (such as wind and solar), they must adapt to suit the variability of supply by introducing features like battery storage, and active load management. A consequence is that conventional concepts of power flows (in the direction of producer to consumer) are being compromised and the expected behaviours of voltage and current levels under abnormal operating conditions are being violated. Under such conditions, graded overcurrent protection is ineffective and different techniques are needed. Protection techniques such as differential, distance, and directional comparison, are well established to shoulder the responsibility of protecting the more complex transmission networks, but their performance comes at a cost.

This work recognises that the techniques traditionally applied at transmission levels may be appropriate for deployment on evolving distribution networks if the burden of additional associated costs can be avoided. Although transmission protection devices may be similar to distribution protection devices in terms of size, technology, and construction, the costs associated with deploying them can be significantly higher due to the additional ancillary equipment and services that they require. Distance protection [17], for example, incurs the additional costs and real estate burden associated with the provision of a compliment of voltage measurements for each protected phase. In contrast, line current differential protection [18] has a dependency upon critical communications provision [19]. Directional comparison schemes based on superposition principles [20] need a combination of both voltage measurements and fast communications.

This project considers adapting established principles, traditionally applied to transmission networks, to deliver protection capabilities aligned with the budgets normally afforded to the protection of distribution networks. Avoiding the need for precise voltage measurements to calculate the accurate impedances required for distance protection, and using voltage inputs only as a means to provide reference for directional polarising, and by using novel voltage acquisition devices (Voltage Cubes) to source the voltage, unconventionally, from the connected LV circuits, a proposal to provide unit protection, based on directional comparison protection principles) for evolving distribution network topologies is proposed. The need for extravagant deployment of conventional VTs is overcome by the novelty of remote signal acquisition. Sampled voltage signals are combined with conventional overcurrent measurements in wirelessly connected Directional Agents to provide robust, selective, plug-and-play protection.

The originality of contribution may be illustrated by the following Table 1, which compares the proposal against typical established approaches.

Table 1: Protection Scheme Requirements Appraisal.

	Feature										
Protection philosophy	Unit selectivity	Directional selectivity	3-phase VT not required	1-phase VT mot required	High-accuracy voltage transformation not required	Input signal frequency tracking not required	High-speed data acquisition not required	High bandwidth comms not required	Symmetrical/fixed-route comms (µs) not required	GPS-class Time-synch (µs) not required	Back-up for communication failure
Candidate proposal	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Time-graded overcurrent protection			✓	✓	✓	✓	✓	n/a	n/a	n/a	n/a
Conventional directional overcurrent protection		✓	✓		✓	✓	✓	n/a	n/a	n/a	n/a
Distance protection	**	✓		*				✓	✓	✓	✓
Current differential protection	✓		✓	✓	✓	✓	✓				
Superimposed component (delta) directional comparison	✓	✓							✓		
Phase comparison	✓	✓	✓	✓	✓					✓	

Notes :

* according scheme logic

** with auxiliary signalling equipment

Referring to Table 1, it can be seen that, to its advantage, the candidate proposal offers the same unit protection selectivity as the sophisticated protection based on the techniques of: numerically implemented line current differential protection, delta direction comparison protection, and phase comparison protection [21]. Unlike these other methods (especially line current differential protection), however, the candidate proposal does not have such demanding dependencies on the communications and time synchronisation requirements [22].

Whilst both distance protection and directional overcurrent protection can be applied in schemes to provide a form of unit protection, this requires the use of additional equipment to interface the communications to create the schemes. Compared with such conventional aided scheme designs, the use of wireless communications in this proposal offers savings in terms of costs and real estate. Either way, distance protection and directional comparison protection require the use of voltage measurements. Conventionally provided in the form of iron-cored, copper-wound transformers, they are large, heavy, and expensive, and in the case of distance protection, in particular, full voltage measurement is required for each protected phase.

The candidate proposal is implemented around a purpose-intended, small, low-cost voltage acquisition unit providing sampled analogue voltage signal values to Directional Agents for processing. The principle takes advantage of the voltage transformation process that necessarily occurs in the power transformers responsible for converting distributed electrical power quantities to consumer required levels. The concept embraces the ICT facilitated emergence of using sampled analogue values (SAV) provided by combinations of non-conventional instrument transformers (NCIT) and so-called merging units (MU) in digitalisation of electrical substations [23]. However, unlike in a MU in which, typically, 9 streams of voltage and current measurements from different NCIT on the HV network are merged and presented as SAV stream, in this application, a single SAV channel provided from a purpose-designed Voltage Cube acquiring its measurement from the LV network, can provide all of the non-current analogue information required for the protection. Accordingly, significant savings in terms of reduced complexity, componentry, insulation, isolation, and installation can contribute to a low-cost solution.

Concerning the communications, the directional comparison scheme need only transmit the equivalent of a binary state (forward or reverse indications) to satisfy the functional requirements of the scheme. At transmission levels sub-cycle protection operating times might be expected and protection which incorporates communications requires them to be accordingly fast to achieve this. Further, for many line unit protection schemes, precise knowledge of, and control over, the communications paths and associated delays may be critical to assure security and dependability of tripping [24]. At distribution levels, protection operating times are more relaxed and, with directional comparison principles not requiring communications symmetry, communications delays of the order of tens of milliseconds across switched networks can be accommodated. With line current differential protection and phase comparison schemes, in the event of communications failures, they will naturally block tripping. With the directional comparison scheme however (like distance protection) the default can be managed according to the scheme logic which, in most cases nowadays can be freely programmed by a user to suite their preferences (permissive tripping, or blocking).

Thus, a candidate solution for protection of evolving distribution networks is proposed and researched in this thesis. The candidate solution has three principal attributes which guide three threads of research and, hence, the thesis structure. These three threads define what the author considers to be the significant contributions of this work to the body of knowledge. The candidate, therefore, makes the following declaration in this respect:-

The author of this work believes that the research work detailed in this thesis makes the following novel/key contributions to the general area of power system protection development:-

- A new approach to the provision of unit protection for distribution networks based on directional comparison techniques.
- A novel approach to the provision of voltage signals for polarising directional protection for distribution networks based on sampled analogue values of voltage signals acquired from connected low-voltage networks.
- A novel application of wireless IEC 61850 Ethernet communications combining sampled-analogue-value (SAV) and generic object-oriented substation event (GOOSE) services to implement directional comparison unit protection schemes.

Thesis Structure

In presenting this work, this PhD thesis is structured along broadly conventional lines. The work is guided by literature review which, in particular, guides the formation of the introductory chapters. After the introductory chapters, the three chapters following Chapter 5 respectively address, planning and research methodologies, research activities, and results. These three chapters (Chapter 6, Chapter 7, and Chapter 8) are each arranged into three parts, with each part of each one aligning with one of each of three described research threads.

- Directional protection principles.
- Acquisition of suitable polarisation quantities [2].
- Wireless interconnectivity.

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[2] Polarisation is a technique employed in protective relaying, whereby a reference quantity is established in order for the relay to determine the direction of the current flow at the relay location. This reference quantity is referred to as the polarising quantity, and it is against this reference that an operating quantity is compared [25]. Typically, a polarising quantity may be the voltage signal (voltage polarisation) associated with the protection operating quantity (for example phase current), or a complimentary quadrature line-line voltage from the other phases (cross-polarisation), a suitable other current signal (such as the negative sequence current for negative sequence polarisation), or a memorised voltage value (memory polarisation). The selection is made with consideration to the application.

The resulting overall thesis structure, therefore, is as follows:-

- Chapter 1 introduces key concepts and components of electrical power systems. Traditional power system models are presented, and conventional power flow characteristics are explained. Opportunities for connecting additional generation from other (renewable) sources are outlined, and their impacts on power flow characteristics are discussed.
- Chapter 2 introduces the need to provide electrical power systems with protection. Key principles of protection are introduced. The enabling impact of ICT, particularly in IEC 61850 [26] manifestation, to provide advanced complementary control and automation opportunities, is elaborated.
- Chapter 3 concentrates on how the parts of the electrical power system focussed on distributing power to consumers might be protected. Conventional protection techniques applied to distribution systems are outlined. How the inclusion of dispersed embedded generation into the distribution network is changing operational requirements is explored. The concept of providing protection with a sense of directionality is introduced.
- Chapter 4 discusses how directional protection concepts may be adapted for smart distribution network applications. A novel approach to the design and application of wide-area principles of protection and control to evolving electrical distribution networks is described. Appraising this concept and its associated components are the core of this work.
- Chapter 5 presents a literature review.
- Chapter 6 introduces the strategies and tools employed by the research. Expected research outputs are outlined. Planning (including summary work breakdown and methodologies employed) to achieve these outcomes is presented. A range of research techniques including literature survey, feasibility study, system modelling, protection simulation and testing, are identified as appropriate to the research. A mixture of these is employed to attain research outcomes. The first part of the chapter associates with evaluating the strategy to apply directional protection to distribution networks. A strategy is outlined to develop a generic distribution network, to verify the model, and to use the model to test protection performance. The second part of the chapter associates with assessing the feasibility of acquisition of LV polarising signals. The third part of the chapter associates with assessing the feasibility of using wireless communications to implement proposed directional protection schemes.
- Chapter 7 details the research activities undertaken. The first part of the chapter associates with evaluating the application of directional protection

to distribution networks. The second part of the chapter assesses LV polarising signal acquisition. The third part of the chapter assesses using wireless communications to implement the proposed directional protection scheme.

- Chapter 8 presents the results obtained from the research activities. The first part of the chapter associates with evaluating the application of directional protection to distribution networks. The main allocation of this is associated with simulation testing. Results are presented to verify a generic distribution network model created to evaluate directional protection, to verify the development of purpose-designed directional overcurrent protection relay simulation model, to verify the development of a purpose-designed unit protection simulation scheme based on intercommunicating simulated directional overcurrent relays, and to demonstrate the performance of the unit protection scheme simulation model under various network configurations. The second part of the chapter summarises evaluation of LV polarisation issues. Feasibility study outcome is presented. Critical literature review is complemented by rudimentary field tests. The third part of the chapter summarises the use of wireless communications to implement the proposed directional protection scheme. Observations from literature review supplement obtained results.
- Chapter 9 draws conclusions from the research activities.
- Chapter 10 outlines opportunities to extend the research.

Publications

At the time of writing, two papers are accepted for conference publication.

Both are accepted for oral presentation at The 16th International Conference on Developments in Power System Protection (IET DPSP2022), to be held 7-10 March, Gateshead, UK.

Conference paper details are:-

- “Distributed Low-Voltage Measurements for use in Electrical Distribution Networks’ Protection, Control, and Automation Schemes”. S. Potts, and P.A. Crossley.
- “Distribution Network Protection Schemes formed from Wirelessly Connected Directional Agents”. S. Potts, and P.A. Crossley.

Chapter 1 Electrical Power Systems Introduction

As illustrated in the Figure 1, a typical electrical power system provides generation of electrical power, transmission of the electricity over high voltage electrical circuits, and scaling down (transformation) of the electricity to lower voltages for distribution, and consumption.

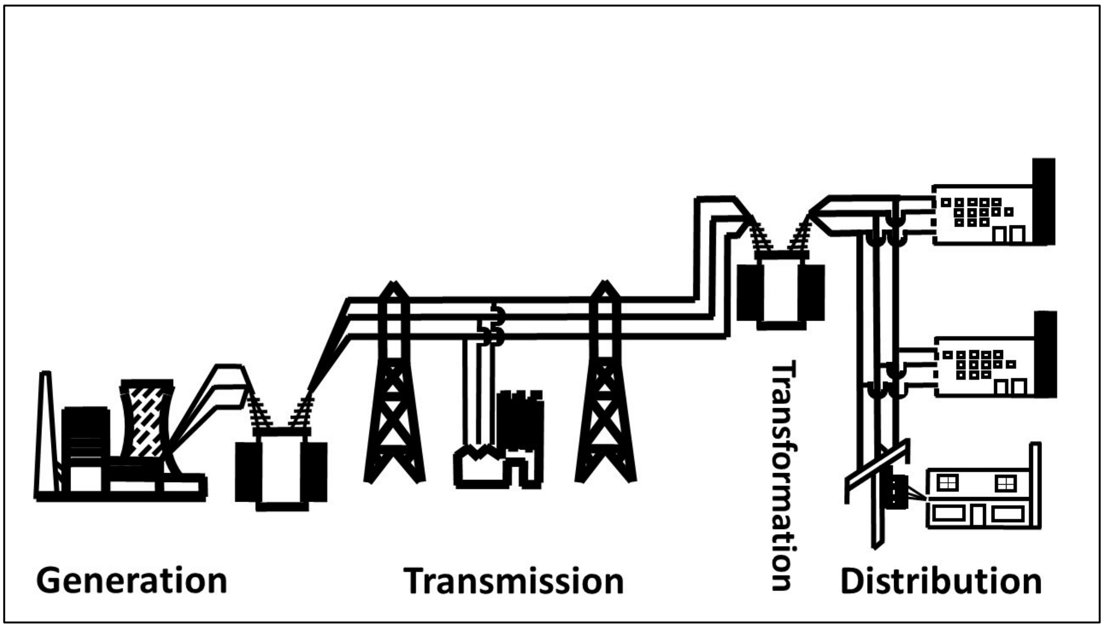

Figure 1: Electricity Supply System.

(adapted from [27])

For transmission, high voltages are used so that losses are minimised [28], and for reliability the network may be highly interconnected [29] - parallel paths and meshed connections are employed to achieve high levels of availability and stability. For distribution, lower, more easily managed voltage levels are employed [30], and the network topology is generally simpler with less interconnection. Often, single feeders emanating from distribution substations are used to connect consumers to the network.

Protection equipment is provided to ensure safe operation of the network [31]. This protection is intended to rapidly detect defective plant or any intolerable or unwanted conditions on the power system and to initiate remedial action. Control equipment allows the system topology to be switched and configured for effective operation. Whilst this can be performed manually, it is often automated to improve effectiveness and efficiency. The capabilities of protection and control equipment (and associated automation) developed enormously with the adoption of ICT into the industry. Now, integrated protection automation and control (PAC) systems are the norm to ensure that electrical power systems are operated effectively, efficiently, and safely [32].

With recent shifts towards renewable sources for energy, the traditional models of electrical power system networks are changing. Dispersed generation is being embedded within the distribution networks [33]. This is changing the patterns of energy flows in the networks. In turn, this is requiring a change to the techniques used to manage network operation (including protection). Of particular interest to this study are the implications on protection of dispersed sources of generation embedded within the electrical distribution networks.

Electrical power systems have been built around the economics and logistics of matching the needs of efficiently generating electricity to effectively satisfying demand profiles. Generation requires a ready supply of consumables such as fuel, whereas demand is dictated primarily by residency. The two are rarely coincident. Conventional thermal generation of electricity requires fuel to heat water to convert it into steam to drive a turbine to spin a generator. Lots of electricity requires lots of fuel and lots of steam. For this reason large thermal power plants (conventional generators) are generally sited where fuel and water are either readily available (for example the Trent valley in the UK with its local reserves of coal and water from the river) or readily accessible (for example nuclear stations on the coast, where sea water is in abundance, and fuel can be easily shipped in). Demand for electricity tends to be at its greatest in built up areas, such as areas of housing, industry, and commerce. Areas of greatest demand are generally not coincident with, nor welcoming of, large-scale generation facilities. To connect supply to demand, it is usually necessary to transfer electricity in large quantities from large concentrations of generation to dispersed remote loads. Figure 2 illustrates typical power flows in conventional electrical systems, highlighting the predominant flow path from generation through transmission to distribution.

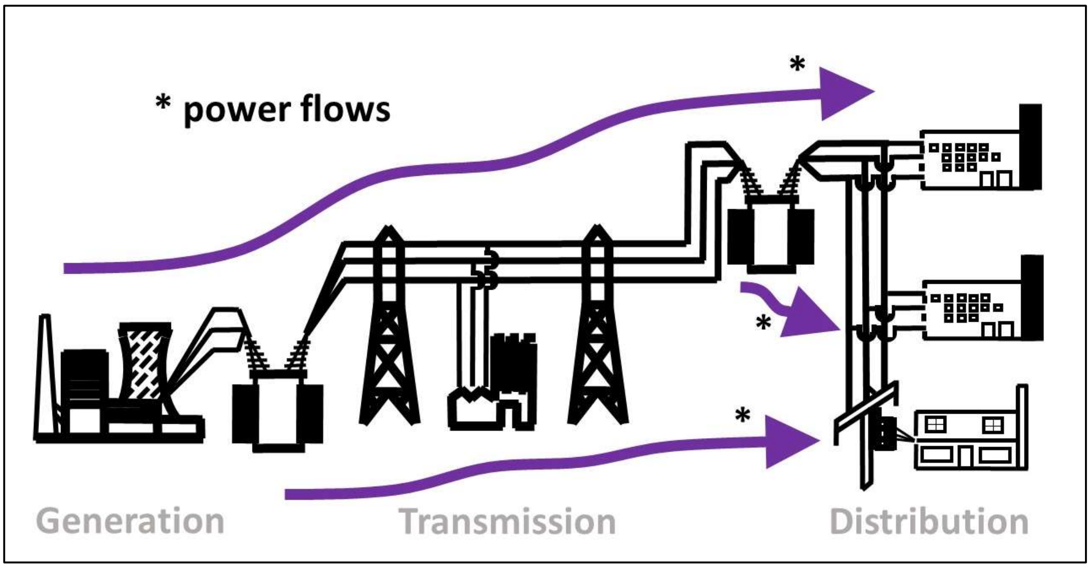

Figure 2: **Electrical Power Flows in a Conventional System.**

Connecting an electrical source to deliver power to an electrical load requires an electrical circuit. Under the right conditions, the source will try to drive a current through the circuit to power the load. The circuit does not, however, allow the electricity to flow freely. The amount by which the current is restricted is referred to as the electrical impedance of the circuit. Transferring the electricity against this impedance wastes energy, causing losses. Since power in an electrical circuit is the product of the current multiplied by the voltage, for a fixed amount of power transfer, the higher the voltage the lower will be the current. Also in an electrical circuit, power losses increase according to a relationship between resistance to current flow, and the square of the magnitude of that current (I^2) [34], so raising the voltage reduces losses significantly, and hence improves the efficiency of the transmission. This is why electrical power is transmitted over long distances at high voltages (typically 400,000 V, 275,000 V, or 132,000 V in the UK). It is not practical, however, to handle such high voltages where the electricity is used. For most commercial and domestic applications, a 'safe' 'usable' voltage is much lower – typically 230 V [3] or 110 V. To make the electricity convenient to handle, it needs to have the voltage scaled down from the level it is transmitted at, to levels at which it will be consumed. This is done with electrical power transformers. This is

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[3] Although widely quoted as 240V, strictly, the mains voltage in the UK is officially 230V (-6%, +10%).

done in stages, with the following voltage transformations typically being performed in the UK.

400 kV : 132 kV
275 kV : 132 kV
132 kV : 33 kV
132 kV : 11 kV
33 kV : 11 kV
11 kV : 400 V

Careful connection to the three-phase distribution system at the 400 V level provides the single-phase 230 V (AC) supply that is familiar to domestic consumers in the UK. Voltage transformation is made by robust power transformers and other associated equipment which are housed together in dedicated areas known as electrical substations [35]. Electrical substations delivering, for example, 33 kV, 11 kV, and 400 V are used to scale and distribute the electricity (that is provided over the transmission network from the generators) to the consumers. This consumer side of the supply chain is, therefore, known as the distribution network. Referred to as ‘conventional’, this type of electrical transmission and distribution system has a strong grid supply formed of large generation sources connected to a network of transmission lines. From grid supply points on the transmission network, power is supplied radially to the many diverse loads via distribution networks.

Environmental issues, however, are forcing changes on the way power systems operate. Realisation of the negative environmental impact caused by burning fossil fuels is ushering in a change towards supplying our electricity demand from renewable sources. Clean energy generation is displacing fossil-fuelled generation. For example, wind-sourced electricity in particular is displacing coal in the UK [36]. As previously noted, renewable energy is not constrained in the same way that the siting and operation of thermal power stations were. Large quantities of water are not required, and energy can be harnessed where it is available. Although large-scale generating arrays (such as offshore windfarms) are playing a major role, smaller generators are also attractive and are being integrated into the power system. Offering connection possibilities at distribution level voltages, these sources of generation and be dispersed and embedded into distribution networks at convenient connection points as illustrated in Figure 3.

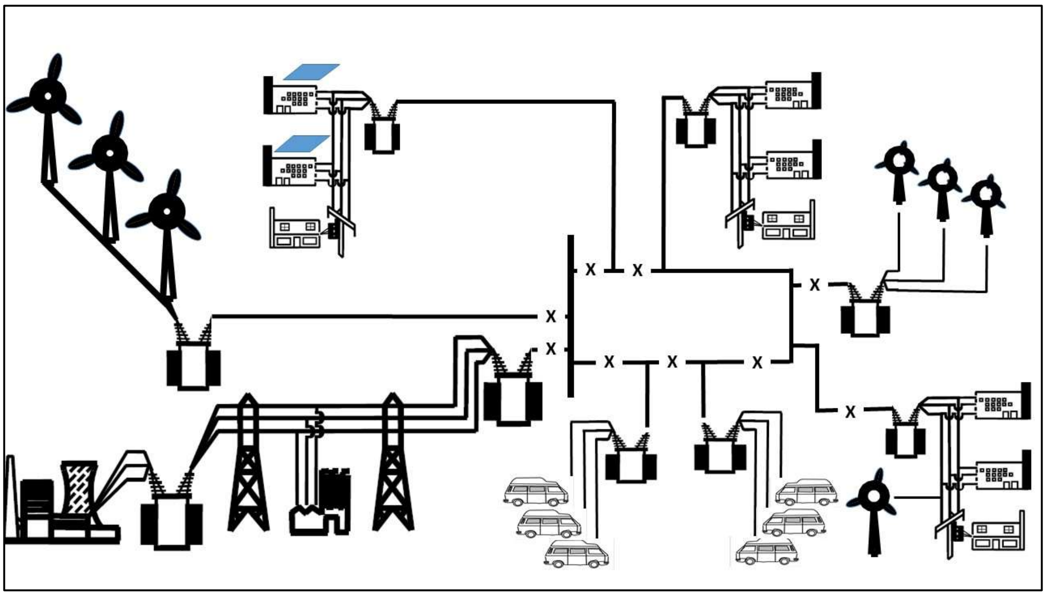


Figure 3: Electrical Power System featuring Dispersed and Embedded Generation as well as Conventional.

The integration of Dispersed Generation (DG) and other low carbon technologies (LCT) into distribution networks has an impact on how they operate [37]. Unlike on conventional systems, when DG is embedded within the distribution networks, power no longer flows in clearly defined unidirectional paths from grid supply to load [38]. Figure 4 illustrates the effect.

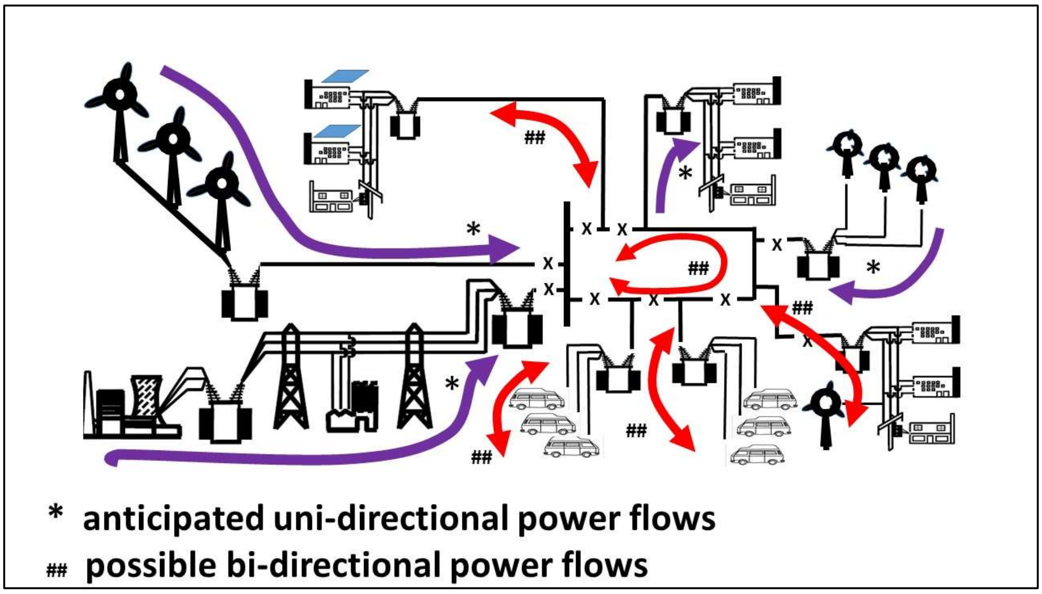


Figure 4: Illustration of Power Flow Possibilities in Electrical Networks with Dispersed Generation.

To align with network operating constraints such as guaranteeing frequency of supply and respecting voltage tolerances, generation from low-carbon technologies requires careful interfacing to connect to the network. Typically, interfaces are implemented with power electronics devices and control circuitry, which inherently limit current flows. The impact of this is significant when network faults occur as the interfaces limit the amount of power that flows between connected items of plant under some fault conditions. The different characteristics of the power flows caused by introducing of embedded generation with such power electronics affects the parameters that are measured by devices to protect the networks against faults [39]. This can cause traditional approaches, based on magnitude alone, to become ineffective [40]. Dyśko et al. highlight that "In the light of anticipated changes in the UK distribution system leading towards active networks with high penetration levels of distributed generation (DG), a number of major challenges must be addressed with respect to power system protection." [41]. The work of this thesis investigates using comparisons of electrical power flow directionality information as a contribution towards the provision of protection to meet these challenges.

The principle of this directional comparison approach to system protection is outlined in Figure 5, which shows power flow direction-sensing devices using a communications network to share directional information which can be compared (DirComp) to form a wide-area protection scheme.

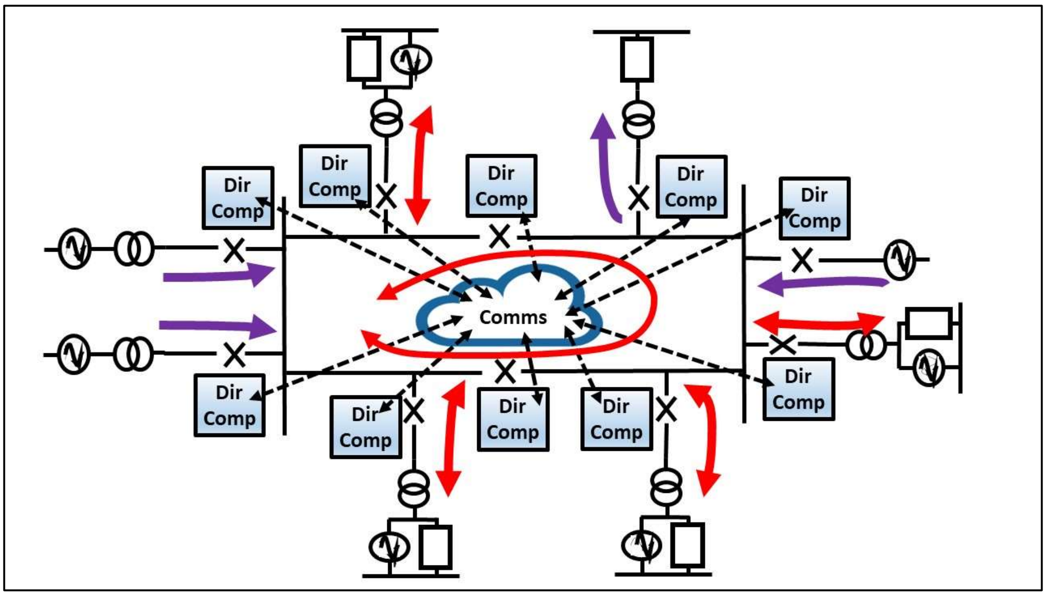


Figure 5: Directional Comparison Protection – A System Approach.

Notes:

1. The double-ended red arrows are indicative of potential bi-directional power flows
2. In this example the directional comparison devices are shown for illustrative purposes only. Their sensing directions, and interconnections will be tailored according to the specifics of the application

Chapter 2 Electrical Power System Protection

Protection is provided to rapidly detect defective plant and/or abnormal operating conditions on an electrical power system, and to take remedial action. Operation of the protective equipment (widely referred to as ‘relays’) either isolates or initiates the isolation of faulted sections of the power supply network. Its purpose includes (but is not limited to) avoiding damage to affected plant, damage to other connected plant, system instability, as well as safety hazards to personnel and other lifeforms. To achieve this, protection must operate reliably in a timely manner, and should be selective so that it doesn’t operate for unwanted conditions outside its intended zone. Proper accuracy and co-ordination of the protection system is essential to ensure that the minimum amount of plant, or ideally the faulted plant only, is disconnected from the network as a result of a fault. The protection system must operate as quickly as possible to minimise the amount of damage and disturbance caused by the fault and to minimise safety hazards.

2.1 Basic Principles of Electrical Power System Protection

Protection schemes are implemented using techniques to measure and compare quantities acting on the protected plant. In general, protection is based on electrical quantities. The basic principles applied to implement protection techniques can be summarised as magnitude, ratio, directional, and difference.

Overcurrent protection is a technique that compares the magnitude of the current flowing in a piece of protected plant. Applied current values are compared with set values (magnitude and/or time). If the values are exceeded, isolation (tripping) of the affected circuit is initiated. In its simplest form, overcurrent protection can be realised with fuses. Fuses provide cheap protection, but their operating characteristics are prescribed by the materials used, and choice is limited by operating voltages. Overcurrent relays provide more flexible protection since their operating characteristics can be adjusted, but they represent a more expensive solution since current transformers (CTs) are needed to interpose between system currents and those required to be measured by the protection devices. Overcurrent devices are widely deployed, providing inexpensive protection. Grading relies on current magnitude thresholds and time delays. This can lead to slow operation for faults within a protected zone as well as unwanted operation for faults outside the protected zone. Combining voltage and current phase relationships allows directional qualifications to be applied. Providing a directional element to overcurrent protection can help with selectivity, by ensuring that the protection only operates for faults in the direction that the protection is intended to sense. Generally, the direction is defined as 'forward' when sensing into the protected zone, and 'reverse' when sensing out of the protected zone. This improvement in selectivity generally requires a voltage signal to be made available. This may not be available for lower voltage applications and, where it is, inclusion of voltage transformers inevitably increases complexity and costs.

In applications where both voltage and current signals are available, a ratio technique can be used. Comparing the ratios of voltage and current signals provides values of system impedances. This type of protection is widely applied to the protection of transmission lines where changes in measured impedances can be indicative of the distance along a transmission line at which a fault has occurred. Because of this, the technique is widely referred to as distance protection. With the extra inputs available to distance protection, selectivity is improved compared with magnitude and directional protection, but errors in, for example, current transformer (CT), and voltage transformer (VT) measurements, mean that selectivity is not perfect. Comparing the difference between, say, currents entering and leaving a protected zone allows Kirchhoff's Current Law to be applied to provide unit protection for the protected plant.

Overall, protection acts as an insurance policy and the capability of the protection is likely to reflect the value of the asset being protected. Accordingly, transmission protection generally commands a premium (for example distance protection requiring a full set of VTs in addition to the CTs), compared with distribution protection which is likely simply to employ overcurrent protection.

2.2 The impact of ICT on protection

The introduction of microprocessors and ICT into protection and other electrical substation devices brought new opportunities and associated new terminology [42]. The acronym IED, standing for intelligent electronic (substation) device, was adopted for the new generations of multifunctional protection, control, and automation equipment. Compared with their forerunners, as well as more functionality, IEDs afford other benefits such as better accuracy, self-monitoring, and space savings. An advancement sported by IEDs which afforded significant benefits is a compliment of digital communications [43]. Cost-effective communications changed the way substations could be designed to be operated. Interrogation and control of equipment could be effected remotely without the need for site visits, saving time and costs. Additionally, commands could easily be shared between devices to form operational schemes which, without the need for supplementary communications equipment or hardwiring, brought down overall scheme costs. Not surprisingly, protection equipment suppliers were keen to lever the benefits of communications to afford technical and commercial advantage. System designs started to evolve around proprietary communications implementations such as GEC Alsthom's Courier protocol [44]. But such proprietary implementations made it difficult to mix-and-match devices from different suppliers. Attempts at standardisation were made, and less constrained protocols such as ModBus and DNP3.0 found favour, but even those protocols are open to interpretation and, with most suppliers being defensive of their own implementations, utilities making a commitment to a particular communications protocol could find themselves tied in to a limited number of compliant suppliers. The need for harmonious open communications standards, to facilitate 'plug-and-play' interoperability of devices from different manufacturers, was apparent. The IEC 61850 series of standards was developed to address this need [45], [46].

2.3 IEC 61850 Communications for Protection

IEC 61850 is a standard for intelligent electronic substation device (IEDs) communications [26]. It focusses on standardising device modelling and communications to improve electrical substation design and operation. It was adopted and developed by the International Electrotechnical Commission Technical Committee 57 (IEC TC 57) from work initiated as the Universal Communications Architecture v2 (UCA2) by the IEEE.

Originally, because of the attention paid to substation communications, it was known as a Universal Communications Architecture (UCA). Whilst it is often referred to as a communications standard, it is more than that: it encourages a different approach to substation engineering. ABB state "IEC 61850, the global standard for communication in substations, is bringing open, interoperable systems, and flexible architectures to the substation automation domain" [47]. Hodder, Kasztenny, McGinn, and Hunt, propose that it offers to deliver substation implementations that are claimed to be cheaper to design, install, commission, and operate [48]. Other proponents of the potential benefits of IEC 61850 include Childers [49] and Redfern et.al. [50].

IEC 61850 is structured into a number of parts which are illustrated in the following tabular listing (Table 2):-

Table 2: IEC 61850 Standard Component Parts.

IEC 61850-1	Introduction and overview
IEC 61850-2	Glossary
IEC 61850-3	General requirements
IEC 61850-4	System and project management
IEC 61850-5	Communication requirements for functions and device models
IEC 61850-6	Configuration language for communication in electrical substations related to IEDs
IEC 61850-7-1	Basic communication structure - Principles and models
IEC 61850-7-2	Basic communication structure - Abstract communication service interface (ACSI)
IEC 61850-7-3	Basic communication structure - Common Data Classes
IEC 61850-7-4	Basic communication structure - Compatible logical node classes and data classes
IEC 61850-8-1	Specific communication service mapping to MMS
IEC 61850-9-2	Specific communication service mapping sampled values
IEC 61850-9-3	Precision time protocol profile for power utility automation

IEC 61850 allows substations and associated equipment to be defined and designed in terms of communicating abstract data models. The abstract data models are self-describing using Translatable Mark-up Language (XML) notation within a Substation Communications Language (SCL format) described within the standard. As well as, for example, protection IEDs, SCL can also be used to model the logical behaviour of other plant such as control devices, switchgear, and instrument transformers.

Communications can be either peer-to-peer, or client-server, and are implemented using Ethernet (TCP/IP or LAN). These are mapped to standard communications protocols. The standard mappings include the Manufacturing

Message Specification (MMS), Generic Object-Oriented Substations Events (GOOSE), Sampled Measured/Analogue Values (SMV/SAV), and Precision Time Protocol (PTP). MMS uses the OSI 7-layer model [51] and typically allows reporting functions such as extraction of event and/or disturbance records. GOOSE typically facilitates binary command transfer between IEDs. SMV/SAV facilitates transfer of digitised (numerical) measured analogue input signal values between transformation units (electronic instrument transformers or merging units) and IEDs. PTP facilitates accurate time-synchronisation of IEDs via communications ports. Two connection ports are defined – one connecting to the so-called 'Station Bus - the other, to what may be referred to as the 'Process Bus'. The division of services between the Station Bus and the Process Bus is sometimes blurred (they may even be joined), but generally the Process Bus is used for time-critical activities such as conveying SMV/SAV and PTP, whereas the Station Bus is used for less time critical services such as reporting of events. GOOSE, which is capable of transferring binary command signals in messages between IED applications in under 4 ms, may reside on either bus according to the demands of the application.

Whilst all the services make significant contributions to substation automation, it is the features and benefits of GOOSE and SAV/SMV that are or particular interest in this study. The SAV/SMV services are of interest for their ability potentially to transport voltage measurements to Directional Agents from remote locations. GOOSE services are of interest as they may be able to convey (binary) directional data between Directional Agents.

2.4 Unit and Wide-Area Protection

Non-unit protection such as overcurrent protection and distance protection generally takes measurement information from a single relaying point and uses that information to determine whether or not to initiate tripping. Since information is taken only from one point, measurement may be quite simple to effect, but decision making is not very selective. Unit protection such as current differential protection, on the other hand, generally takes measurement information from more than one relaying point. Combining measurements from all terminals of the protected plant to determine whether or not to initiate tripping makes the decision making more selective, but increases complexity and costs. Combining non-unit protection terminals such as distance protection or directional devices with communications channels to transfer command information to produce (communications-aided) schemes can provide a type of hybrid unit protection solution. The relative advantages and disadvantages of each approach means that often there is no one ideal solution and a compromise or combination based on cost of provision and performance requirements is made. For the protection of transmission lines and distribution feeders, the choice historically has been dictated in part by the cost, availability, and suitability of appropriate communications services. With the increasing prevalence of information and communications technology (ICT), satisfying these constraints is less of a concern than it was pre the ‘digital age’, and as ICT has penetrated the disciplines of power system networks monitoring, protection, and control, so it has become possible to concentrate P&C information from multiple sources across the network to allow a wider area perspective. Thus, it is possible to implement so called wide-area monitoring schemes (WAMS) [52] or wide-area monitoring protection and control (WAMPAC) schemes [53]. Such schemes take data from across the network to enable strategic decisions to be taken to isolate or reconfigure items of plant in order to provide system resilience or stability. Typically, the data is provided by IEDs and will comprise both analogue and digital values. Analogues may be quantities such as bus voltages, power flows, current phasors, etc., and digitals might be circuit breaker status, isolator status, etc. Examples of wide-area applications include using phasor measurements acquired at multiple points across a network to improve network operations [54].

At the distribution level, an example of protection and control with a wide-area perspective is Fault Location, Isolation, and Service Restoration (FLISR) [55]. With FLISR, information is transferred between equipment such as IEDs deployed across the network. This information is used to rapidly determine the location of a fault on the power system. Once the fault is located it can be closely contained by distributed (but interconnected) automation IEDs to provide unit protection. Close containment by unit protection means that only the absolute minimum of necessary (but sufficient) amount of plant is isolated to contain the fault. By isolating as little of the networks as is necessary to contain the fault, the impact of the fault to consumers is minimised, and restoration of the supply to as much of the unfaulted network as possible can be effected. Integral to successful FLISR operation is the ability to control devices remotely over the network. Wide-area communication connecting the distributed intelligence of devices such as IEDs using standard protocols such as those described by IEC 61850 enables this to be achieved.

Cao et al., consider extending the possible scope of wide-area scheme to include the potential for wide-area adaptive protection (WAAP) for future networks [56]. As well as considering the impact of diversity of generation in future networks on protection, it also acknowledges influences such as flexible demand-side management on network operations and management. Beyond using wide-area data to effect local protection and control, Cao et al propose collection of information from across the network to facilitate wide-area supervision and control at a higher level of abstraction. With WAAP, they argue, that unlike conventional protection that isolates faults only, collection of system-wide information affords the opportunity for early detection of changes of system parameters or topology changes, and that by responding quickly at a system-wide level, potentially evolving (and potentially more serious) damage can be avoided. By exerting influence at system level, WAAP is predicted to act as an important safeguard for future grids operation. There is, however, a recognition that the necessary adaptive techniques may need to become more widespread before the potential benefits might be realised.

The scope of the work of this particular thesis, however, restricts focus to considering protection against faults, and excludes the broader context of control and automation.

Chapter 3 Distribution Network Protection

Most distribution networks in the UK are protected against faults by provision of time-graded overcurrent relays monitoring for phase faults and earth faults [57]. Figure 6 shows a conventional radial distribution network with a fault indicated by F1.

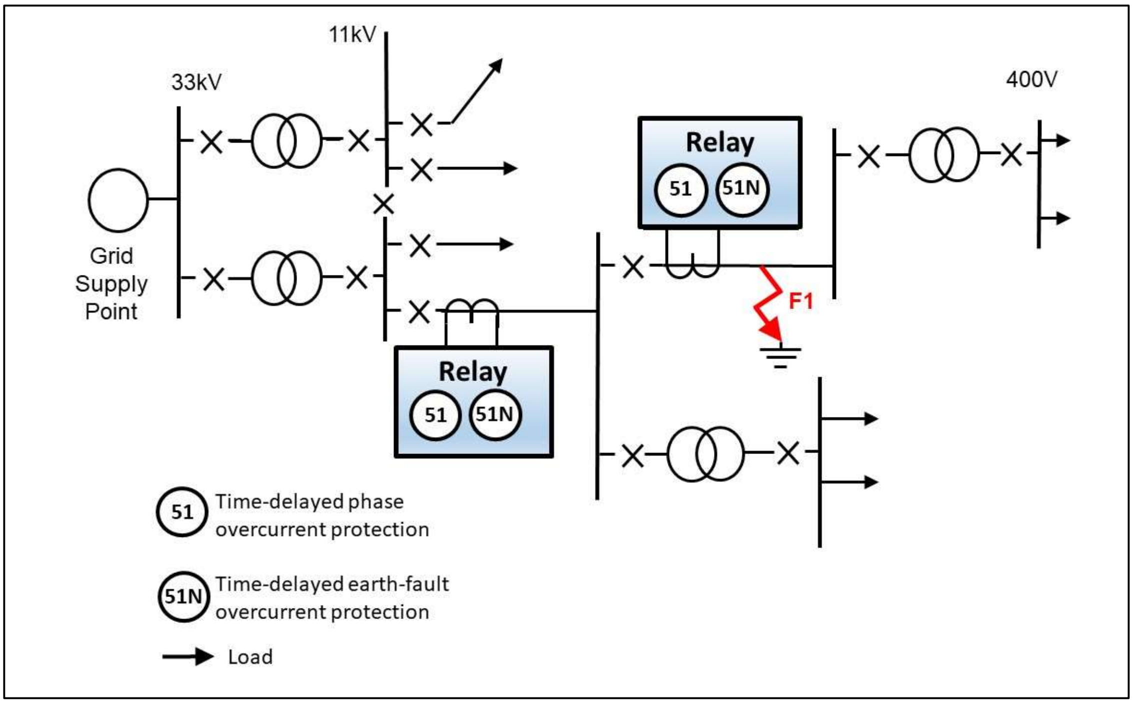


Figure 6: Time-Delayed Overcurrent Protection applied to Radial Distribution Network.

In Figure 6 power flows from a (33 kV) grid supply point on the left of the figure, towards the loads on the right of the figure. In the absence of faults, the power should be expected to flow through a combination of power transformers and radial feeders to a multiplicity of connected loads. In the presence of a fault (such as that shown as F1), the flow of power from sources to loads is disturbed. In this example of a radial network, it should be clear that power always flows radially from grid supply towards the loads and/or faults (always from the left to the right of the figure in this example). Typical application of phase-fault overcurrent protection (51) and earth-fault overcurrent protection (51N) is shown in the example.

Figure 6 also shows typical UK supply arrangements. Many UK distribution feeders operate at 11 kV and are sourced from duplicated 33 kV:11 kV or 132 kV:11 kV transformers. Each individual transformer is capable of supplying all the connected loads, but duplication of the transformers means that 'normal' supply can be maintained in the event of any one transformer failing or being taken out-of-service for maintenance, replacement, etc. The transformers generally feature low-impedance earthing on the low-voltage (downstream) windings. This restricts potential maximum earth-fault current magnitudes to approximately 50-70% of the maximum phase-fault values. Using system data, the prospective load currents and fault currents can be calculated. Guided by prospective current values, application of simple rules allows the protection relays to be set appropriately.

When a dispersed (embedded) generator is connected to a radial feeder network, the networks starts to exhibit the characteristics of a smart network [58]. In this case, the nature of the currents (including fault currents) sensed by the protection relays will change. Fault currents sensed by the protection may increase, or decrease, depending on the fault location, the protection location, as well as the type and location of the generator location. Figure 7 shows a distribution network featuring an embedded generator with possible fault scenarios indicated by F1 and F2.

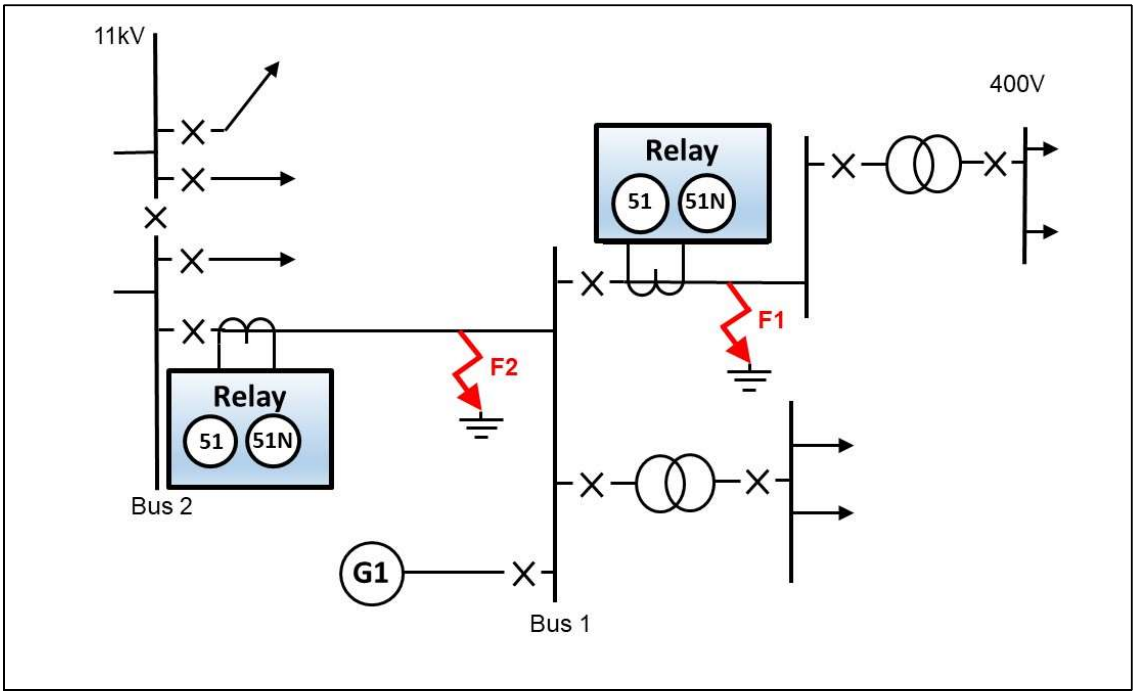


Figure 7: Radial Distribution Network with Embedded Generation.

Grading studies are employed to determine how best to protect the network. They must take into account the maximum and minimum current contributions from all sources including the embedded generators. All feeder and generator interface protection systems should operate correctly for all possible operating conditions. The inclusion of embedded generation should not adversely affect the network protection, and any fault type (for example, earth faults at F1 or F2) should be properly cleared before any damage may be caused to primary plant (either on the utility's network, or on plant embedded in the network).

In Figure 7, overcurrent protection settings are configured with an assumption that for a fault at F1, the fault current supplied by G1 is sufficient to operate the relay at Bus1-G1. But, the fault level provided by generator G1 is likely to be very low compared to the bulk supply from Bus 2, so the overcurrent may be unlikely to operate correctly for a fault at F2. Adding a circuit breaker (CB*) - and associated protection - installed on feeder section 1-2 at Bus 1, as shown in Figure 8, might help overcome this exposure. It should be noted, however, that the benefits offered by the improvement must be weighed against the additional costs incurred.

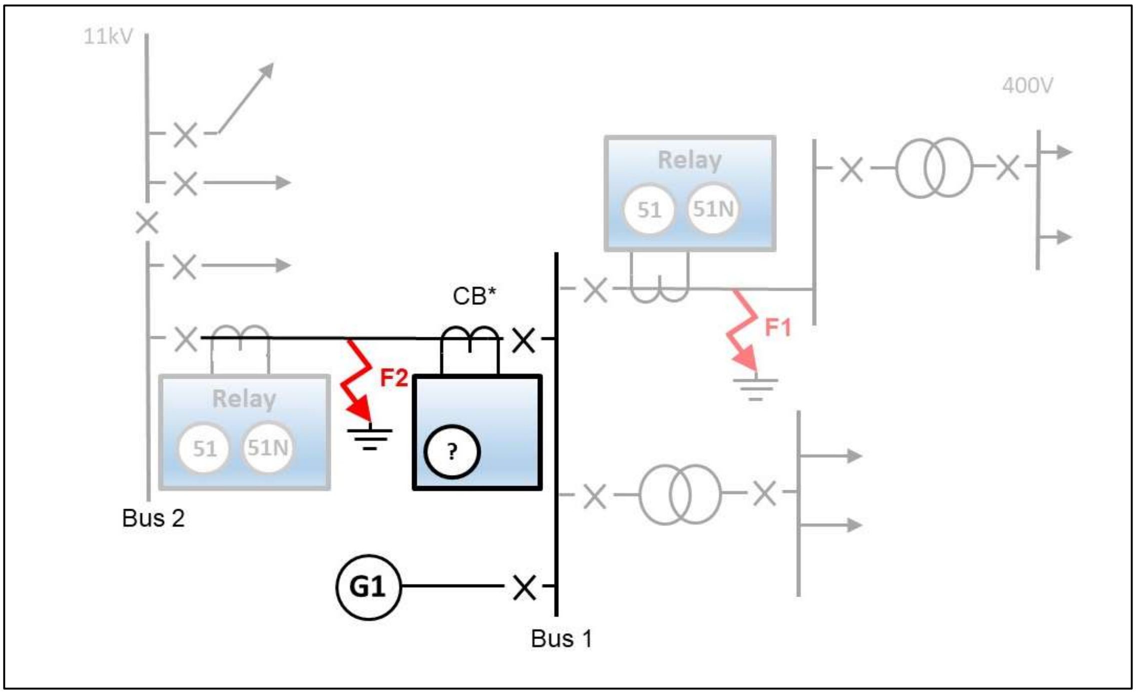


Figure 8: Radial Distribution Network with Embedded Generation, Additional Circuit Breaker, and Associated Additional Protection.

If, as might be the requirement for a future 'smart' distribution network, the embedded generation at Bus 1 is capable of supplying the downstream (low-voltage) loads within statutory voltage and frequency limits then, with increasing levels of renewable distributed generation in active distribution networks, conventional overcurrent relays might not provide proper protection [59], and so a strategy will be needed to adequately protect the feeder between Bus 1 and Bus 2, and control the breaker at CB*. Research work is targeting the challenges associated with developing and demonstrating protection and control schemes for distribution systems with embedded generation [60], [61], and various techniques including adaptive protection are being investigated [62]. Another possible strategy, however, is to use information about the system voltage to qualify the overcurrent protection. As well as the additional circuit breaker, and protection, this would also require provision of voltage measurement at Bus 1 and a cost benefit analysis may be required to justify the provision.

The qualification of overcurrent by voltage could applied by either so called 'voltage-controlled', or 'voltage-dependent' overcurrent protection. With voltage-controlled overcurrent protection, the system voltage is used to adjust the pickup setting and the characteristic of the overcurrent element. With voltage-dependent (also known as voltage-restrained) overcurrent protection, the system voltage is used to adjust the pickup setting and the characteristic of the overcurrent element. Alternatively, as is considered in this study, a voltage signal could be used to polarise the overcurrent feature to provide an overcurrent element that is sensitive to the normal direction of current flow. Complementing an overcurrent protection device with voltage polarisation [25] affords the possibility to deploy directional overcurrent protection to the benefit of distribution networks with embedded generation [63], [64]. A commercial advantage of this directional overcurrent approach, over that of voltage-dependent or voltage-controlled, is that protection is dependent upon the relative phase information of the voltage signal, rather than the precise magnitude of the voltage signal (so the requirements on the transducers is less), and a single voltage signal can be used to polarise all three phases (so that only a single-pole transducer is required). The potential for applying directional protection based on phase overcurrent devices polarised with busbar voltage is highlighted in Figure 9.

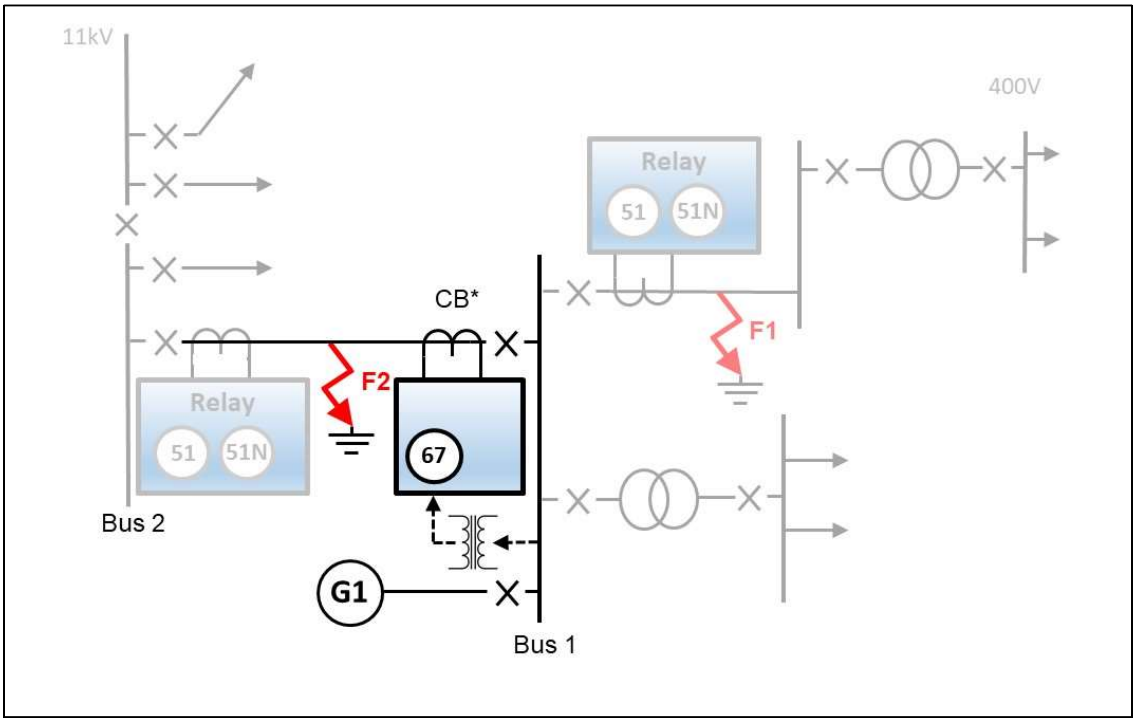


Figure 9: Radial Distribution Network with Embedded Generation, Additional Circuit Breaker, and Phase Overcurrent Protection Directionalised from Local Busbar Voltage.

As well as cost, lack of space may make provision of a measurement voltage transformer at Bus 1 impossible. The voltage measurement requirements to implement a directional overcurrent protection element can be less demanding than those needed to implement more accurate measurement techniques such as distance protection. For directional protection the voltage is only required for establishing the relative direction or phase of the fault current [65] whereas in distance protection measured voltages and currents are compared to determine the impedance of the line up to the point of fault and compare the measurement with a predetermined value [66]. With such a reduced constraint on the voltage signals required to implement directional protection, a potential opportunity might be to compromise quality and quantity of voltage transducers in favour of an option that affords savings in terms of cost and space. So, rather than using a three-phase transformer rated at the busbar voltage (11 kV in this example), a potentially smaller and less expensive alternative might be to use a single-phase 0.4 kV voltage. Such a signal could be taken from a transducer at a downstream (low-voltage) supply point and provided as a polarising signal for the 11 kV protection element at CB*. The principle is shown in Figure 10.

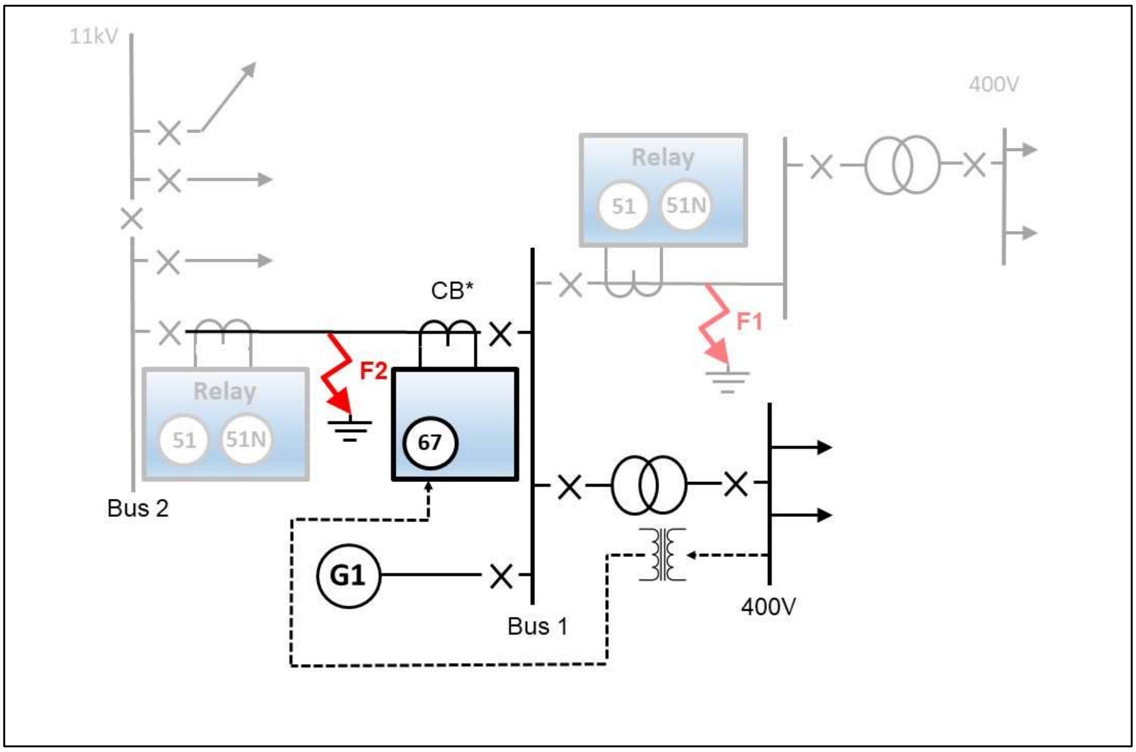


Figure 10: Radial Distribution Network with Embedded Generation, Additional Circuit Breaker, and Overcurrent Protection Directionalised from LV Signal.

Making a ‘directional’ output available from a directional overcurrent element could allow adjacent relays to be controlled to provide, for example, sympathetic tripping or blocking. This would facilitate more sophisticated protection schemes such as that shown in Figure 11.

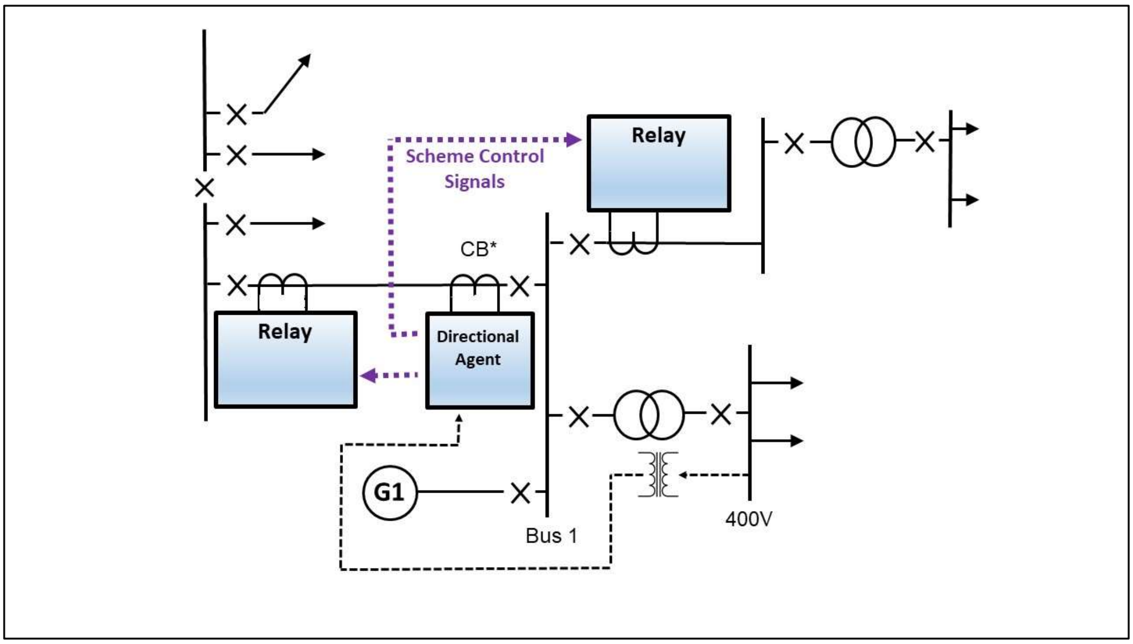


Figure 11: Directional Overcurrent Protection Hosting Directional Agent Functionality to Provide Auxiliary Directional Indication Annunciation.

The directional overcurrent protection outlined in Figure 9 is clearly operating as a non-unit protection. It could, however, be possible to combine directional overcurrent relays in a similar way in which distance relays may be connected to form so called 'aided-schemes' to act like unit protection. An example of a possible directional overcurrent aided-scheme implementation is shown in Figure 12.

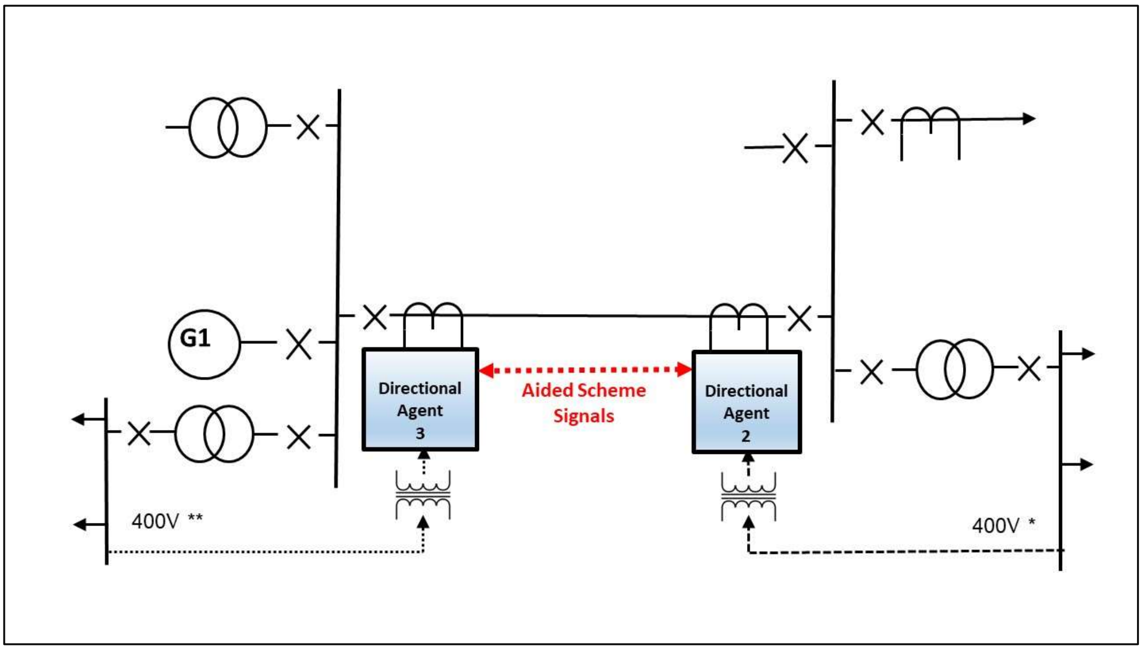


Figure 12: Directional Overcurrent Aided-Scheme Protection.

In Figure 12, the non-unit directional overcurrent protection is being configured with the communications of aided-scheme signals to provide a type of unit protection.

In aided-schemes, binary command information (signals indicating, for example, Zone1 Trip, or Forward Directional Trip) are transferred between protection terminals of a protected zone. Received commands are used (generally in conjunction with local measurements) to determine whether, or not, to initiate tripping, or to block tripping. Within the scope of IEC 61850 is a GOOSE messaging service. GOOSE was specifically developed to provide a mechanism for transfer of such binary command signals, and in this work, it is proposed to use GOOSE messaging for the command signal communications between protection devices to implement (potentially wide-area) unit schemes. So, Figure 12 could be representative of a distribution network protection scheme implemented using directional overcurrent techniques embedded within Directional Agents, using GOOSE messaging [67], to transfer commands, in accordance with IEC61850, between terminals of the protection scheme.

A seemingly similar alternative solution to the directional overcurrent scheme of Figure 12 (generally more associated with protection of transmission lines) may also be considered. Often described interchangeably as either 'Superimposed Directional Comparison Protection' or 'Delta Directional Comparison Protection', an illustrative example of the principle is shown in Figure 13.

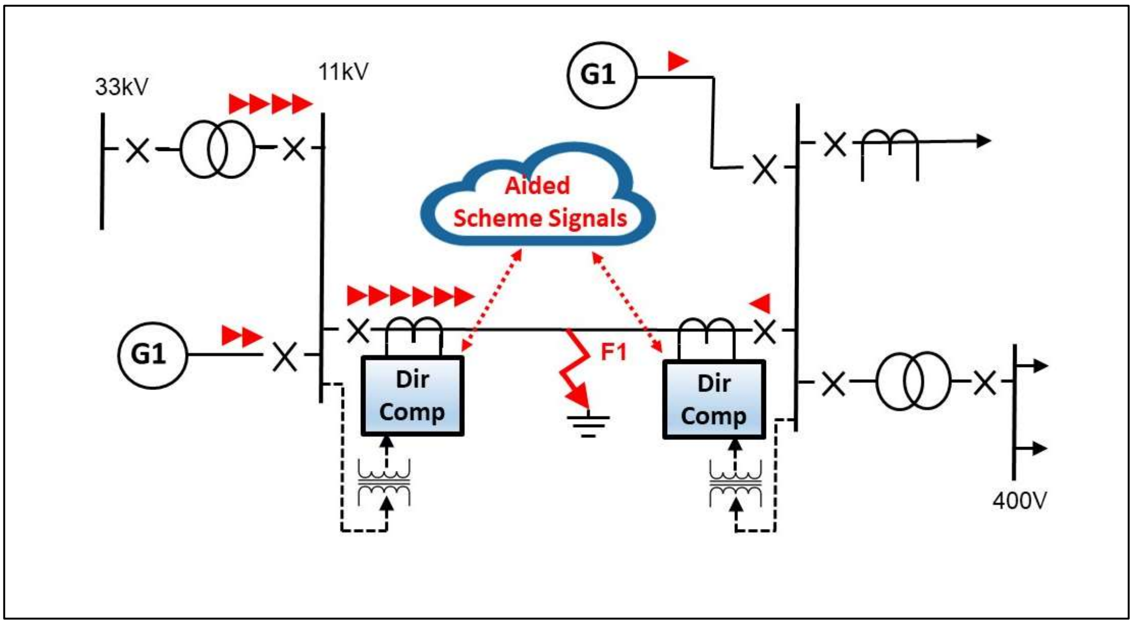


Figure 13: Directional Comparison Scheme illustrating Superposition Principle

A directional comparison protection scheme is a type of unit protection scheme constructed from directional measuring units. Measuring devices located at each terminal of the protected zone sense the 'direction' of system impedances and current/power flows sensed at those terminals. Combining these senses of flow can then be used to determine the if the power is flowing correctly across the network zone from source(s) to load(s), or whether, as for example in the case of a faulted zone, the flows are abnormally converging within the zone.

Described by Rose, et al. [68], principles of superposition (delta components) can be used to rapidly determine fault directionality. In conjunction with high-speed communications, the technique can offer fast clearance for faults internal to the protected zone. As well as fast operation, the principle offers good discrimination and selectivity for both internal and external faults. As with the directional overcurrent aided-scheme example suggested previously, using an LV voltage signal for polarisation offers an interesting possibility for consideration as demonstrated in Figure 14.

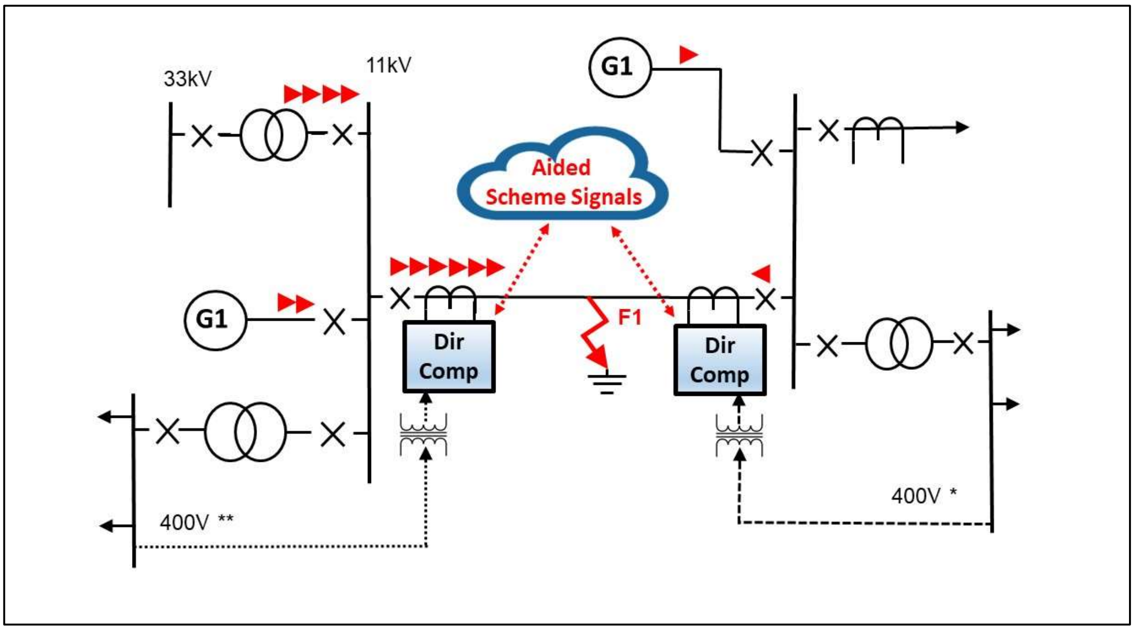


Figure 14: LV-Polarised Directional Comparison Scheme.

In Figure 14 the red arrowheads are indicative of the directions and relative magnitudes of the power flows across the networks that are contributing to the fault.

Directional comparison protection may be attractive when considering possible scenarios for the wide-area protection of future distribution networks which may include multiple embedded generators, additional circuit breakers and controlled sectionalising switches, etc., as shown previously in Figure 5. The key elements of the corresponding wide-area protection scheme are highlighted in Figure 15.

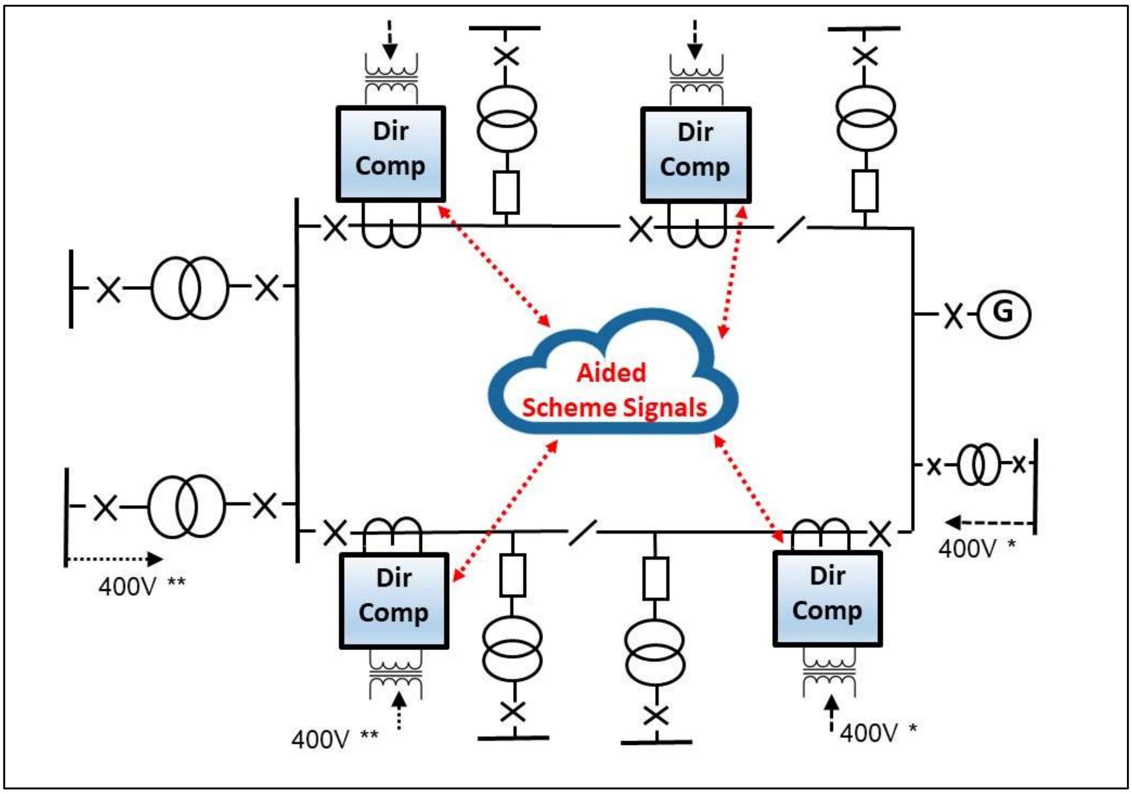


Figure 15: Wide-Area Directional Comparison Protection Scheme with LV Polarisation.

Directional overcurrent aided-schemes, and/or the potentially faster directional comparison unit protection schemes, stand to offer the necessary performance requirements of selectivity, security, and dependability, to serve smart distribution networks to deliver against increasing resilience demands.

Chapter 4 Developing Directional Protection Concepts for Smart Distribution Network Applications

To exploit low-carbon energy sources effectively, electrical networks need to change [41]. They will need to support features such as integration of dispersed generation, energy storage, and dynamic load management. Referred to as smart grids/networks, these dynamic systems are made possible by the incorporation of information and communication technologies (ICT).

This work looks at enhancing protection techniques used on traditional networks to meet more demanding system requirements associated with smart grids. To protect distribution networks with embedded dispersed generation, the possibility of applying an established technique in a new way, by engaging with the ICT technologies, is investigated. Determination, and use of power flow information, as a basis for protection and control of complex distribution network topologies, is researched. The concept of 'intelligent', interconnected, 'Directional Agents', communicating to form wide-area aided directional schemes, is explored. The proposed schemes share characteristics with other wide-area schemes such as Wide-Area Monitoring and Protection and Control (WAMPAC) [69], Fault Location Isolation and Service Restoration (FLISR) [70], and the Rationalised Auto-Transformer Schemes (RATS) designed for UK railway protection applications [71], [72], [73]. In such schemes, power system network information is acquired and/or derived at local relaying points and communicated to other locations on the network. Combining the communicated information enables the health of the network to be assessed. Based on informed assessments, the network can be managed effectively by appropriate switching of the configuration in response to occurrences of abnormal operating conditions. Traditionally, protection for electrical distribution networks has been widely applied using time-graded overcurrent techniques. Essential to provide the current measurements necessary for protection, some form of current transformer devices (CTs) are generally available at relaying points. Improved protection can be provided if system voltage measurements are also taken into account. Traditionally, however, on distribution networks, the additional costs of providing voltage transformers, have generally outweighed the potential extra benefits that their provision can bring. Consequently, corresponding voltage transformers (VT) are not normally deployed on MV distribution networks for protection purposes.

In its simplest form, time-graded overcurrent protection relies on recording significant differences between the magnitudes of currents flowing under normal operating conditions compared with those flowing during faulted conditions. Further, in most cases, the protection does not take into account the direction in which the current is flowing.

When dispersed generation is introduced, the flows of current within the network are changed. Directions of power flows can reverse, as the network responds, to balance changes in generation, load, and, if present, faults. The potential fault current levels that can be sustained by embedded generation are significantly lower than those from traditional grid supplies, so fault levels can vary significantly according to the type and amount of connected generation. There may be insufficient difference between the current levels of faulted conditions compared with healthy conditions for non-directional time-graded protection to distinguish between them. Different approaches to protection are required to maintain safe and effective operation of the changing network compositions. Making assessments taking account of the directions of power flow on the networks offers potential opportunities to achieve this. To make directional assessments, however, details of voltage signals as well as current signals are required. Thus provision for some form of voltage measurements needs to be made.

This work considers this provision. Deploying directional protection on smart distribution networks is studied. Unlike in traditional approaches, however, rather than taking the necessary voltage signals from VTs connected at the conventional relaying points to provide input for directionality assessments, the work considers the potential for taking information from other voltage signals located elsewhere on the network. To this end, a proposal is made for unit protection for smart distribution networks based on directional principles. The unit protection comprises communicating Directional Agents. The Directional Agents make current measurements at conventional relaying points. These current measurements are used in conjunction with voltage measurements taken from locations other than the relaying points to provide directional protection elements. The required voltage measurements are realised with compact acquisition units referred to as Voltage cubes. The Voltage Cubes provide Directional Agents with voltage measurements using (ideally wireless) Ethernet communications. Command information transferred between Directional Agents to form the unit schemes exploits similar communications facilities.

To introduce the proposed scheme, a reconsidered simplified two-terminal derivative of the wide-area scheme of Figure 15 is presented in Figure 16.

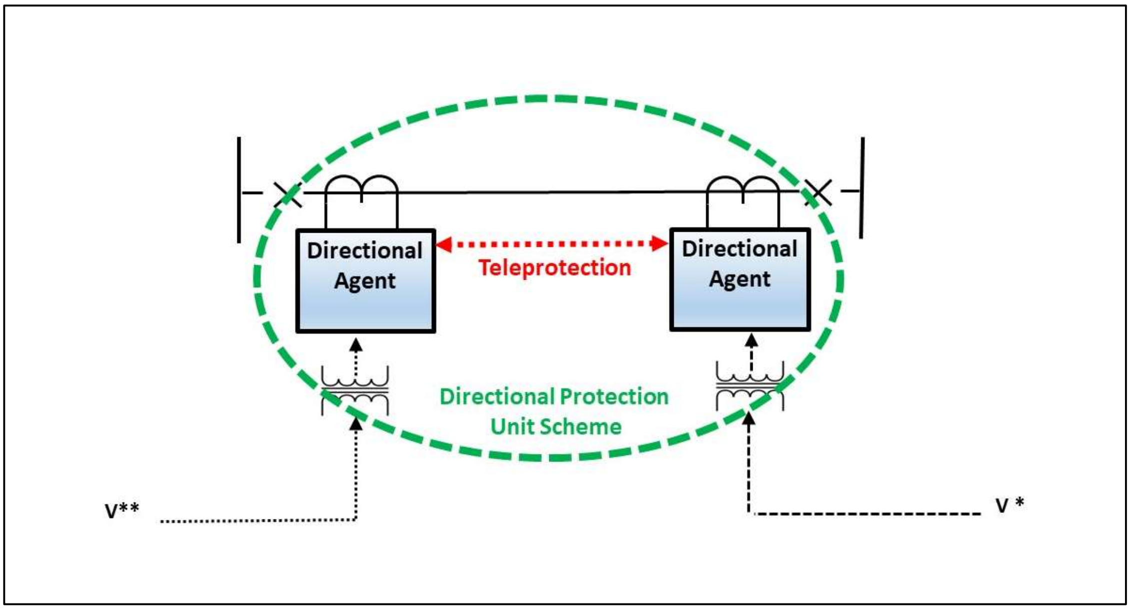


Figure 16: Directional Protection Unit Scheme.

Figure 16 outlines a (two-terminal) Unit protection scheme based on directional principles. It features two Directional Agents taking current measurements at conventional relaying (CT) locations and receiving voltage measurements taken from other (remote) locations. The Directional Agents are connected using communications channels to exchange teleprotection commands to form the unit protection scheme.

4.1 Directional Agents

A crucial part of the protection schemes introduced in this chapter, and illustrated in the previous Figure 16, is the Directional Agent. The following Figure 17 depicts a Directional Agent.

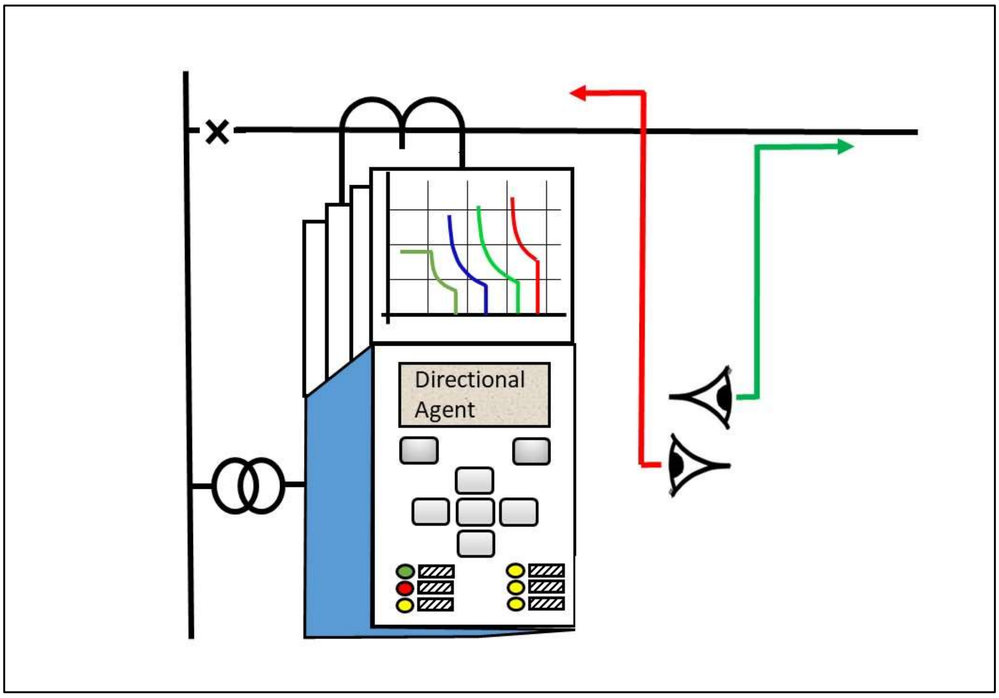


Figure 17: Directional Agent.

Note that in Figure 17 (and other related figures), the symbolic eyes are intended to give a sense of direction. In this specific case, the right-facing eye (complemented by the green arrow) is in the direction of a protected feeder and is intended to indicate a forward sensing protection element. The left-facing eye (complemented by the red arrow) is directed behind a protected feeder and is intended to indicate a reverse sensing protection element.

Directional Agents combine current measurements together with phase information obtained from system voltage inputs. Using these inputs, an indication of the direction of power flow at the relaying point can be determined.

As outputs, the Directional Agents should provide circuit breaker control signals and directional command signals. The circuit breaker control signals (typically TRIP/CLOSE commands) provide signals to initiate circuit breaker tripping, annunciate alarms, etc. Typically these would be provided as voltage-free output contacts, although other mechanisms (such as GOOSE messaging) could be considered to match the substation technology deployed. The directional command signals should be provided in the form of a teleprotection interface to allow exchange of, for example, 'Forward Directional Fault' indication to a remote equivalent device. The directional command signals can be used at the receiving Directional Agent terminals together with locally derived signals to implement appropriate unit scheme logic. As inputs, the Directional Agents take current signals and a voltage signal, and are capable of receiving the same type of teleprotection commands that they output to other Directional Agents. Also available for other conventional overcurrent protections, the current signals are supplied from protection CTs. The CTs may be of the conventional wound copper/iron core type, or alternatives (such as optical or Rogowski Coil). Either way, for this study, they are assumed to be co-existent with the Directional Agent and provide an interface conforming to 'normal' protection relay input expectations such as those described in IEEE C37.111 (IEC 60255) [74], and IEEE C37.92 [75], etc. The system voltage input is only required to provide phasing referencing information for comparison purposes. It should be taken from a location which should be on the protected part of the network but which may be remote from the relaying point; indeed it may even be resident on the LV network at a consumer connection point. For most applications, a single voltage measurement should suffice. Being taken from a location which may be remote from the relaying point, the system voltage input requires special attention compared with a more conventional relaying application, where a simple local VT input might be provided. The Directional Agent requires the (remote) voltage signal to be transformed, isolated, and presented in a suitable form. Transformers are a simple and effective way of providing transformation and isolation. If the polarising voltage for the Directional Agent is taken from the LV side of the network, the size and the costs are much reduced compared with, say, an MV VT. The lowest voltage encountered on a distribution network is usually at a consumer connection points and so sourcing a voltage signal from there should afford the smallest, and hence cheapest possibility. Indeed, some suppliers of protection IEDs offer voltage inputs rated for connection to LV circuits [76] Connection to a mains frequency low voltage supply is an option for consideration, but low-level analogue signals do not readily lend themselves to connection over long distances – particularly in the harsh EMC environment of electrical substations, and so conversion to a representative digital signal for transmission via a suitable communications link provides a more robust proposition. It should be possible to exploit the teleprotection interface of the Directional Agent to provide measured voltage signals from the Voltage Cubes in the form of communicated sampled analogue values (SAV) signals as well as for the transfer of GOOSE commands, thereby saving on overall costs.

Typically, the teleprotection interface should be conformant to allow command signals and sampled analogue signals to be exchanged over Ethernet using the GOOSE and SAV/SMV mechanisms described in IEC 61850.

4.2 Distributed Low-Voltage Measurements

Consideration of a simple compact device to provide a suitable polarising voltage signal for the Directional Agents is included within the scope of this work. It is envisaged that the polarising voltage signals required by the Directional Agents could be provided by 'Voltage Cubes'. The Voltage Cubes could be similar in construction and appearance to the 'power cubes' often used to provide low-voltage DC supplies from AC mains outlets. The Voltage Cube should provide measurement for a single AC system voltage. The voltage measurements provided by the Voltage Cube should be derived from locations which may be remote from the relaying point, but connected to the protected network. The measurements should be acquired at a convenient LV connection points on the network (typically consumer connection points such as a 230 Vac 13 A socket outlets might be considered). The measurements should be converted to numerical values at the measurement points for transfer to the Directional Agents as sampled analogue values (SAV) ideally according to the international standard IEC 61850-9-2. Thereafter, they should be broadcast as SAV/SMV messages over wireless Ethernet (Wi-Fi) [77] or transmitted over wired (copper) or optical Ethernet cables, for communication from the measurement point to the Directional Agent.

A conceptual example of a Voltage Cube is provided in Figure 18.

Figure 18: Voltage Cube Conceptual Model.

The example shown in Figure 18 is intended for wireless Ethernet communications. This might be deduced from observation of the provision of a radio antenna on the device.

4.3 Unit Protection realised with Directional Agents and Distributed Low-Voltage Measurements

Unit protection schemes, employing communications-aided directional overcurrent techniques and/or (delta) directional comparison techniques, offer the potential performance requirements for selectivity, security, and dependability for protection of smart distribution networks to deliver against increasing resilience demands.

Whilst these schemes could be realised using ‘hard-wired’ analogue voltage connections with metallic pilot communications circuits, they would likely experience problems associated with the harsh EMC environment of electrical substations. The integration of ICT and digital communications facilities within the network provides robust features which can mitigate the problems of reliably transferring information in the substation environment. The Directional Agents and Voltage Cubes can both be considered as intelligent electronic substation devices (IEDs). In that scenario remote voltage measurements can be made from numerically sampled analogue values which, as well as teleprotection commands, can be communicated using secure and reliable high-speed Ethernet communications. In the substation environment the de-facto standard for communications is IEC 61850. IEC 61850 has services that can be exploited to implement the teleprotection requirements of schemes such as that of Figure 16. Employing IEC 61850 for scheme communications, specifically with (IEC 61850 part 8-1) GOOSE for (teleprotection) transfer of directional logic control signals, and (IEC 61850 part 9-2) for SAV transfer of voltage measurements, could represent a practical modern scenario to implement the scheme. Figure 19 presents such a scheme. It provides an illustration of how this proposal to use Voltage Cubes, combined with Directional Agents and IEC 61850 communications services to form a directional unit protection scheme could be realised.

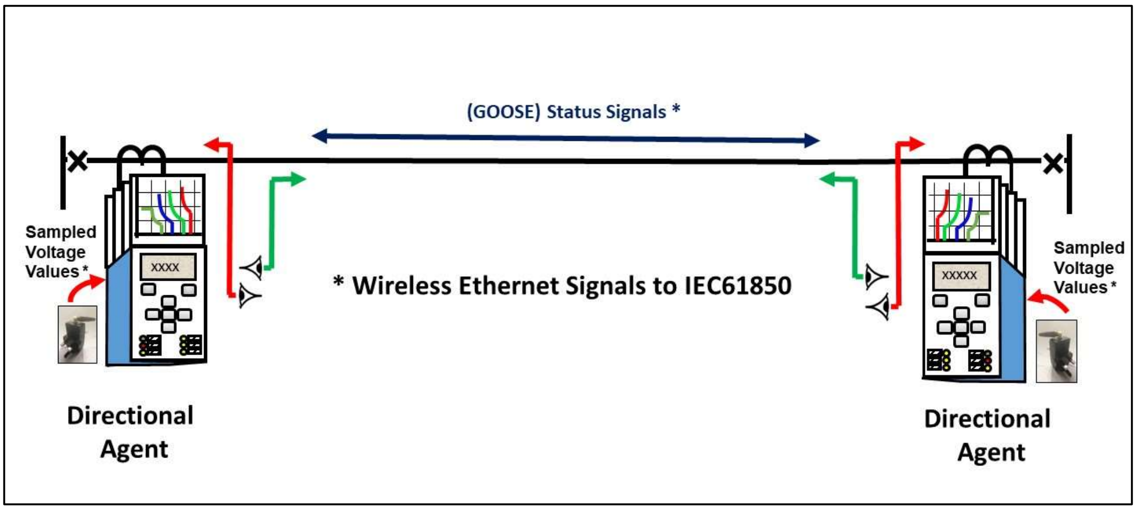


Figure 19: Unit Protection Scheme featuring Directional Agents.

Replicating a protection scheme based on the principles illustrated in Figure 19, forms the core of the work presented in this thesis.

Chapter 5 Literature Review

The perceived original contributions arising from this work direct this literature review. A candidate solution to the challenge of protecting evolving distribution networks is identified as having three principal attributes:-

- Unit protection based on directional comparison techniques using
- Sampled analogue value acquisition of low voltage polarising signals, all
- Interconnected with wireless Ethernet communications.

This review is, therefore, arranged into will three parts. The first concerns advancing the techniques applied for distribution protection. Protection arrangements based on directional comparison unit schemes are considered for their potential to offer transmission-quality protection for distribution-level costs. Literature concerning directional comparison protection is, therefore, identified and appraised. The second part associates with the provision of measured voltage signals as sampled analogue values. The third part assesses the feasibility of using wireless Ethernet communications to interconnect devices forming the protection schemes.

5.1 Directional Comparison Unit Protection

Concerning the design of directional comparison protection, different techniques have been developed to detect directionalities. The most straightforward one involves a simple comparison between the phase of measured voltage and the phase of the current signals. For practical reasons, the technique is generally applied as a qualifier and tripping is permitted only when significant current is present. Known as directional overcurrent protection, as discussed previously in Chapter 3, (typically) a voltage signal is used to polarise the current measurement to give a sense of direction. Tripping is initiated if, and only if, the current is above setting and the power is flowing in a specific direction relative to the relaying point. A different method described by Johns, et al., [78] and [79] employs the principles of superposition to determine the directions of power flow. Sometimes referred to as superimposed directional comparison protection (or delta directional comparison protection) the technique has been quite widely applied for the protection of transmission lines [80]. One example implementation is provided by GE in the form of its MiCOM P40 transmission protection product line. A comprehensive description of how the techniques are implemented in the specific MiCOM P545 device is provided in the associated Technical Manual [81].

Modern directional overcurrent protection devices generally use numerical filtering techniques such as Discrete Fourier Transforms (DFT) to extract specific frequency components (such as the fundamental) from power system signals. Extracted frequency components are then used as inputs to the protection elements. DFT is a relatively simple and inexpensive technique to implement, but the response of this technique is rather slow (≈1 cycle), and so it is not generally used for main protection on HV transmission lines.

The (delta) superimposed-component method uses the changes inflicted on system currents and voltages immediately post-fault, to determine fault direction. The changes (deltas) are determined by applying the principles of super-position to the waveforms. Typically, a rolling one cycle window stores a frame of current data and compares it with a similar frame of samples taken exactly one (or two) cycles previously. Under steady-state conditions, the delta outputs (differences between the equivalent samples stored in the two frames taken around the sample being processed) will be zero. A change in system conditions will cause delta signals to be generated until the power system signals settle into a post-fault condition. The directional element is made by comparing the relative displacements of the current and voltage delta signals. The technique requires carefully controlled, high speed signal sampling and processing. The direction can be determined quickly (typically <1/4 cycle) but is only valid for a short period (≈1-2 cycles according to the length of the filter windows). Requiring high-speed, high-accuracy digital signal processing it is complex and has been costly to implement. It and has, therefore, generally been more popular as transmission line main protection, and particularly more recently, in applications seeking to exploit the potential of solutions employing IEC 61850 process bus implementations [82]. As ICT costs continue to fall, however, it is likely to become a more attractive proposition for cost sensitive applications such as sub-transmission and distribution network protection [83], and value adding applications such as wide-area directional comparison schemes [84].

Against a backdrop of evaluating digital radio for use on distribution network protection, Hunt, McCreery, Adamiak, and King, present a practical paper concentrating on using directional comparison for distribution protection [85]. A directional comparison Blocking (DCB) scheme is described. They note that "As the number of distributed generators and cogeneration facilities increase, directional overcurrent protection and distance protection may not be selective enough for reliable protection without the implementation of pilot protection schemes such as ... directional comparison blocking". They also considering the possibility to use GOOSE to implement the necessary communications for the scheme implementation. So, there is an overlap of thinking between the work of Hunt, et al., and the proposal from this thesis, with a convergence on the principles of using GOOSE messaging to implement unit protection based on directional comparison techniques. Their work on evaluating GOOSE for the directional comparison application compliments and, in particular, helps offset the deficiencies in the current work caused by the lack of access to suitable resources for practical testing. Whilst the paper does not provide the exploration of different techniques that was sought in this work, it reinforces the credibility of the part of this proposal for using GOOSE messaging to implement directional unit protection. General alignment, and hence mutual support, is noted. A notable feature of Hunt, McCreery, Adamiak, and King's work, and how this one differs, is that Hunt, et al., concentrate their efforts on analysing the impact of using the technology to implement a scheme where the GOOSE messaging is resident on a process bus. Not requiring separate process bus provision, the proposal in this work offers potential cost-optimisation advantages. It is noted that the paper advises that the digital radio successfully sends an IEC 61850 GOOSE message within 10 to 15 ms 99% of the time. Interpreting GOOSE functionality, if transmission is unsuccessful, the repetition mechanism of GOOSE will ensure that the event message is retransmitted until it 'dies'. With a repetition interval decaying from, say, 5ms, it may be assumed that the probability of successful transmission within an additional 15ms might approach 99.99%. It may be further assumed that that figure will increase further still to 99.9999% within 45ms – a figure that should be highly reassuring for qualifying distribution protection applications. In the context of this thesis the Ethernet communications are likely to be dedicated to serving just the functionality of the scheme. Whilst that functionality might be conveniently considered in terms of its similarities with both process bus traffic and station bus traffic, the practicality is that the signals of interest, whilst potentially sharing the same physical Ethernet port on a Directional Agent, traffic will exist as SAV and GOOSE streams and, even in combination, will require significantly less bandwidth than in Hunt's study. The concepts of separate station bus and process bus need not impact this proposal, and dedicated links may be provided for exclusive use of the protection application. Encouraged by the work of Hunt, et al, and benefiting from relatively (in Ethernet terms) low communications requirements, overall, the proposal in this thesis is expected to provide a highly robust solution.

In [86], Montenegro, Gardner, and Ennis, acknowledge the problem of providing adequate protection on distribution networks with large penetrations of distributed generation. The solution they offer seems to be heavily tailored towards a specific application. It uses polarised negative sequence current with tailored settings. The work is interesting, but considered not really relevant to the scope of this work.

In [87], Fitzgerald, Bo, Denning, Weller, and O'Keeffe, describe a directional technique for protecting distribution networks that claims "has been proved to be fast in response, simple in principle, and easy to implement". It describes a solution with one device acquiring signals from all CT/breakers on busbar. It uses directional comparison techniques in a 'centralised' solution. The relative merits and drawbacks of centralised versus distributed protection approaches have been, and continue to be, debated. These arguments are considered to be outside the scope of this work which seeks to offer an evolutionary approach to existing practice, rather than a clean-sheet approach. Since the approach upon which it is building is constructed on distributed overcurrent devices, associations with a centralised approach are not obviously forthcoming.

Similarly motivated towards maximising the utilisation of distribution networks by enhancing existing protection as Hunt et al [85], Polajzer, Pintaric, Roser, and Stumberger offer a novel approach to combining overcurrent protection with GOOSE messaging to improve protection of MV distribution networks [88]. They also propose supplementing overcurrent protection with GOOSE messages. In the case of Polajzer et al, the proposal establishes to gain advantage from advanced differential time grading of overcurrent operation aided by GOOSE interventions. The proposal does not, however, consider directionalising overcurrent protection as a vector for improvement and the work is not, therefore, considered contributory in this context.

5.2 Voltage Measurement through Acquisition of Sampled Analogue Values

A novel approach to sourcing voltage polarisation signals to provide the reference for directional decision making is proposed in this research. Taking advantage of the voltage transformation process inherent in power transformers, the burden of isolating/insulating and transforming the voltage can be substantially relaxed in the duties of the measuring voltage transducers if the polarising reference voltages are measured on the LV side of the network. It is suggested that small, low-cost, voltage acquisition devices capable of delivering digitally streamed values can obviate the need for the conventional high-voltage transformers that might ordinarily be required for the provision of directional protection. In this thesis a small, low-cost, (wireless) Ethernet-connected voltage acquisition unit referred to as a Voltage Cube is researched as an alternative to a conventional protection VT. The concept behind the Voltage Cube is to adapt the techniques that are being adopted in the digitalisation of substation design and operation (the influences of ICT and in particular the associated IEC 61850 standard [26]) to bring impact at component-level rather than system-level deployment. Part 9-2 of the IEC 61850 standard associates with the provision of sampled analogue values of measurands (current and voltages) to IEDs for processing for protection, control, monitoring, and automation. Schmid and Kunde [89] investigate the use of the technologies for current and voltage measurement and explain how the separated technologies of sensors and digital communications are brought together with the use of merging units (MU). In the high voltage environment associated with transmission substations the mix of sensor technologies coupled with the large number of measurands involved is well serviced by this multi-box approach. Whilst technologically advanced, and presenting many savings opportunities at transmission system level, it does not appear to represent a cost-optimised solution that would be commercially attractive for distribution applications. The Voltage Cube proposed in this thesis is intended to avoid this dismissal and challenge the perceived association between IEC 61850-9-2 implementation and high-cost solutions. The Voltage Cube shares some commonality of objective with key enablers of substation digitalisation [23]. In this area, at present, state-of-the-art implementations are driven by the demands of high-voltage substation deployment (and the costs that such applications can sustain), but familiarity and acceptance is growing and that should stimulate costs to fall. Pate provides a useful summary of transducer technologies, coupled with a timeline of their adoption [90]. Such adoption of emerging technologies has a habit of driving costs down as volumes rise, spurning spin-off developments in related fields. This further drive down costs, further increasing accessibility and acceptance into new markets. The Voltage Cube proposal may be poised to exploit such reducing costs. Further, in the case of the Voltage Cube, with a requirement to provide only one sampled analogue value stream for the directional polarising reference signal, there is no need to make generous provision for multiple data streams, nor is there a benefit in maintaining a division between the sensor (NCIT) technology and the digital communications (MU) technology and the associated costs that separate packaging incurs. Compact integration becomes possible, and because the translation from a high voltage level to a more manageable consumer level (400V) has been avoided by the LV location of the sensor, size and cost savings can be significant compared to a more generic HV solution. The maturity of the enabling technology for providing current and voltage signals via digital communications in sampled analogue value form, is further reinforced by Thomas et al. [91], who state that "Non-conventional instrument transformers (NCIT) have now reached a level of maturity and performance that enables implementation of fully digital current measurement in high-voltage substations". However, like Bertolotto, Faifer, and Ottoboni [92], the work concentrates on using ICT to exploit the operational benefits afforded by optical sensors for improving the acquisition of current measurement in HV substations, and reducing costs of wiring between devices, whereas in the potential application of the Voltage Cube, a principal benefit that the technology could bring is the flexibility afforded by exploiting the communications to facilitate remotely siting the device in an LV environment. Of particular note in Bertolotto, et al.'s work is the attention paid to the high degrees of accuracy that can be afforded by the technologies. In the case of the Voltage Cube application for use in directional comparison protection applications, accuracy is not a major issue. In effect, only phase information is critical (it is the phase that provides timing reference) and an error even as high as 1ms equates to an angular error of only approximately 18^{0} (at 50Hz) which could be 'hidden' within a blinder region on a conventional directional characteristic (set at, say $\pm 70^{0}$) such as that illustrated in Figure 41. The reduced accuracy demands also encourage inexpensive implementations.

5.3 Wireless Communications for PAC Schemes

A PhD Thesis by Palak Parikh provides an informative starting point for a literature survey on the topic of wireless communications for PAC systems. In the work, entitled "Investigation of Wireless LAN for IEC 61850 based Smart Distribution Substations" [93], Parikh presents an introduction to IEC 61850, GOOSE and wireless communications for the substation. Parikh explores the theory considerations and conduct of wireless communications for the substation. Parikh extensively details simulation exercises and practical measurements and tests on such communications. Parikh manages the Thesis through to a notably concise conclusion "From the thorough investigation, wireless LAN with 54 Mbps data speed is suitable for implementing various smart distribution substation applications up to throughput of 8000 Kbps." Given that directional comparison unit protection functionality is incorporated within their MiCOM P545 IEDs making use of 64kbps, it seems that the wireless LANs should be able to deliver against project objectives. With this potential capacity overhead, it would seem possible to consider a scenario in which the two communications interfaces required to host the IEC 61850-8-1 GOOSE services for the teleprotection commands, and the IEC 61850-9-2 SAV/SMV services for the polarisation signals required by the Directional Agents could be jointly hosted by a single wireless interface. Such an approach in which the communications interface requirements are minimised must be encouraging from a cost perspective.

In papers [94] – [102], Parikh and others provide further reassurances as to the suitability of the technology for the application as detailed in the following appraisals.

In [94], Parikh, Kanabar, and Sidhu, provide an introduction to wireless Ethernet technology and elaborate on feasible uses. In it, they argue a case for wireless LAN technology being feasible for application to protection and automation at distribution level "Wireless LAN can be considered for various smart grid applications, such as distribution substation automation and protection, and monitoring and control of distributed energy resources, especially ... where data rate requirements and radio interferences are comparatively less..." "... wireless Ethernet ... therefore ... can be considered for these applications". The paper concludes that wireless Ethernet could be useful for applications like communications-aided line protection.

In [95] Kunsman & Kranich particularly consider interoperability aspects of wireless communications. They observe that "Broadband wireless mesh networks based on IEEE 802.11 provide the best interoperability because they support open standards including TCP/UDP/IP, 802.11 (WiFi) and 802.3 (Ethernet). To integrate field devices and avoid unconnected assets, some wireless mesh routers can also support secure network connections to devices supporting modern automation such as DNP-3 protocol and IEC 61850 MMS and GOOSE communications". This can be interpreted as another positive endorsement for the technology marriage.

In [96], Ali (B.M), Ali (M.A), Abdala, Othman, and Hashim, (by virtue of simulation studies) also conclude that WLAN should be OK for peer-to-peer IEC 61850 Substation communication systems. As the intended configuration of communications required by this proposal is peer-to-peer, Abdala, Othman, and Hashim's paper provides encouragement.

In [97], Parikh, Smith, and Pilon, report on the use of industrial wireless technologies for protection. It is of note that 'protection', 'automation', and 'monitoring' are quoted in the title of the paper, but that 'control' is not. Whether or not it can be inferred that wireless GOOSE is suitable for isolation (i.e., breaker opening) but not restoration (breaker closing) is not clear, but they state that "A single IED platform ... can be applied with IEC 61850 GOOSE using robust wireless technologies.". Further, "High performance unlicensed technology can transport IEC 61850 GOOSE Ethernet frames natively, allowing for data rates of up to

1.25Mbps with a latency tuneable to as low as 5ms." The performance they characterise does, therefore, seem suitable for applications such as fault clearance on distribution feeder protection or railway protection for which sub-cycle operation is not required. More work might be required to determine the suitability of the technology for applications to control breaker closing. Since, however, this application is concerned with protection (and tripping/opening circuit breakers) rather than control (potentially closing breakers), the concern is, for now, dismissed as out of scope of this work.

In [98], Rogers, Bartman, and Rowland, examine the use of (ISM) band unlicensed radios for GOOSE type applications – essentially, GOOSE radio. They observe that "Radio communications solutions have been successful in time critical IEC 61850 GOOSE applications in distribution circuits", adding that a solution can be achieved "reasonably well." They conclude that "Radio communication is a cost-effective and reliable solution for extending protection and control networks", with a bold statement "for a Distribution application requiring GOOSE messaging with a latency of 20ms, unlicensed radio provided a solution." Since the intended application for this research is for distribution protection, and since, consequently, operating times of the order of 100ms may be acceptable, the implications of potentially 20ms communications latency should not provide too much concern, especially if it allows the application to extend to hard-to-reach (in terms of communications) locations.

In [99], Rinaldi and others investigate the performance of wireless Ethernet and its suitability in IEC61850 guise for use in distribution applications. Containing some detail of implementing IEEE 802.11ac, the paper "investigates an application where a wireless link has been used to connect the DER and DESS automation systems located in a building. The experimental test is aimed to evaluate if communication performance offered by IEEE 802.11ac is in accordance with the requirements of the automation application in Smart Grids." The investigation considers the performance of communication of the IEC 61850-5 standard for different service levels in term of transfer time, time synchronization, availability and security. The paper concludes that IEC 61850 electrical automation may benefit from a suitable wireless connection, adding that an IEEE 802.11ac link "is able to fulfil IEC 61850 requirements even regarding critical applications (1.4ms of transfer time, compatible also with protection applications) unless the network is loaded with heavy traffic". Again, this reinforces the justification for selecting wireless communications technology for PAC implementations based on IEC 61850, particularly since in this application the communications links are likely to be dedicated just for the communications to implement the protection schemes, rather than supporting shared links such as process buses and station buses.

In [100], Smith, Vico, and, Wester, in the context of a study of wireless communications, state that "IEC61850 GOOSE messaging is ideal for the type of protection message used in distribution communication-aided protection schemes". A general conclusion that may be drawn from the paper is, therefore, that point-to-point radio Ethernet is suitable for reliable GOOSE messaging. With an intent to use point-to-point wireless Ethernet communications to interconnect the Directional Agents and Voltage Cubes to form the unit directional comparison schemes proposed in this work, it seems that Smith, et al.'s research gives credence to the proposal.

In [101] Palak, Kanabar, Sidhu et al evaluate communications technologies for distribution automation systems (DAS) with distributed energy resources (DER). In essence they are comparing and contrasting the use of wired and wireless communications for PAC style applications. In the paper, the use of the OPNET tool to model a communications network is described. OPNET Network simulator is a tool that can be used to simulate the behaviour and performance of any type of communications network. The simulation study is used to compare the performance of wired and wireless communication systems for different messages. These messages include GOOSE as well as measured values. Simulation results are compared with actual performance of commercial devices. (Note that the commercial devices have a limited (57.6 kbps and 115.2kbps) data rate – sufficient for directional comparison unit protection schemes). One might conclude that the technology is well matched to the application. The paper concludes "that the message transfer time delay of GOOSE message and measured (metered) values for wired technologies ... and wireless technologies ... is within the allowable range." Further, "The trend in the simulation and experimental results shows that for higher throughput and less delay communication requirements (e.g. urban area) wired communication can be suitable due to its high data rate availability. Whereas, for the rural area distribution network with dispersed DERs, wireless communication with repeaters can be more feasible technically as well as economically. This work shows the clear indication for the potential applications of various communication systems at distribution level for the future smart grid." This is encouraging in terms of the intended application.

Parikh, Sidhu, and Shami continue the work in [102] and demonstrate the feasibility of 'real-world wireless LAN' for IED communications. They provide practical re-assurance about the suitability by describing a "laboratory prototype development of wireless enabled IEC 61850–based substation devices, such as wireless IEDs and a merging unit (MU) playback, using an industrial embedded system with a hard real-time platform." Again, this is encouraging for the intended application.

In [103], Apostolov introduces an extension to the GOOSE messaging provision of IEC 61850. Designated routable GOOSE (R-GOOSE) it is designed to extend the characteristics of GOOSE messaging to make it more suitable for communications outside of a substation LAN environment – for example by increasing security. Apostolov explains that "the expansion of IEC 61850 outside of the substation is the next step in the evolution of the standard (IEC 61850) that improves its functionality in order to better serve the smart grid." ... "(R-GOOSE) brings some significant benefits for wide-area distributed applications, especially when they are based on wireless communications technologies. The cyber security features defined in IEC 61850 90-5 and IEC 62351 provide a high level of security, which is a key requirement for DAPS." (DAPS - distribution automation and protection). Apostolov concludes that "R-GOOSE ... allows the development and implementation of high-speed peer-to-peer communications-based distribution system protection and automation applications" resulting in "improved reliability of the distribution grid." Supported by Mackiewicz [104] it can be concluded that R-GOOSE serves its intended purpose to provide a mechanism for routable GOOSE - that is to extend the reach of GOOSE, potentially over WLAN wireless Ethernet, to a remote location.

As a means of providing substation event notification between substations over WLANs, R-GOOSE seems to offer an ideal transport mechanism for command transfer between Directional Agents located in different substations to provide directional comparison unit protection [105]. As such, it could be exactly what this research proposal requires.

The general feeling of encouragement is boosted further by Mekkanen, et al., who report the use of wireless GSM as feasible for applications such as Loss-of-Mains using IEC 61850 MMS messaging [106], and by Abdel-Latif, et al., who observe that "The wireless communication network offers advantages over conventional techniques such as no pilot wire that can break, faster response, lower cost compared to leased lines." [107]. Thonet and Deck report on an example of wireless communications being commercially adopted into substation environments [108], and Dehalwar, et al. conclude simply "that IEEE 802.22 can be used for real-time of some protocols of IEC 61850." [109].

Some caution, however, needs to be exercised. Persello and Steinhauser sound warning under the heading ‘Possible Application Limitations of WiFi Communications in IEC 61850 Systems’ [110]. But limitations are not specific to IEC 61850 compliant implementations. At the 2006 Power Systems Conference “Advanced Metering, Protection, Control, Communication, and Distributed Resources”, Moxley and Fodero issued a more general warning that “appropriate precautions should be taken when using communications as part of a distribution protection approach.” [111]. They do, however, temper their work by suggesting “that radio communications may be better suited to command-based schemes such as directional comparison rather than data-based schemes such as current differential”. Despite such assurances however, cyber security is an inevitable hot topic of concern when operational communications paths are seen to offer potential hacking routes into mission critical installations. Accordingly, even though IEC 61850 was defined specifically with critical electricity supply requirements in mind, potential cyber security issues must be addressed.

Also in 2006, this time at the IEEE PES Power Systems Conference and Exposition, whilst acknowledging that “wireless data communications are becoming widespread in many industries, since they offer significant benefits over wired communications, including low-cost installations, rapid deployment, easy user access, and mobility.”, Cleveland recognised that “at the same time, the use of wireless technologies in power system environments presents a number of security and reliability concerns. These concerns include the impact of noisy electrical environments on the wireless media, the reliability of the currently available commercial wireless equipment, the overloading of the available bandwidth (particularly during emergency conditions), and the security of communications.” [112].

In the context of cyber security the suitability of wireless communications in general, and R-GOOSE in particular have been questioned. Concerning the relationship of cyber security with wireless substation communications, EPRI take a pragmatic approach and declare an inevitability that requires attention at the Organisational Level. EPRI assert that “The upcoming generation of engineers and operators has grown up with wireless connectivity and will expect to use these technologies in substation applications. The organization deploying wireless technologies in a substation must implement a security posture that assumes the wireless technology is inherently insecure. Appropriate defense-in-depth security measures to assure safe operation of the substation must be deployed.” [113]. In the context of R-GOOSE, Utsun, et al., offer suggestions for potential tools with which an Organisation might secure its assets [114].

Whilst respecting the gravity of the issue of cyber security, it seems that the advantages of wireless technologies for these types of applications outweigh the disadvantages, and that, proceeding with appropriate caution, deployment seems inevitable. A final paper on this subject by Kanabar, et al., is chosen to endorse the argument [115]. Entitled "Wide Area Protection & Control using High-Speed and Secured Routable GOOSE Mechanism", it compares and contrasts the relative merits of delivering wide-area PAC solutions based on Routable-GOOSE (R-GOOSE) and/or Synchrophasor platforms. Assessing the communications requirements for providing truly wide-area (e.g. national/international) systems such as System Integrity Protection Schemes (SIPS) and Centralised Remedial Action Schemes (CRAS), it is motivated by the need potentially to transfer large volumes of traffic using R-GOOSE under systems disturbances. A dissimilarity between the problem faced by Kanabar et al.'s work, and the subject of this Thesis, is that whereas SIPS/RCAS schemes may experience multitudes of reportable events, the proposed directional comparison scheme should not. R-GOOSE messages are event driven, and a retransmission mechanism means that, during event activities, network traffic is heavy, whereas under steady operating conditions, R-GOOSE traffic tends to shy away merely to provide a heartbeat. When system events are limited, such as in a directional comparison unit protection scheme, the potential consequences of network overload being evaluated in Kanabar's paper are unlikely to be a concern. Kanabar et al. acknowledge that R-GOOSE meets the needs to satisfactorily deliver GOOSE functionality across substation boundaries. Their concern seems to be that increasing boundaries bring increasing traffic and that could lead to overload. The paper concludes that "The GOOSE mechanism has already been used for protection and control over LANs. In order to use the GOOSE over WAN for WAPC applications, this paper presents implementation of IEC TR 61850-90-5 based on R-GOOSE protocol." A takeaway, therefore is that, for supporting a directional comparison unit protection scheme in which catalytic events are likely to be few and far between, R-GOOSE can deliver the teleprotection services required.

Not only do the academic works cited demonstrate support for the readiness of the technology for the proposed application, manufacturers' publications are also indicating the market-readiness of the technologies. Two indicative examples are provided. In [116], GE Digital Energy present their Multilin DGT. Using wireless communications the product provides a solution for Distributed Generator Trip Control (DGT).

Features and Benefits claimed are:-

- “Cost-effective wireless and fast transfer trip solution
- Transfers trip and status confirmation faster than standard breaker reclose time
- Point to Multipoint system supports up to 7 generation sites
- Long range communication - up to 30 miles
- Packaged for immediate outdoor installation
- State of the art software enables easy configuration and system management”.

In [117], SEL Inc. present their SEL-3060. It is a “multipurpose Ethernet radio for distribution automation wireless applications”. It claims an operating range of up to 15 miles – sufficient for short feeders. Significantly, it also claims to implement point-to-point GOOSE. From the manufacturers’ claims, it appears that either could meet the basic needs of the proposal.

With commercially available products supporting the required functionality, coupled alongside strong academic supporting evidence, it seems that a proposal based on exploiting the technology could be well founded.

Chapter 6 Research Strategy, Planning, and Models

This chapter introduces the research strategies and tools employed on the project presented in this thesis. It also outlines planning aspects associated with the research for the project. To this end expected research outputs are identified, planning (including methodologies and summary work breakdown employed) to achieve these outcomes is presented and a summary of resources employed (including tools and modelling details) is provided.

A range of research techniques including literature survey, feasibility study, system modelling, protection simulation and testing, are identified as appropriate to the research. A mixture of these is employed to achieve the research outcomes.

- Literature review guides knowledge acquisition.
- Feasibility models enable conceptual ideas to be evaluated.

To evaluate the proposal, constituent components are defined and modelled. Complimentary electrical distribution network models provide an environment in which different network operational scenarios, including faulted network conditions can be simulated. Application of protection models to the network allow protection techniques to be applied, studied, and developed. In the modelling and testing activities, a generic distribution network model is created, performance of the model is verified by benchmark testing, protection performance is evaluated by testing different protection simulation model arrangements against different configurations of the network model, and test results are evaluated to qualify the merits of a protection approach based on using directional principles to protect the network.

As set out previously, in this work evaluation is ordered into three parts. Consistent with this ordering, this outline of the evaluation strategy, planning and modelling is ordered into three sections.

Based primarily on simulation modelling, section 6.1 associates with evaluating the application of directional protection to distribution networks. Including an outline of modelling and verification strategies, this part of this chapter outlines activities to develop a generic distribution network, verify the model, and use the model to test protection performance.

Section 6.2 associates assessing the feasibility of acquisition of LV polarising signals.

Section 6.3 associates assessing the feasibility of using wireless communications to implement proposed directional protection schemes.

6.1 Directional Agents Research Strategy

Directional Agents can be considered as an instance of directional protection embedded within a suitable hosting device. In essence they use measurements of phase currents in combination with voltage signal(s) to determine direction of current flow.

To study the how the polarising voltage signal(s) affect directional decision making, it is necessary to develop a suitable evaluation environment. This requires a model of the distribution network, a strategy for testing, and suitable models of protection devices for testing. With these in place, different protection techniques can be evaluated.

6.1.1 Distribution Network System Modelling Strategy

A significant part of the foundation work of the project is to develop distribution network model(s) that will allow the performance of different protection schemes to be evaluated.

In this work, DIgSILENT's PowerFactory software is used to model the behaviour of representative parts of distribution networks. The models can be used for simulation testing (where relay operation is simulated in software), or the outputs from the models can be used in conjunction with specialist test equipment to stimulate real protection devices. PowerFactory is chosen as it is a well-established tool. It is appropriately licensed and widely used for similar work at the University of Manchester. The tool was, however, new to the author at the start of the work. It was therefore deemed appropriate to exercise caution with the author's initial use of the PowerFactory software. An early protection benchmarking exercise provided an opportunity to raise the author's understanding of, and competence to use, the tool. The benchmark testing also provided opportunity to verify the model. Taken together, therefore, the activities in this exercise should serve to demonstrate both the correctness of the model, and the competence of the researcher to use it effectively.

The project entails a study of network scenarios such as those presented previously through Figure 6 to Figure 15. Whilst testing on an actual distribution network might be interesting and offers the possibility to yield truly realistic results, it is simply not practical. It is necessary, therefore, to model network operation. Modelling of the distribution network scenarios presented previously in

Figure 6 through Figure 15 will permit the project objectives of evaluating protection performance to be addressed.

Individually modelling each network topology to provide appropriate vectors for protection evaluation is a valid approach for developing a test strategy. Allowing for iterative developments from a simple model enables quick initial progress, but as the scenarios become more complex, the iterations become more involved and difficult to manage. Developing a single model that can be configurable to host any foreseen scenario may take longer initially, be but it can preferable and is the approach adopted in this work. Developing a single configurable network can minimise overall development effort. This affords better opportunities for quality management since only one version needs to be proven and maintained. Configured to simulate a simple passive radial distribution network (as per Figure 6), benchmark protection testing can be applied to verify the model against known rules and criterion. By switching additional functions in/out of a verified model, the effects of influencing factors (for example introducing embedded generation into the network) can be carefully controlled, and the performances of different protection techniques responding to these effects can be critically evaluated. The network model presented in Figure 20 is considered to be capable of hosting any of the scenarios that are required to be simulated for the project and is accordingly chosen for development.

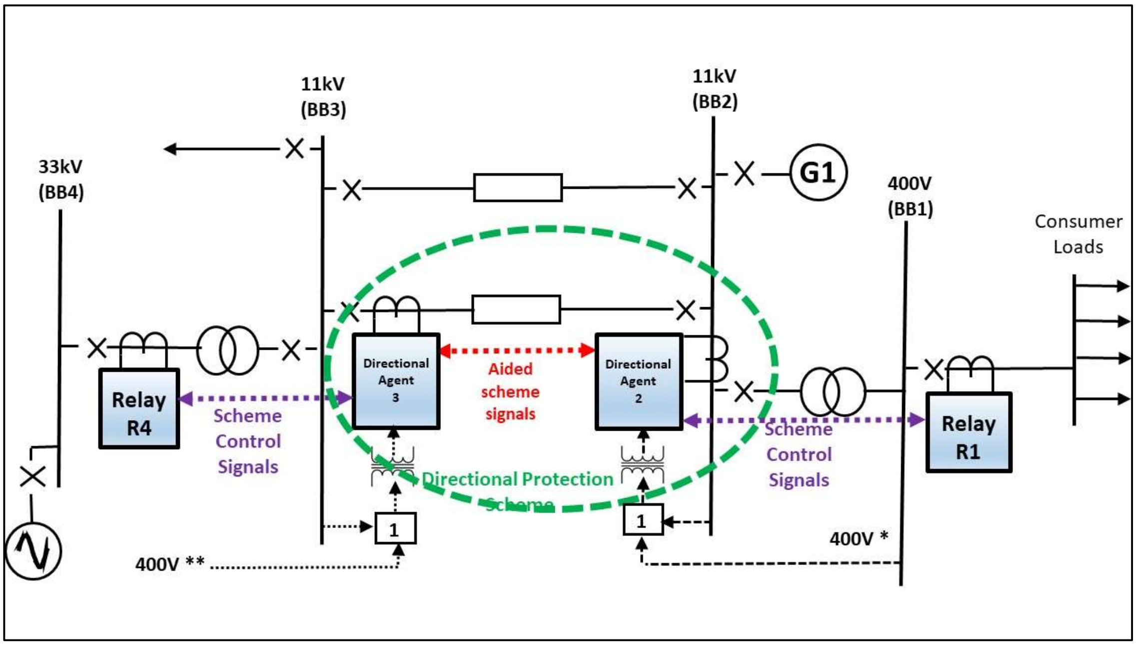


Figure 20: Generic Model for Distribution Network Simulation and Testing.

The model presented in Figure 20 incorporates a directional protection scheme for study. The protection scheme is formed by the two Directional Agents (3 and 2) connected by a communications (aided-scheme) signalling channel.

The distribution network comprises features three voltage levels:- 33 kV, 11 kV, and 400 V.

A grid supply point (GSP) energises the network via 33 kV busbar (BB4).

Loads can be connected at busbars at both 11 kV (BB2/3) and 400 V (BB1/CL).

Relays R4 and R1 are overcurrent relays similar to those introduced at Figure 6. They serve as a useful tool with which to verify the performance of the simulation model as it is developed.

G1 represents a distributed source of generation similar to that introduced in Figure 7. The embedded generation is connected at 11 kV busbar (BB2).

Both Directional Agents are each provided with current and voltage inputs.

As well as being configured for use with Directional Agent3 in a directional scheme, if desired, Directional Agent2 can be configured to provide independent non-unit protection such as the generic protection introduced in Figure 8. The non-unit protection could be a directional overcurrent function polarised from the local busbar voltage (as in Figure 9), or from a low-voltage busbar (as in Figure 10).

The possibility to extend the study in a later stage, to potentially supply the polarising voltage signal in the alternative form of a sampled analogue value (SAV) data stream from a Voltage Cube or equivalent, is desirable.

The Control Scheme signals introduced in Figure 11 could, for example, be annunciation outputs of directional indication signals from Directional Agents used to control other protection devices in the scheme. For such usage, there is a need to connect the functions between devices using the digital input/output (I/O) mapping capabilities of the IEDs under test.

To implement unit schemes such as the communications-aided directional overcurrent scheme outlined in Figure 12, output signals should be exchanged between connected Directional Agents. In practice, the signals could be exchanged using a communications channel – probably with GOOSE messaging - between connected IEDs. For simulation testing, however, it may be acceptable to use 'virtually hardwired' connections for simplicity instead. The possibility to extend the study in a subsequent stage to incorporate full GOOSE messaging is desirable. Similar considerations apply to the scenarios presented in Figure 13 and Figure 14 where the Directional Agents (Directional Agent3 and Directional Agent2) could provide a (delta) directional comparison protection scheme rather than one based on aided directional overcurrent principles.

6.1.1.1 A Generic DIgSILENT Model of a Distribution Network

Figure 20 presents a network model that is to be used to evaluate protection performance in this study. For effective evaluation of the protection performance, there needs to be confidence that the network modelling is valid. Simulation of the model allows performance to be examined by allowing interaction with protection. Replication of predicted protection operation against a theoretically characterised model can provide that confidence. This exercise is designed to demonstrate validity of the simulation model to provide that confidence.

The network model of Figure 20 is designed to be a generic configurable one that can mimic the network configuration of Figure 6. Figure 6 models a passive radial distribution network for which the flows of current are predictable. Accordingly, the theoretical performance of applied overcurrent protection can be calculated. Confirmation of the performance of the protection applied to the simulated model against the calculated values will give a benchmark of model validity, providing confidence that modelling capabilities are adequate for further protection testing and performance evaluation.

In this exercise, the DIgSILENT PowerFactory (Version 2018 SP1) is used to model and simulate the generic distribution network model presented in Figure 20. To verify the model, the model is configured to mimic the characteristics of the passive radial network presented in Figure 6. Overcurrent protection is then applied to the network and its performance simulated. Theoretical settings values can be calculated and associated performance expectations derived. Comparison of test results from the model against calculated values can be used to verify the model.

An equivalent model of the network, prepared using the DIgSILENT PowerFactory software is shown in the following (annotated) Figure 21

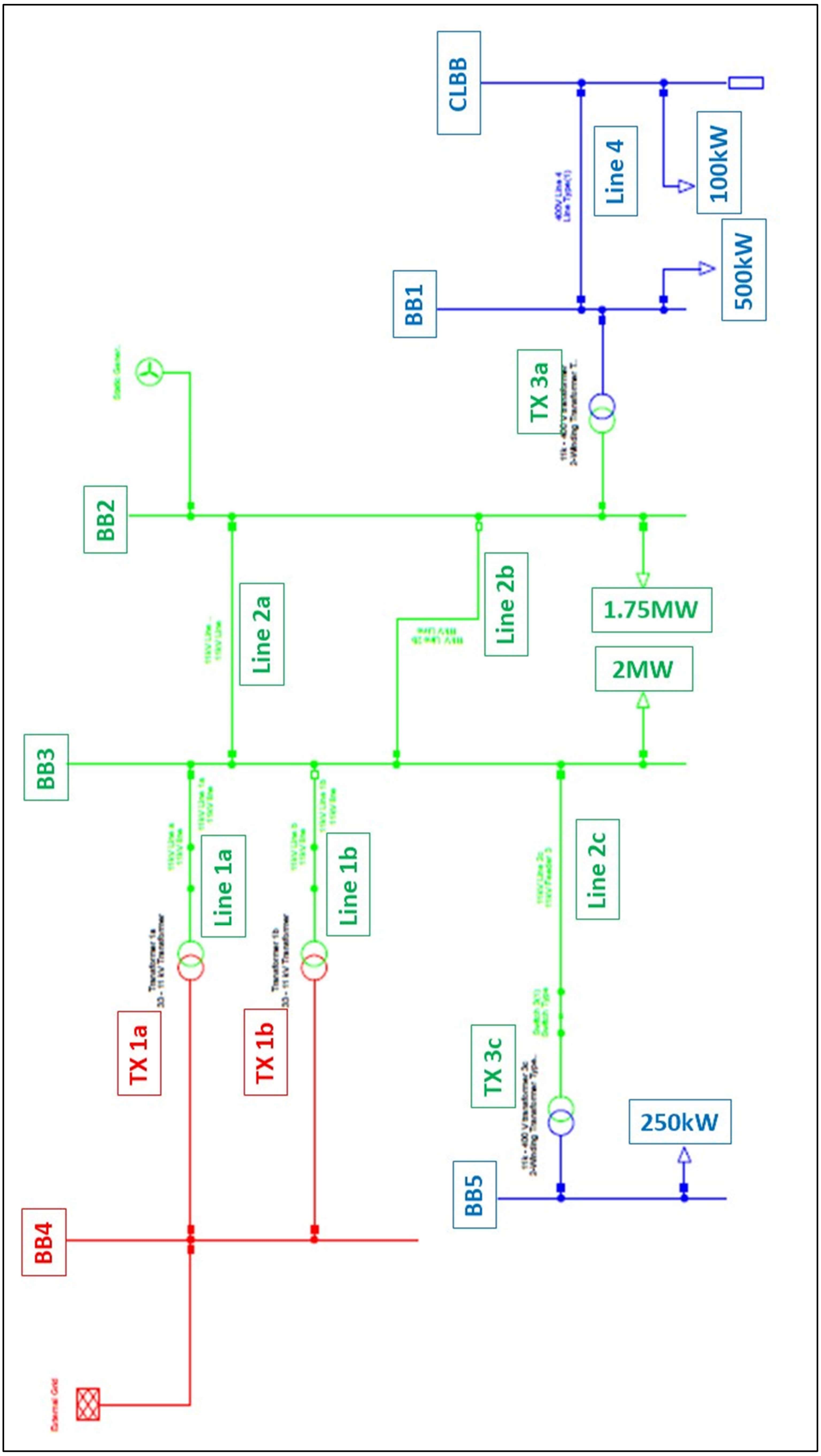


Figure 21: Generic UK Distribution Network modelled in PowerFactory.

In the previous Figure 21, colouring has been applied by the DIgSILENT software to indicate system voltage energisation levels. Red colouring indicates network components energised at 33 kV (BB4), green indicates 11 kV energisation (BB2, BB3), and blue is 400 V (BB1, CLBB, and BB5). Where applicable (for example in this case, the windfarm generator), grey represents disconnected network.

Additional to the network elements included in Figure 20, the following items have been added to the model to make it sufficiently generic to mimic all network scenarios under investigation.

- A parallel transformer feeder between busbars BB4 and BB3,
- A parallel plain feeder between busbars BB3 and BB2,
- Various loads are added to mimic a realistic operational scenario.

The parallel transformer feeder between busbars BB4 and BB3 is added to make the model potentially more reflective of typical UK practice. It is normal UK practice to have parallel transformer circuits feeding distribution networks so that the supply can be maintained during, for instance, transformer maintenance. It this work, however, the feeding circuit does not form part of the protected network being studied. The parallel circuit is included for completeness, and the parameters of both are identical, but unless otherwise stated, only one feed is 'in-service' at any time. The parallel feed is switched 'out-of-service'; it has no influence and can be ignored.

The parallel plain feeder between busbars BB3 and BB2 is not, however, redundant. It can facilitate the construction of meshed networks to provide opportunities to evaluate later, more challenging topologies such as that presented in Figure 15.

BB1 can provide a source for local LV polarising of directional protection associated with busbar BB2.

For reference, key circuit parameters defining the DIgSILENT model of Figure 21 are presented in the following Table 3:-

Table 3: Generic Network Model Circuit Values.

Reference	Attributes
External Grid	33 kV grid supply point (slack bus)
Generator	11 kV connection to BB2. 8 kW max mech. power
BB4	33 kV busbar
BB3	11 kV busbar
BB2	11 kV busbar
BB1	400 V busbar
CLBB	400 V consumer load busbar
BB5	400 V consumer load busbar
Line 1a, 1b, 2c	11 kV cable (3ph). 1 km. $R_{1,2}$ = 0.08Ω/km, R_0 = 0.1 Ω/km, $X_{1,2}$ = 0.16Ω/km, X_0 = 0.2 Ω/km,
Line 2a, 2b	11 kV cable (3ph). 10 km. $R_{1,2}$ = 0.08 Ω/km, R_0 = 0.1 Ω/km, $X_{1,2}$ = 0.16 Ω/km, X_0 = 0.2 Ω/km,
Line 4	400 V cable (3ph + N). 0.5 km. $R_{0,1,2}$ = 0.02 Ω/km, $X_{0,1,2}$ = 0.129 Ω/km,
TX 1a, 1b	33 kV:11 kV. Dyn1. 15 MVA. Zpps=3 %. Secondary star point 1Ω resistance-earthed.
TX 3a, 3c	11 kV:400 V. Dyn1. 1 MVA. Zpps=5 %. Secondary star point 1 Ω resistance-earthed.

6.1.1.2 Verification of a DIgSILENT Model of a Distribution Network

To provide confidence the proposed network model is reliable to use for the evaluation of different protection techniques, it needs to be verified.

This requires some benchmarking of performance.

In this work verification is by benchmarking theoretical overcurrent protection performance against that delivered by simulated protection performance applied to the network model.

Common practice in the UK is to protect passive radial distribution networks with time-graded overcurrent protection. Short-circuit fault analysis is relatively straightforward, and, by the application of simple well-established rules, theoretical protection settings can be determined.

The network described by Figure 20 has been modelled as a configurable test facility using the DIgSILENT PowerFactory package. The resulting simulation model is presented in Figure 21. The following Figure 22 demonstrates how the generic model can be configured to mimic a passive radial network suitable for application of time-delayed overcurrent protection.

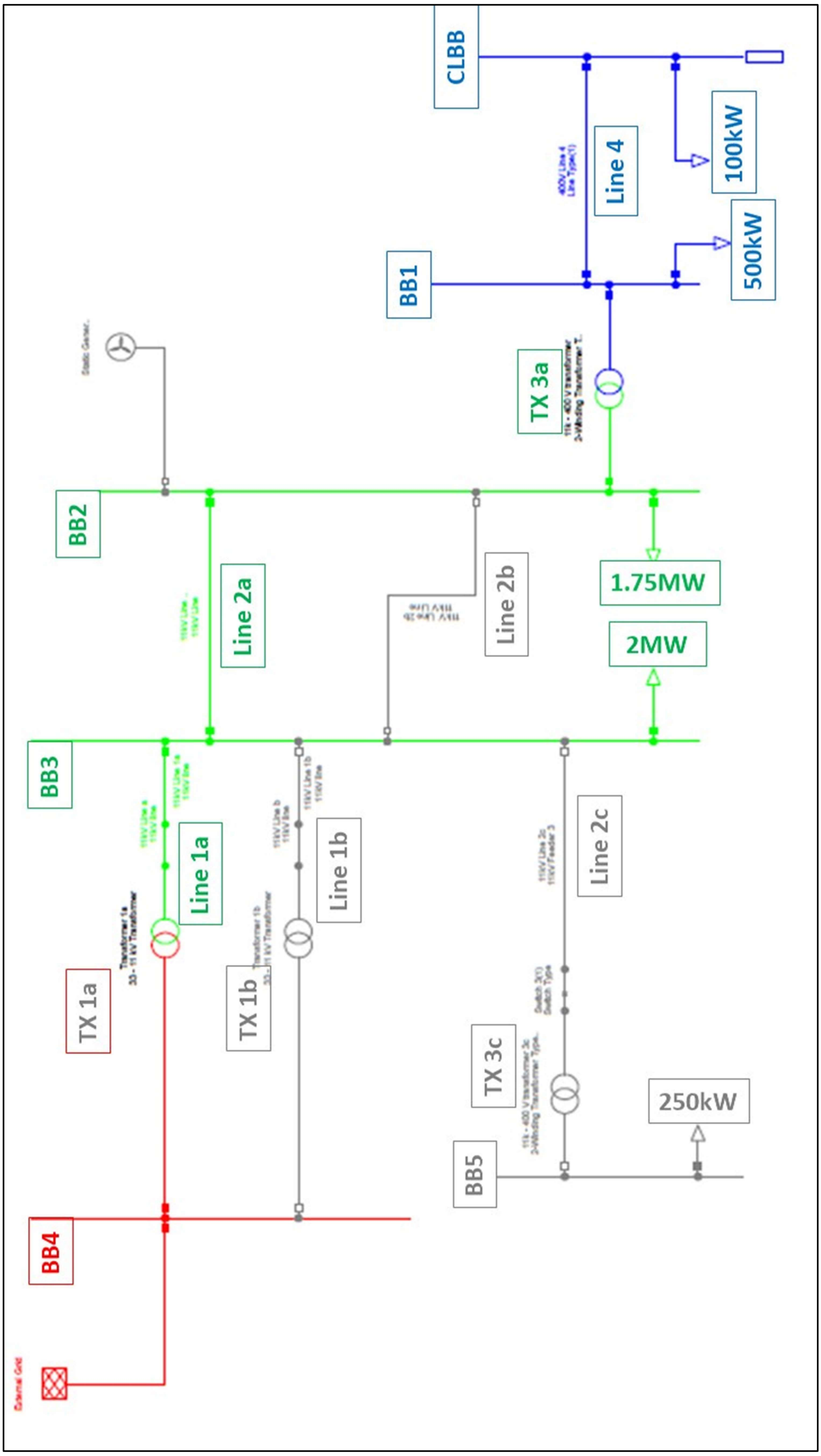


Figure 22: Generic Network Model Configured as Passive Radial Distribution Network.

Configuring the generic model to mimic the simplest passive radial distribution network is achieved by:-

- Disconnection of the renewable energy resource(s)
- Disconnection of one of the parallel 33/11 kV transformer feeder circuits
- Disconnection of one of the parallel 11 kV feeders
- Disconnection of (some) LV consumer load circuits

(As with the previous example (Figure 21), red colouring indicates network components energised at 33 kV, green at 11 kV, blue at 400 V, and grey represents disconnected network.)

Aligned comparison of the calculated theoretical overcurrent setting values, against those yielded by the simulation model, allow verification of the configured model. With a verified configuration of the model, evaluation of protection on an extended model can proceed with confidence.

Principally, this evaluation involves testing protection.

6.1.2 Protection Testing Strategies

Electrical power systems represent significant investments. These investments need safeguarding. In part, safeguarding is provided by the protection equipment which is designed to ensure safe appropriate system operation in the event of abnormal operating conditions being encountered.

The protection equipment can be considered as an insurance policy. Since the asset it is protecting has significant value, the policy must be reliable and robust. Demonstration that the performance of protection is suitable is achieved through comprehensive testing.

To demonstrate functional performance by testing requires that the protection equipment should be stimulated in the same way as it would be in service. To perfectly achieve this would require either full access to the plant it is designed to protect, or construction of an exact replica of the power network to which it is to be applied. Given the magnitude of the investment required, this is rarely, if ever feasible.

In practice, to obviate the need to replicate power systems, their performance is simulated using network models. Outputs from simulation models can be used to stimulate protection devices to test them. To simulate in-service performance, protection devices under test need to be stimulated with signals that are comparable to those which, in practice, come from the outputs of transducers or transformers. These outputs come from measurement devices which have connections to the primary (high voltage) side of plant on the network. Because the signals connected to the protection are taken from the secondary side of the measuring devices, testing using this type of signal is generally known as 'secondary-injection testing'.

Some network modelling equipment is capable of directly supplying signals suitable for secondary-injection testing. A more widely adopted approach, however, is to use a computer simulation package to generate numerical signals that are representative of the signals present on the network. The numerical waveforms generated can then be converted to suitable secondary-injection test signals to stimulate protection devices via intermediary test equipment (amplifiers). In addition, the numerical waveforms generated by the model can be used to stimulate protection devices' software models directly. This is often called simulation testing. The protection does not need to exist in the form of physical devices – just the mathematical models are needed to allow the protection algorithms to be simulated and exercised. Simulation testing is often employed during the development of protection algorithms since ideas can be tried and tested without the need to procure either hardware models or specialist test equipment. Thus, protection algorithms can be evaluated before making commitments to production tooling, costs, etc.

When developing new protection ideas, the approaches of both simulation testing, as well as secondary injection testing are typically used. Both have advantages. Equally, both suffer disadvantages. For example:-

- Simulation testing, in which 'virtual' models of protection devices are simulated and tested in the absence of any hardware has the advantage of not requiring procurement of hardware models nor test equipment. Suitable for execution in an office-type environment, it is very flexible and allows new ideas to be quickly evaluated. It is, however, dependent upon the availability and integrity of the software models to correctly replicate the protection behaviour. This may not always be the case due either to errors in the software, or modelling inadequacies and inaccuracies.
- Secondary-injection testing, on the other hand, requires the procurement of models and deployment of additional test equipment. It affords a more realistic testing environment, but it may require special accommodation and handling. Typically it is performed within a specialist electrical testing

laboratory. It generally takes longer due to setting up and reconfigurations between iterations and is more expensive. Since the testing is performed on devices which are physically representative of the devices that will be applied in practice, it renders more validity to the results.

A commonly adopted approach is to develop and verify the conceptual ideas in a 'virtual' simulation environment, and then to validate the operation with secondary-injection testing. This is the approach originally intended for this work. The approach is attractive since the DIgSILENT PowerFactory software package chosen for this study provides the capability to model power systems to produce outputs that can interface with secondary-injection test equipment. Also, the PowerFactory software boasts a library of protection models to support simulation testing.

This means that a distribution network model produced with the DIgSILENT PowerFactory package can be used for both simulation testing (providing speed, cost, and accessibility advantages) as well as (circumstances permitting) for secondary injection testing to improve coverage and credibility.

6.1.2.1 Distribution Network Protection Simulation Testing

In the absence of hardware models, and/or suitable laboratory space, (such as might be encountered during the Covid19 pandemic) simulation testing provides an opportunity for evaluating protection performance. The DIgSILENT PowerFactory software can be used to model a generic distribution network. Additionally, DIgSILENT models could be used to simulate/emulate appropriate MiCOM protection devices. If simulation models are to be used for testing, the validity of the models needs to be assured. In the absence of evidence of independent homologation/certification, the user must have a strategy to manage the risk of the models not being compliant with expectations. It may be necessary, therefore, to benchmark any models before using them for performance evaluation. As reported in Appendix I, the DIgSILENT models are constructed from generic models and not endorsed by Manufacturers' performance claims. Consequently, such testing is a necessity when using these generic-based models for evaluating new concepts.

6.1.2.2 Distribution Network Protection Secondary-Injection Testing

As well as simulation testing, where practically possible, evaluation could include secondary-injection testing in which representative power system signals are used to stimulate actual physical devices.

Secondary-injection testing can be achieved by using the output from the network model developed within the DIgSILENT PowerFactory suite to control suitable test equipment.

A suitable test equipment for secondary injection test equipment is the Omicron CM range of secondary-injection test equipment.

For this work Omicron is chosen, and is guided by:-

- Suitability of equipment
- Availability of equipment
- Familiarity with equipment

The choice should not be used to imply any kind of endorsement of these products above any other similar products. The choice is guided by pragmatic reasoning.

Whether using simulation testing, or secondary injection testing, appropriate models of the protection are needed to evaluate performance. The following section therefore guides model selection.

6.1.3 Distribution Network Protection Evaluation Models

To demonstrate protection performance, test devices are needed. For simulation testing, software models of the protection devices are required. For secondary-injection testing, physical devices are needed.

In this work, the fundamental protection operating principles being investigated are directional overcurrent protection (realised in Directional Agents) and directional comparison. Because the principles are proven in previously established applications, it may be possible for existing protection models to provide the basic functionality.

For this work, MiCOM P545 devices are chosen as ideal protection models. MiCOM is a brand and trade name introduced and developed by GEC ALSTHOM/ALSTOM in the 1990’s. Through mergers and acquisitions, MiCOM is now offered for different applications by both GE and Schneider Electric.

Px40 is one of the ranges of protection devices in the MiCOM ensemble. Part of the Px40 range, P545 is a high-performance product aimed, predominantly, at protection of transmission lines.

P545 is chosen for this work since it hosts a whole suite of numerical protection elements that can be used to protect transmission and distribution circuits. Whilst the principal features of line differential protection and distance protection are not used in this study, of particular interest may be:-

- Directional and non-directional
  - Phase overcurrent protection
  - Neutral overcurrent protection
- Directional earth-fault protection
- Delta directional protection
- Choice of conventional CT/VT inputs, or SAV inputs to IEC 61850-9-2.

Although other manufacturers provide products that may be equally suitable, the following practical reasons guide the choice to P545:-

- The author of this work collaborated on the design and development of the MiCOM Px40 range of products. Consequently, the author is intimately familiar with their features, design, and operation.
- The author of this work has contributed significantly to the design and development of the principal protection concept (numerical current differential line protection) in the P545 and its predecessor, GEC's LFCB. The author is, therefore, familiar with the fundamental protection concepts offered by the product.
- The protection library of the DIgSILENT PowerFactory network modelling tool boasts inclusion of MiCOM protection devices. This could facilitate modelling and simulation testing of MiCOM Px40 protection functions.
- The University of Manchester benefits from having a small number of MiCOM P545 products in various configurations in its inventory of laboratory equipment. These could be ideal as test vehicles for this work.

The choice of P545 as a test vehicle is made for convenience and should not be used to imply any endorsement of these products above any other similar products.

6.1.4 Evaluation of Protection Techniques

This section (and included sub-sections) presents a breakdown of experimental tasks involved in this distribution network protection study. Following creation of a generic model of a distribution network, overcurrent protection is applied to benchmark performance. Following verification of the model, the work is extended to explore other protection techniques:-

- Voltage measurements are introduced into the formation of protection characteristics to provide the ability to discriminate according to the direction of power flow.
- Embedded generation is introduced into the network, and the contribution of embedded generation on the network is varied in order that power flows can be varied.
- The effect of the location of the voltage-polarisation source can be studied to assess the feasibility of using remote voltage acquisition to polarise Directional Agents.
- Directional protection techniques can be evaluated for differing network topologies.

The generic model produced with the DIgSILENT PowerFactory software is shown previously in Figure 21.

The following Figure 23 shows the same generic model but enhanced with an overlay of potential relaying points and possible fault scenarios.

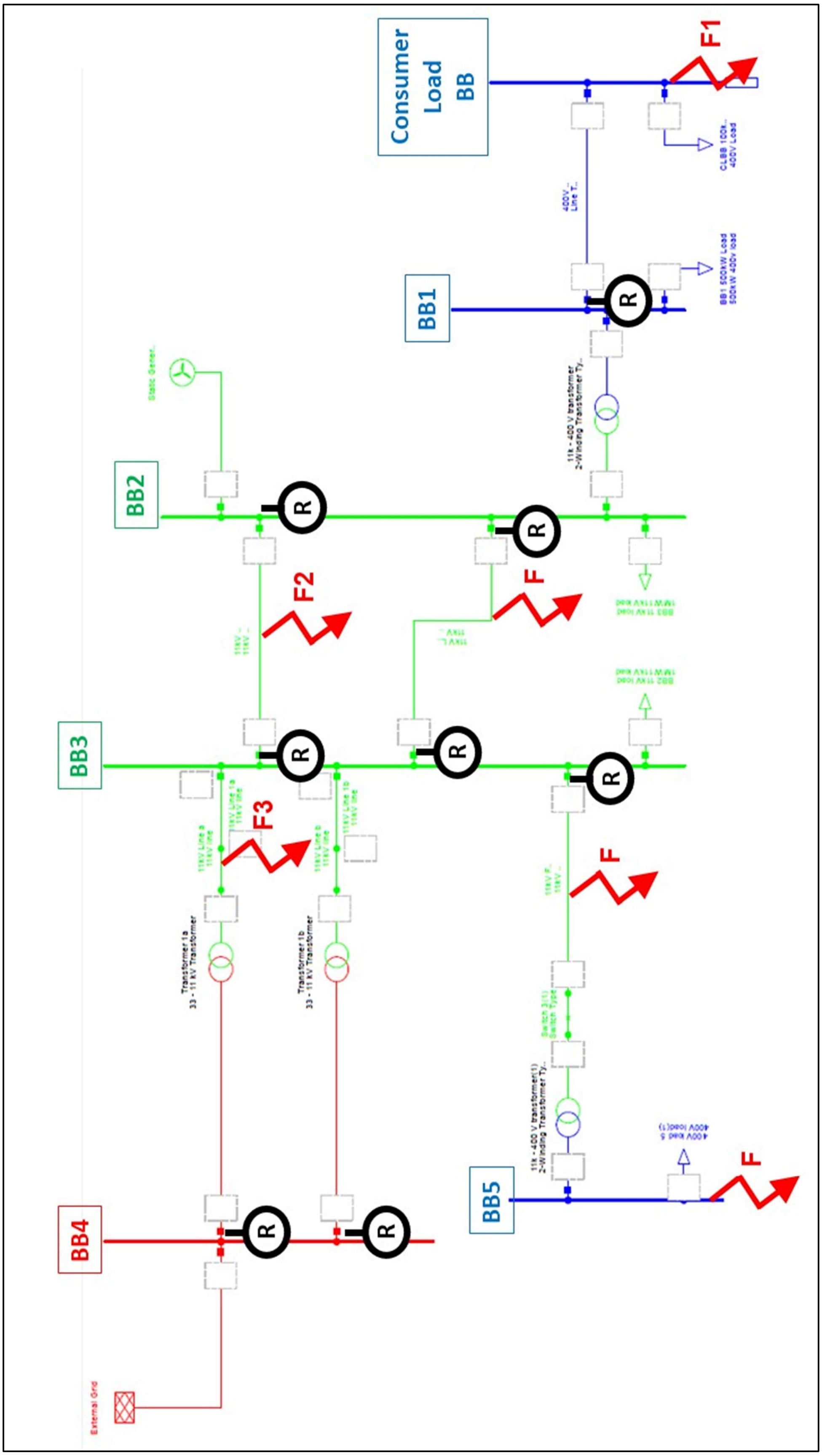


Figure 23: Generic Model of UK Distribution Network with Protection and Faults Scenario Overlays.

The overlaid model provides a vehicle with which different network topologies, various fault scenarios, and potential protection techniques can be explored. Interests include:-

- Evaluation of directional overcurrent protection
- Applying directional overcurrent protection on distribution networks featuring embedded generation
- Impact of polarising voltage on directional protection
- Directional protection principles comparison

6.1.4.1 Benchmarking Development of Overcurrent Protection on a Radial Distribution Network

Non-directional overcurrent protection is used to benchmark the configured distribution network model. Correlation between theory and model output is used to validate the model.

6.1.4.2 Directional Overcurrent Protection Applied to Radial Distribution Network

The overcurrent protection used to benchmark the configured distribution network model is replaced with directional overcurrent protection. The performance of the directional overcurrent protection is evaluated using the DIgSILENT model.

Conventional voltage polarisation techniques are employed for this part of the work.

6.1.4.3 Directional Overcurrent Protection Applied to Distribution Networks featuring Embedded Generation

Embedded generation is introduced into the DIgSILENT network model. The performance of directional overcurrent protection is evaluated for different faulted and un-faulted network scenarios and with varying degrees of generating and load capacities.

With the inclusion of additional generation into the model, control can be exercised over the flows of power across the network. The model is now representative of the system that the Directional Agent model is being developed to protect.

Detailed evaluation of Directional Agent response to differing network topologies and fault scenarios can therefore be undertaken.

6.1.4.4 Directional Comparison Scheme Design

To evaluate the capabilities that directional comparison protection might offer to the challenge of protecting exclusively distribution grids, appropriate relay models are required. Selection and provision of a suitable directional comparison scheme design is considered. The consideration may extend to the design of the directional comparison technique, as well as the implementation for testing.

6.1.4.5 Polarising Directional Protection

Directional protection uses reference signal(s) to polarise (provide a 'direction' for) relay operating quantities [25]. The protection evaluated in this study uses voltage signals to polarise current signals. The polarisation effect is dependent upon the characteristics of the voltage signal provided. Since a novel aspect of this work concerns an alternative approach to providing the polarising signal, this will affect the characteristics of the signal. The impact on directionality caused by changing the polarising quantity source and delivery needs evaluating. Voltage polarising techniques are introduced and the effects of changing the polarising voltage are studied.

6.1.4.6 Directional Comparison Protection Scheme Performance

With verified distribution network models, and suitably connected, appropriate Direction Comparison protection models in place, the effectiveness of the proposed protection provision can be evaluated. Multiple, various-case, fault types are applied to the system and the results analysed and evaluated.

6.2 Distributed Low-Voltage Measurements Research Strategy

The objective of this work package is to assess the feasibility of providing a compact, cost effective AC voltage measuring device that can be used to provide a polarising signal suitable for use by a Directional Agent IED.

The feasibility study considers performance, size, and cost. The performance considers dynamic range, accuracy, and connection requirements.

- A literature review is employed to evaluate the dynamic performance requirements for protection VT inputs.
- The literature review explores signal interfacing and recommends appropriate connectivity.
- Candidate proposals are identified for evaluation as prototypes and analysed for suitability.
- A preferred prototype solution is appraised and assessed to demonstrate proof of concept.
- Recommendations for a proposed solution are made.

The feasibility study appraises what might reasonably be attained with currently available technologies. A suitably qualified demonstrable ‘model’ indicative that the concept could lend itself to industrialisation is promoted.

6.3 Research Strategy to Investigate Unit Protection formed from Directional Agents, Distributed Low-Voltage Measurements and Wireless Communications

The objective of this work package is to investigate the feasibility of implementing wide-area protection of smart electrical distribution network using wirelessly-communicating Directional Agents. The main focus is on determining the suitability of wireless communications to provide services to:-

- Transfer data in the form of sampled analogue values (SAV) from numerical measurement transducers to Directional Agents
- Transfer status information between Directional Agents

Commercial availability of similarly equipped, similarly performing devices is considered.

It is expected that the communications will be conformant to the international standard IEC 61850, and in particular:-

- Part 9-2 for SAV,
- Part 8-1 for status information in the form of GOOSE messages.

The feasibility is primarily informed by literature review. The review considers the communications requirements to implement a unit scheme based on Directional Agents.

The literature review guides:-

- Mapping of the requirements against the service provisions of IEC 61850.
- The implications of utilising the alternative medium of wireless Ethernet.
- Suitability for servicing the requirements of GOOSE messaging.
- Suitability for servicing the requirements of SAV transfer (including time delay implications).
- Technology maturity/readiness/availability.
- Qualification/Demonstration of compliance.

Recommendation(s) concerning the use of wireless communications to implement the proposed scheme are presented.

Chapter 7 Research Activities

This chapter describes the research activities undertaken for the project described in this thesis..

The organisation of activities descriptions in this chapter aligns with the layout of the research methodologies and results discussions of Chapter 6 and Chapter 8. Based primarily on modelling and simulation, section 7.1 associates with evaluating the application of directional protection to distribution networks. Section 7.2 associates assessing LV polarising signal acquisition by means of a feasibility study. Section 7.3 associates assessing the feasibility of using wireless communications to implement the proposed directional protection scheme.

7.1 Distribution Network Protection Activities

Section 7.1 of this work applies distribution network protection. The strategies introduced in Chapter 6are used to develop an electrical distribution network model which provides a simulation environment in which protection techniques, including the concept proposal outlined in Chapter 4, are synthesised.

A distribution network model is developed. Together with suitable protection models, a test environment is established and verified to allow protection techniques to be evaluated. The verification exercise is based on a non-directional overcurrent protection study. Adding directionality into the protection allows the exercise to extend to explore the benefits that unit protection schemes based on Directional Agents might bring to smart active distribution networks which incorporate dispersed embedded generation.

7.1.1 Distribution Network Protection - System Model Development

To facilitate evaluation of Directional Agents, a model of a generic distribution network is developed in the DIgSILENT PowerFactory simulation package. This allows various protection test scenarios to be executed for evaluation. Before the simulation model is used to evaluate different approaches to protecting the network however, the model needs to be proven for correctness.

Evaluation of current flows generated by the simulation model against theoretical values obtained from a conventional overcurrent grading exercise study is used to benchmark the network performance.

To deliver a benchmark-verified distribution network model a structured approach is followed. Using the DIgSILENT PowerFactory software, a suitable distribution network model is prepared for the overcurrent grading study. This model, shown in Figure 22 is then used to simulate the network and predict values of load currents and fault currents occurring on the network. In conjunction, a theoretical analysis of the network is performed to determine the values of load currents and fault currents anticipated on the network. The theoretically calculated values are then compared with the simulation results to verify the model. Agreement between theoretical and simulated overcurrent protection performance is used to validate the model.

7.1.1.1 Partitioning a Network Model into Protection Zones for Current Analysis

The first stage in applying protection to a network is to divide the network into protected zones. Partitioning into zones then guides selection of protective relaying points (and associated measurement locations).

Figure 24 shows the radial distribution network of Figure 22 augmented with a protection overlay.

The overlay shows how the radial feeder is partitioned into four overlapping zones to provide coverage for faults such as those designated F4, F3, F2, and F1.

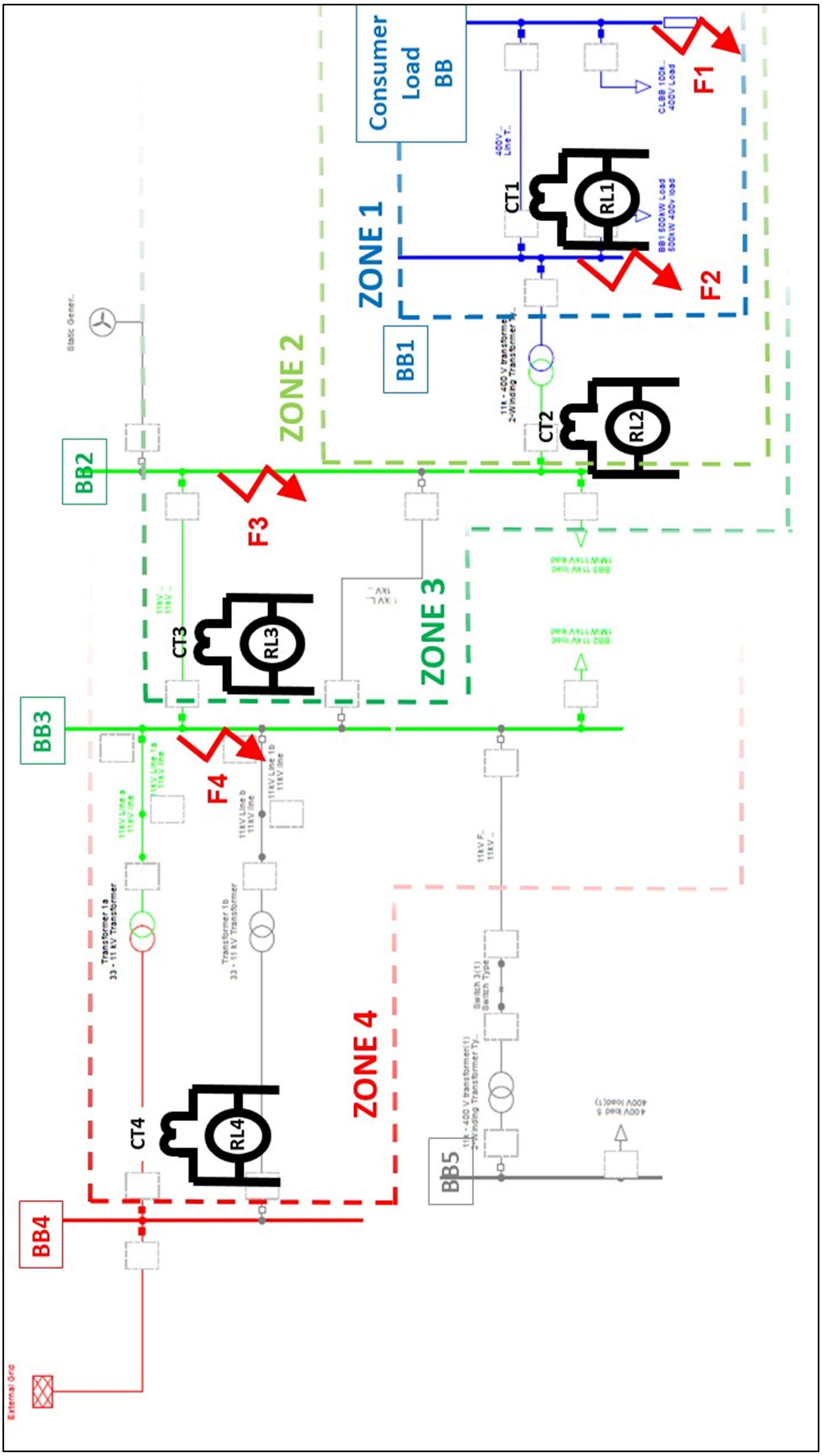


Figure 24: Distribution Network Modelled with DIgSILENT, Configured as a Passive Radial Network, with Protection Overlay.

The overlay illustrates how overcurrent protection (represented by relays RL1 – RL4), together with their associated measuring current transformers (CT1 - CT4), are applied to protect the networks against faults such as the examples shown as F1 – F4.

It should be noted that in practice it is unlikely that IDMT overcurrent relays would be used at 400 V levels across the network, and that fuses would be a preferred option. The principles of grading are, however, similar, and in this study IDMT overcurrent protection is exclusively applied for consistency and clarity of presentation.

7.1.1.2 Theoretical Determination of Zone Currents for Configured Network Model

To calculate the anticipated load currents and the prospective fault currents, a single line diagram (SLD) is used. Whilst the electrical distribution networks being studied are three-phase systems, it can be cumbersome to show all phases on a network diagram. With an SLD, a single line is used to represent a three-phase connection. Figure 24 is a diagram of the network being studied presented in SLD style. For analysis of network currents, it can be useful to further simplify the diagram to remove unnecessary details. A simplified SLD (showing little more than equivalent impedances for the network in question) is shown in the following Figure 25.

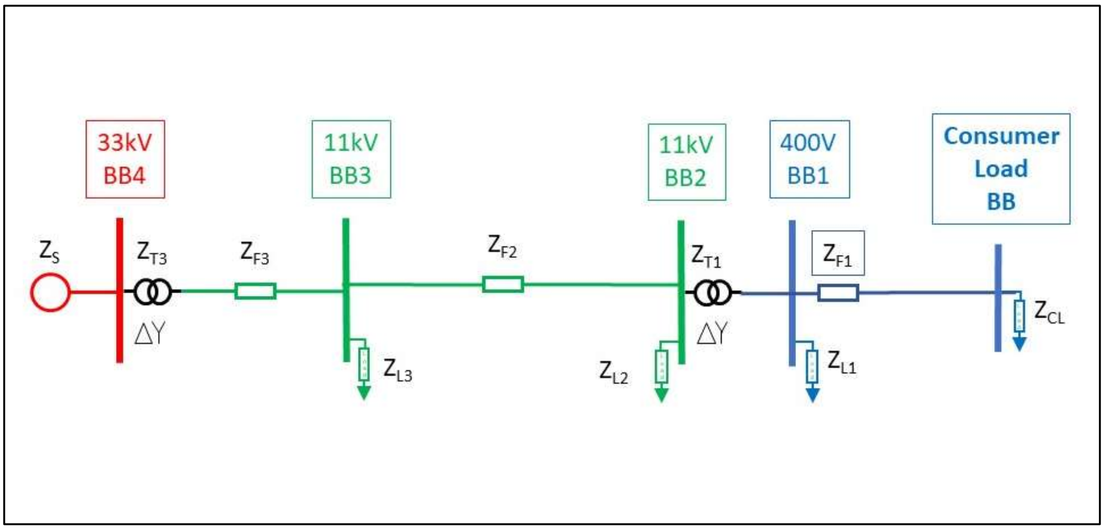


Figure 25: Simplified Equivalent Single Line Impedance Diagram (SLD) of Benchmark Network Model.

It should be apparent that applying simple circuit analysis to the simplified SLD of Figure 25 can provide the theoretical prospective load and short-circuit fault currents.

7.1.1.3 Using the DIgSILENT Network Model to Determine Fault Currents and Load Currents

With a DIgSILENT model of a network such as that presented in Figure 24, the PowerFactory software provides the means to predict network values such as prospective fault currents and load currents. In particular a 'Calculate Short-Circuit' function allows short-circuit faults to be simulated and the prospective fault currents to be determined and displayed, and a 'Calculate Load Flow' function allows the values of load current to be determined and displayed. These functions report the values of the currents produced by the simulator. As well as these, other values such as node voltages can be presented by the output reporting functions to facilitate evaluation.

7.1.1.4 Comparing Theoretical Zone Currents with DIgSILENT PowerFactory Simulation Determined Zone Currents

To verify model performance, the current values calculated from the simplified SLD (Figure 25) can be compared with the equivalent values derived using the DIgSILENT model (Figure 24).

7.1.2 Distribution Network Model – Overcurrent Benchmarking

The system model verification (benchmark protection testing) uses a suite of tests to verify the network model. A time-graded overcurrent scheme is implemented and tested. The MiCOM P545 models provided by the DIgSILENT relay simulation library are used. Verification is by analysis of time-overcurrent plots for the operation of the protection scheme. Correctness of the network model can be further assured by evaluation of the performance of the associated neutral overcurrent protection, as well as by evaluation of protection operation according to a prescribed fault sequence.

7.1.2.1 Benchmark Overcurrent Protection Scheme Design

An overcurrent protection settings study is performed for the distribution network. Predicted performance of the overurrent protection is compared with that delivered by the DIgSILENT PowerFactory simulation model.

Agreement of theoretical values with practically-determined equivalents, will serve to validate the DIgSILENT simulation model. To this end, a time-graded overcurrent scheme is designed to protect the distribution network and applied to the simulation model. Network simulation is used to confirm the values of load currents and fault currents occurring on the network. In an iterative process, overcurrent protection performance is analysed to refine the model and the corresponding applied protection (connection, configuration, settings, etc.). Demonstrations of convergent and conformant protection performance provide model verification.

In this study, protection Zones 1-4 are protected by relays RL1 – RL4 as shown in Figure 24. MiCOM P545 relays have been selected for this study as they should be capable of providing a range of protection principles including directional comparison, directional overcurrent and, of most interest in this particular benchmarking exercise, non-directional overcurrent protection. The non-directional protection comprises phase overcurrent protection, neutral overcurrent protection, and sensitive earth-fault protection

As is common with phase-segregated protection, independent connections are provided for the phase overcurrent ($I>$) element inputs in the P545. The P545 is, however, a multifunctional relay. To accommodate all of the functions within the constraints of the availability of input/output terminal numbers, some compromise is required. Accordingly, no separate input is made available for the standard neutral current (*IN*>) elements. Instead, the product relies on deriving a neutral current from a summation of the phase CT inputs (*I*>). This derived input neutral current is used as input to the standard neutral current elements (*IN*>) with 'virtual' connections made internally by software. Also with the MiCOM P545 relays, an additional sensitive current input connection is also provided. This has separate physical connections and is typically used for sensitive earth-fault (SEF) protection. As a SEF function, it is particularly suited to use in unit protection schemes of the aided directional earth fault (Aided DEF) type. Since directional schemes could be implemented using either the *IN*> elements or the *ISEF*> elements, it is critical that the implications of how the different ways the input quantities are supplied to the protection, as well as how they consequently affect operation, are understood. To ensure correct understanding, an exercise to compare the performance of these elements is undertaken. The primary purpose of this particular exercise is to verify the model, but it can be useful to extend the comparison of the operation of the independent element (*ISEF*> for which the operating current can be measured), to cross check the operation of the neutral current element (*IN*>for which the input, being derived from the operating currents of the phase elements, cannot be directly measured), to assure correct understanding and application. In this benchmarking exercise, RL1 is the most downstream relay (furthest from the source). It protects Zone 1. Zone 1 has three phase-paths and a neutral path through which currents flow. Hence protection is provided in the form of three-phase overcurrent (*I*> on the phase currents), and neutral overcurrent (*IN*> on the derived neutral quantity). Connecting the *ISEF* input to measure actual neutral current flowing allows the element (*ISEF*>) to provide reference neutral current protection for comparison with *IN*>.

Relay RL4 is the most upstream (closest to the source) of the protection devices. Delta-connected to upstream BB4 and protecting Zone 4, the protection has no neutral connection and hence only phase overcurrent (*I*>) is provided. Relays RL3 and RL2 protect star-connected 11 kV Zones 3 and 2. Having phase and neutral connections, the protection features phase overcurrent protection (*I*>), and neutral overcurrent protection (*IN*>). The separate sensitive protection (*ISEF*>) is not used in RL2, nor in RL3.

7.1.2.1.1 Determination of Benchmark Scheme Current Settings

In this exercise, just first stage non-directional overcurrent elements are used. The first stage of the phase elements (*I>1*) are configured as IDMT. The first stages of the neutral (*IN>1*) and the sensitive element (*ISEF>1*) are configured as definite time (DT).

A rule-of-thumb relating to the maximum load current ($I_{load\ max}$) and the minimum prospective fault current ($I_{min-fault}$) to the setting current (I_S) for an overcurrent relay setting is described by the following relationship:-

$$2I_{load\ \max} < \cdot I_S < \frac{1}{2} I_{\min-fault} \quad \text{...} (1)$$

To use equation (1) to determine the current setting for an overcurrent relay, it is it is necessary to know the anticipated load currents and the prospective (sort-circuit) fault currents.

Generally, protection devices do not measure the primary system voltages and currents. Transducers, usually in the form of transformers are used to provide isolation and to scale the magnitudes of the primary system signals to match the expectations of protection inputs. Equation (1) can be applied using either primary, or secondary values. If secondary values are used, then the protection settings should reflect the effect of these transducers/transformers. Protection current inputs are generally rated at either 1A or 5A nominal (In). The protection CTs are required, therefore, to scale the primary currents in line with nominal expectations. Choice is made from standard values of CT ratios (e.g., 200:5 A) and finer adjustments made in the protection settings to match the specific requirements of the application (e.g. 120% In).

To apply protection correctly, as well as accounting for the transducers/transformers ratios, the transformer connection arrangements must be correctly assigned and configured (to ensure, for example, correct phasing), and the correct settings must be applied. In some relays, including the MiCOM relays, provisions is made to accommodate CTs with either 1 A or 5 A nominal currents. In such relays, care is required to ensure that, where applicable, the appropriate '*transformer*' compensation settings are applied for both protection functionality, as well as for '*measurement*' reporting.

In this particular exercise, only current-operated protection elements are being studied and, therefore, only settings associated with these current inputs need attention. The studied elements are the phase elements, the (derived) neutral elements, and the sensitive current inputs. The phase overcurrent protection elements (*I*>) require CT connection for each of the three protected phases, the neutral overcurrent protection elements (*IN*>) are often supported by a CT measuring in the neutral connection. Some three-phase relays can, however, internally derive a neutral current from the three phase currents, and in the MiCOM P545 relays used in this exercise, the neutral current protection element exclusively uses an internally derived quantity. So, in this exercise, for the IN> elements, only derived inputs are used. The derived element input quantities are provided by the phase CT inputs and so separate CTs are not used for the IN> elements. There are no associated CT settings to be accounted for. The sensitive earth fault element (*ISEF>*) is intended to use a separate sensitive transformer input (typically a core-balance CT). As will be discussed in the results, the SEF input is being used in this exercise to stimulate an additional relay input and to compare operation of neutral current protection, rather than to particularly provide SEF protection. Either way, a CT in the neutral circuit is, therefore, required for connection to the ISEF> inputs.

The simplified SLD of Figure 25 is a convenient vehicle with which to examine circuit parameters and predict prospective current flows for the configured distribution network model of interest. It should be remembered, however, that whilst the SLD shows a single line circuit, the distribution network is actually a three-phase, multi-conductor system. This is particularly significant when considering the implications of multi-phase transformers in the network. When connecting the inputs of protection relays, it is necessary to recognise the multi-conductor nature of the circuit which may, or may not, include neutral and earth paths. Protection must be considered for all current paths. To recognise all the current paths, and to determine the necessary relay input assignments, it is particularly necessary to consider the transformer connections.

For the configured distribution network under consideration, there are two three-phase delta-star transformers. Typically, in the UK, the neutral in the star side is resistance-earthed, and the example arrangement is shown in the following Figure 26.

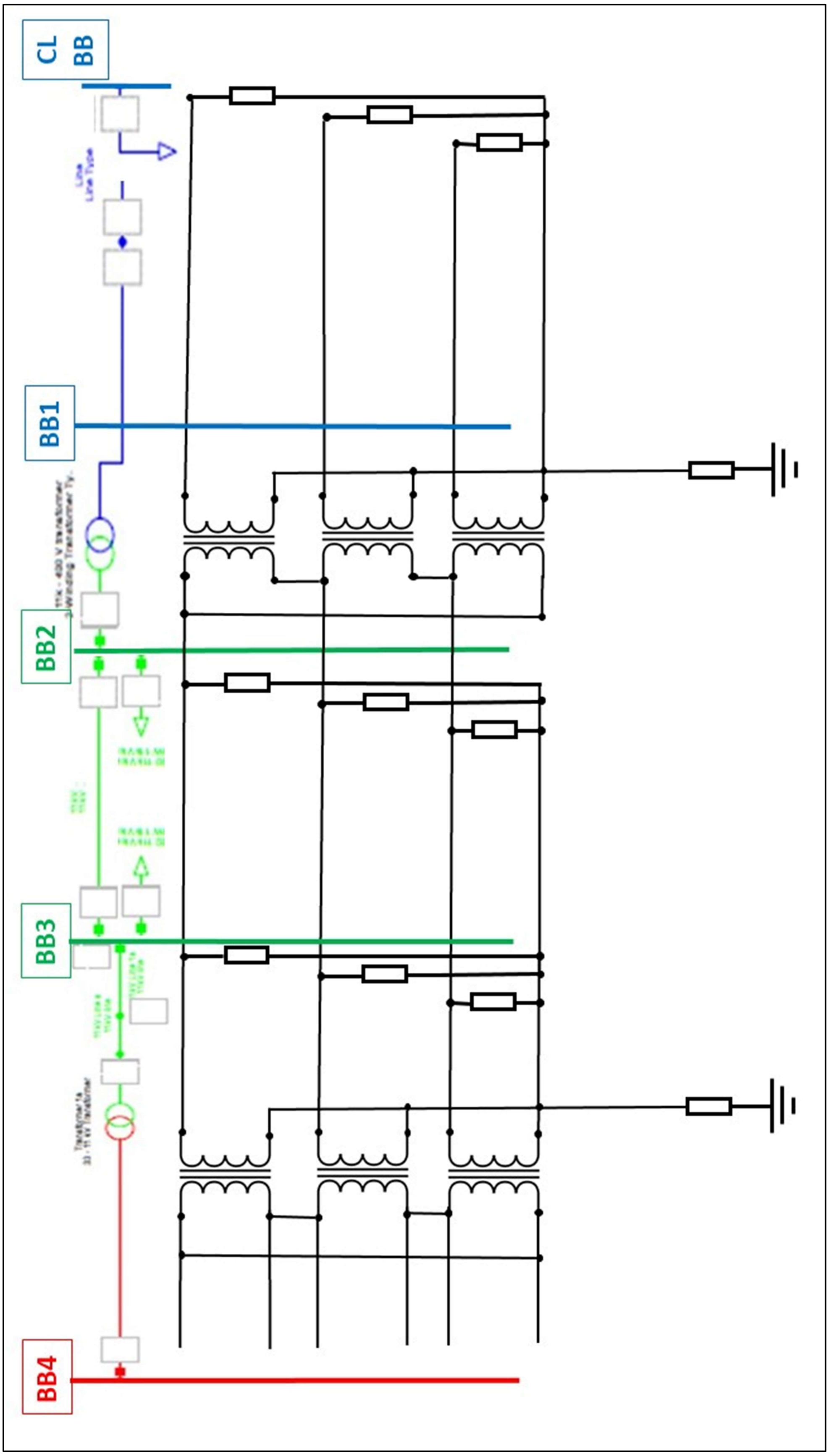


Figure 26: Distribution Network Model Transformer Winding Arrangements.

Overlaying the locations and connections of the instrument transformers (CTs and/or VTs) and the associated relay inputs brings clarity. For this demonstration example with current-only protection, the overlay in the following Figure 27 illustrates the impact on CT placement (and hence relay positions).

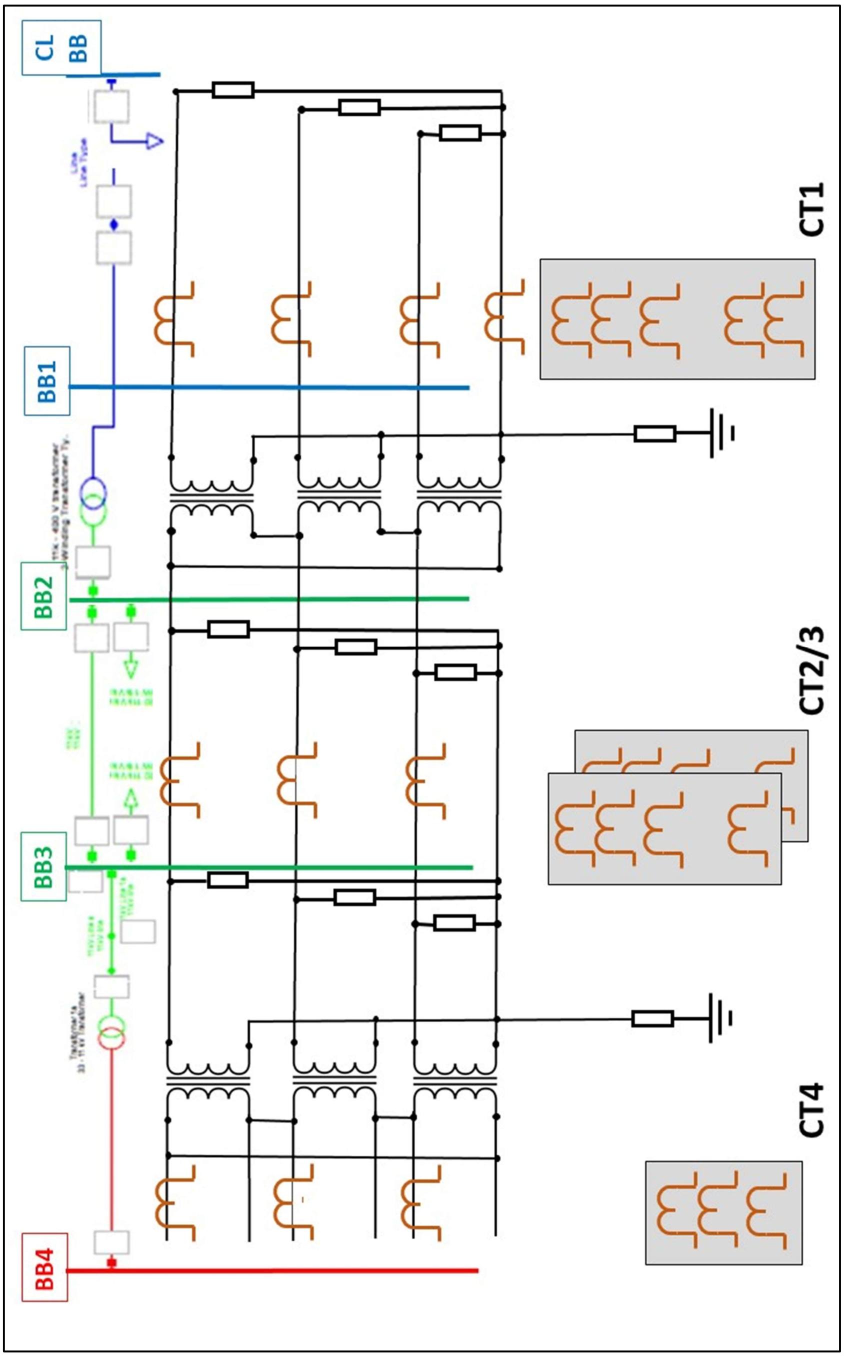


Figure 27: Distribution Network Model – Power Transformer and Instrumentation (Protection CT) Transformer Locations.

Notes:

1. CT4 (supplying RL4) has phase inputs only, due to the 3-wire HV delta connection.
2. CT3 and CT2 (supplying RL3 and RL2) have similar arrangements. Each has phase inputs and a neutral inputs, but the neutral inputs are derived from a summation of the phase inputs.
3. CT1 (supplying RL1) has an additional separate sensitive input compared with RL2 and RL3.

Connections to these relay inputs can be made according to the following Figure 28.

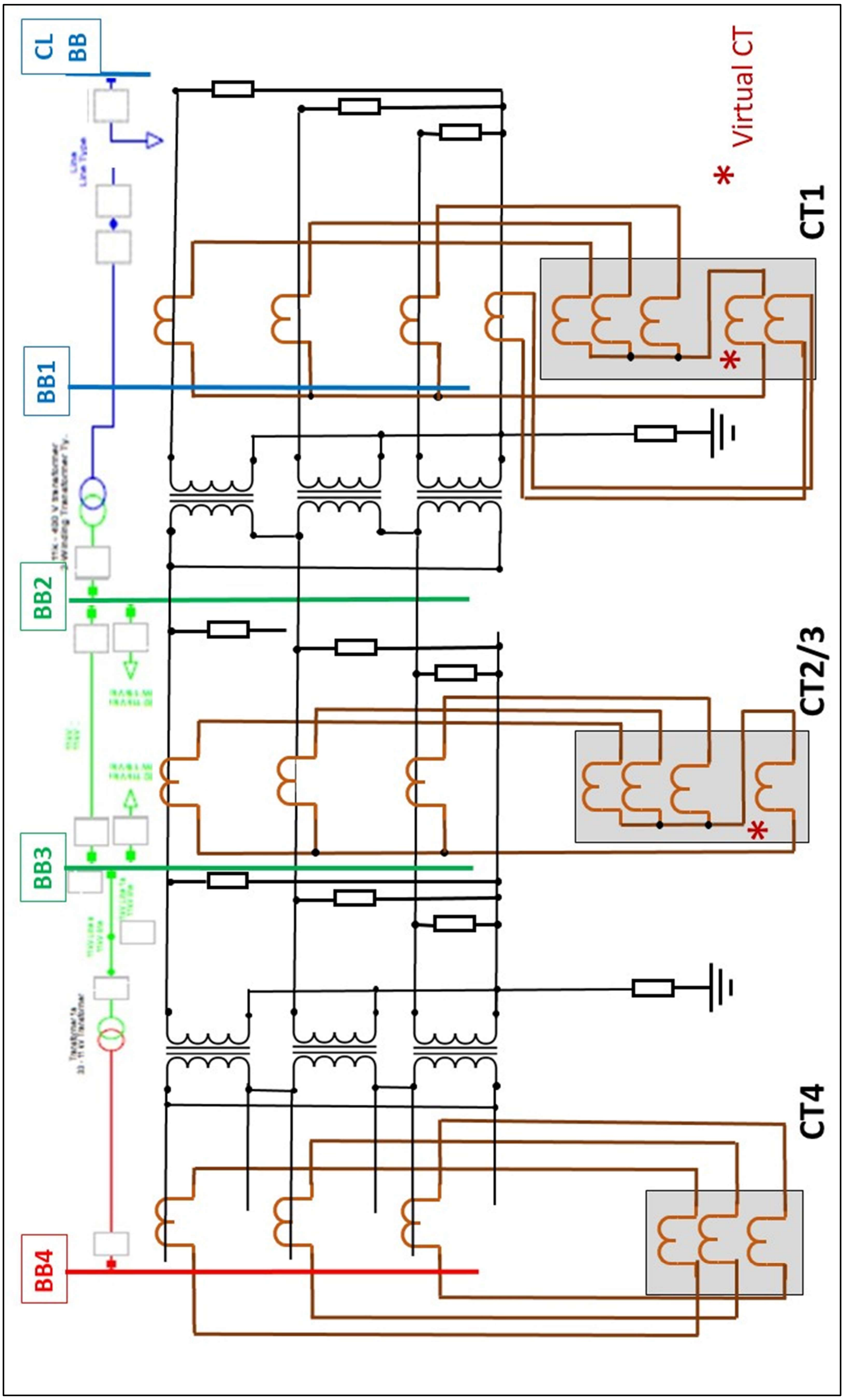


Figure 28: Distribution Network Model - Instrument Transformer (CT) and Protection Current Input Connections.

Notes:

1. The winding and connection arrangements of CT3 and CT2 are the same. Only one is shown for clarity.
2. The figure recognises that in P545, the neutral elements are based on derived currents. The associated CTs are, therefore, shown for completeness, but are indicated as being 'virtual'.

With the relay connections defined and the CT ratios accounted for, the prospective load and fault currents can be determined, from which the current settings can be finalised and the PSM values applied.

7.1.2.1.2 Determination of Benchmark Scheme Timer Settings

After the current settings have been calculated, attention can then turn to calculating the associated Time Multiplier Settings – TMS. Various characteristics relating PSM and TMS to operating time are recognised. These include inverse definite minimum time (IDMT) characteristics defined by IEC/BS [118] examples of which are Standard Inverse (SI), Very Inverse (VI) and Extremely Inverse (EI). For this benchmark exercise a Standard Inverse (SI) inverse definite minimum time (IDMT) characteristic is used. The SI characteristic may be represented graphically, or mathematically. The mathematical representation is given by equation (2):-

$$t_{characteris} = TMS \times \frac{0.14}{(\frac{I}{PSM \times I_N})^{0.02} - 1} \text{..} \quad (2)$$

Where:

$t_{characteristic}$ is the IDMT relay operating time,

TMS = Time Multiplier Setting,

I is the current applied,

PSM is the Plug Setting Multiplier,

I_N is the nominal current.

I and I_N may be arbitrarily chosen either as primary values, or as secondary values, or as values chosen referenced to common base. But, they must both be chosen relative to the same reference.

Starting with the most downstream zone, the steps involved to time grade the relays are as follows:-

1. Establish the time that an external device should clear a downstream fault clearing time (e.g. instantaneous/consumer fuse operation time).
2. Add a grading margin (400 ms in this case) to this value to allow upstream devices to provide delayed back-up for the case of downstream protection not clearing a fault.
3. Use this time value in equation (1) with the previously determined current setting (*PSM*) for the zone relay to calculate the required *TMS* for the zone relay.
4. With the selected *TMS* setting applied, the actual operate time for the relay to operate for a short-circuit fault at the downstream terminal of the protected zone can be checked.
5. Also, with the selected *TMS* setting applied, the operating time of the relay can be calculated for a maximum in-zone short circuit (i.e. a fault at the busbar local to the relay).
6. The process (Steps 2 – 5 can be repeated for the next most upstream relay using the value calculated in step 4 as the starting time (step 1) for the next iteration, and then repeating as necessary for all other upstream devices.

7.1.3 Using the Simulator to Benchmark Overcurrent Protection Scheme Behaviour.

Creation of an accurate simulation model for analysis of protection settings requires knowledge and understanding of the simulation tool/environment, the protection philosophy, and the chosen protection products.

In this exercise, the DIgSILENT PowerFactory software is being used to provide the simulation environment. Overcurrent protection provided in the form of MiCOM P545 products is being applied.

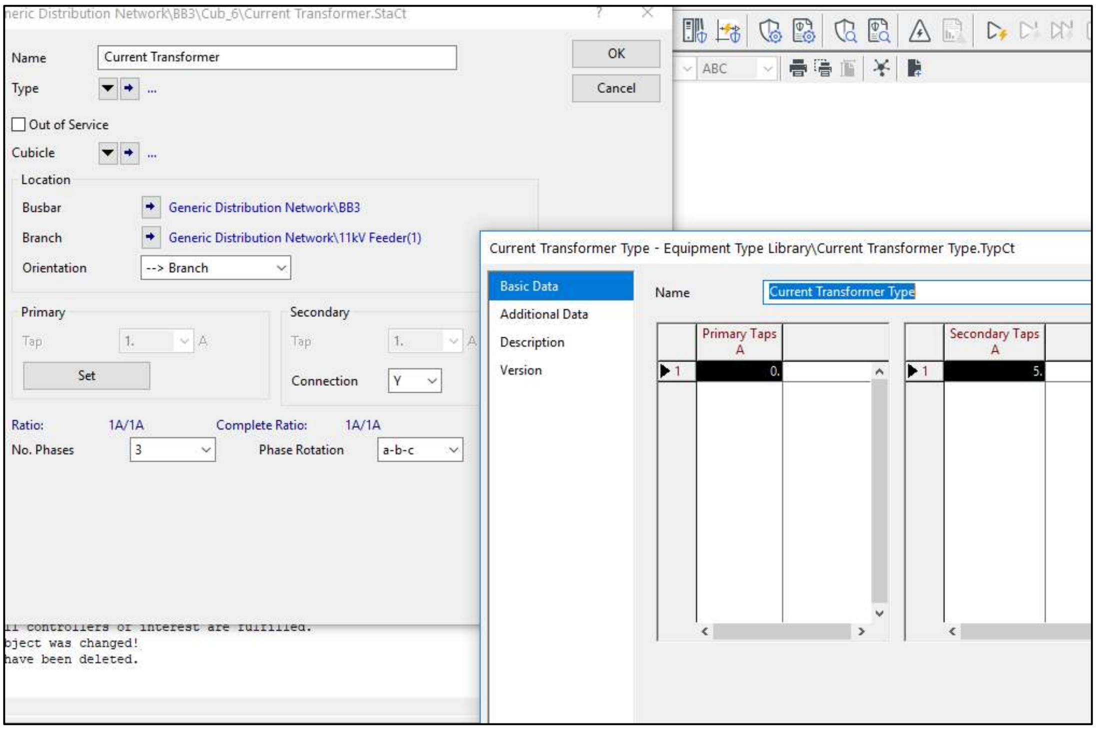
This section describes the use of the software to apply and set the protection, as well as to generate informative reports, etc., concerning network and protection performance.

Note that the tool used in this exercise is the DIgSILENT PowerFactory SP1 2018 version.

Before applying and setting a relay in the DIgSILENT environment, the network model first needs to be created (starting with the busbar allocations, then the transformers, lines, etc.). Thereafter, the instrument transformers (CTs) must be chosen and allocated. The chosen relay data model(s) are then 'imported' into the simulation workspace. The CT inputs of the relays must be matched to the ratios of the CT models by appropriately configuring the relay models. Finally, the relay settings can be programmed.

Section 6.1.1.2 describes how an experimental network model which is created and configured within DIgSILENT is verified. To simulate a protection scheme for this network model, simulation models of the CTs and relays must be added.

The following screen shot (Figure 29) is illustrative of the procedure to allocate simulation CTs in the model.



eric Distribution Network\BB3\Cub_6\Current Transformer.StaCt

Name: Current Transformer
☐ Out of Service
Location
Busbar: Generic Distribution Network\BB3
Branch: Generic Distribution Network\11kV Feeder(1)
Orientation: --> Branch
Primary Tap: 1. A
Secondary Tap: 1. A
Connection: Y
Ratio: 1A/1A
Complete Ratio: 1A/1A
No. Phases: 3
Phase Rotation: a-b-c

```
ll controllers of interest are fulfilled.
bject was changed!
have been deleted.
```

Current Transformer Type - Equipment Type Library\Current Transformer Type.TypCt

Name: Current Transformer Type

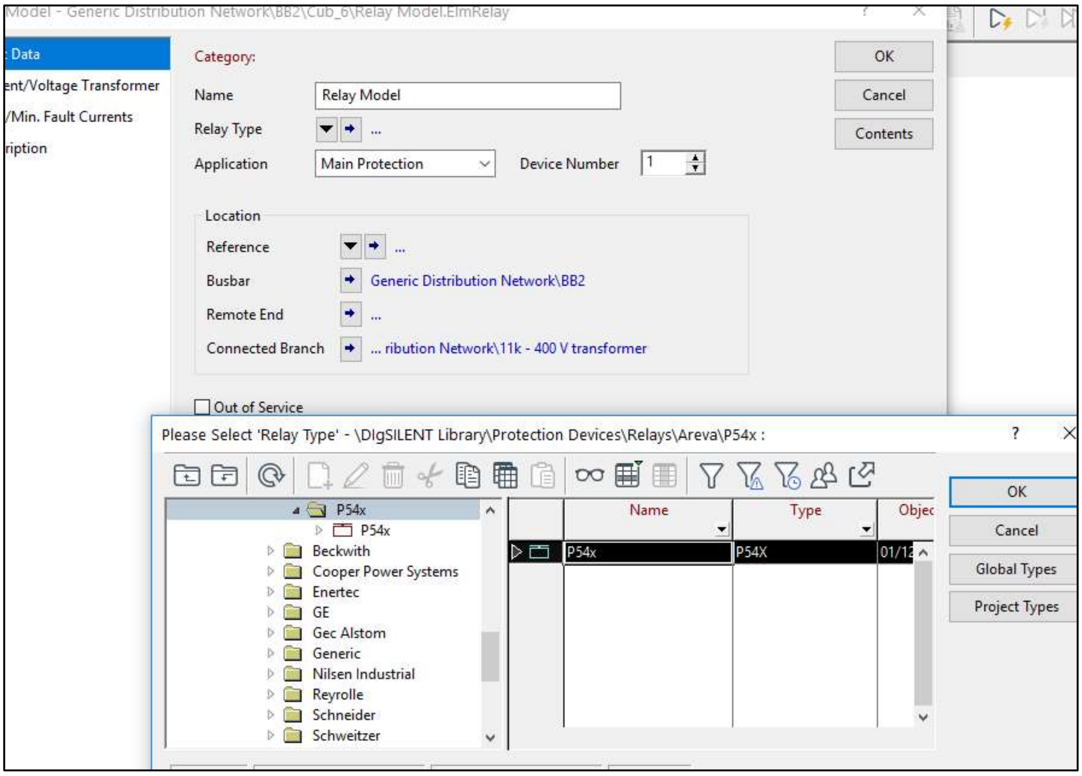
	Primary Taps A
1	0.

	Secondary Taps A
1	5.

Figure 29: Allocating CTs in a DIgSILENT Model.

Within the simulation tool environment, the procedure to add a CT model starts with selection of the (CB) location intended for the CT. Then the 'add a new device' feature is selected and the – *Current Transformer* option is chosen. Next, the choice is either to select *Global Type* or *Project Type* to re-use a model, or select *New Project* to create a new one, as per the screenshot. In this case once a 'New Project' type has been created it can be used throughout the simulation. CTs need to be added for all current inputs, as applicable. For example in this case, CT models must be added for the phase current inputs of the P545, and for the SEF input of the P545. Since the P545 does not have a dedicated neutral current element input (*IN*> uses a derived input) no neutral current CT needs defining.

The following screen shot (Figure 30) is illustrative of the procedure to add a simulated protection device into the model.



Model - Generic Distribution Network\BB2\Cub_6\Relay Model.ElmRelay

Category:

Name: Relay Model

Relay Type: ...

Application: Main Protection

Device Number: 1

Location

Reference: ...

Busbar: Generic Distribution Network\BB2

Remote End: ...

Connected Branch: ... ribution Network\11k - 400 V transformer

☐ Out of Service

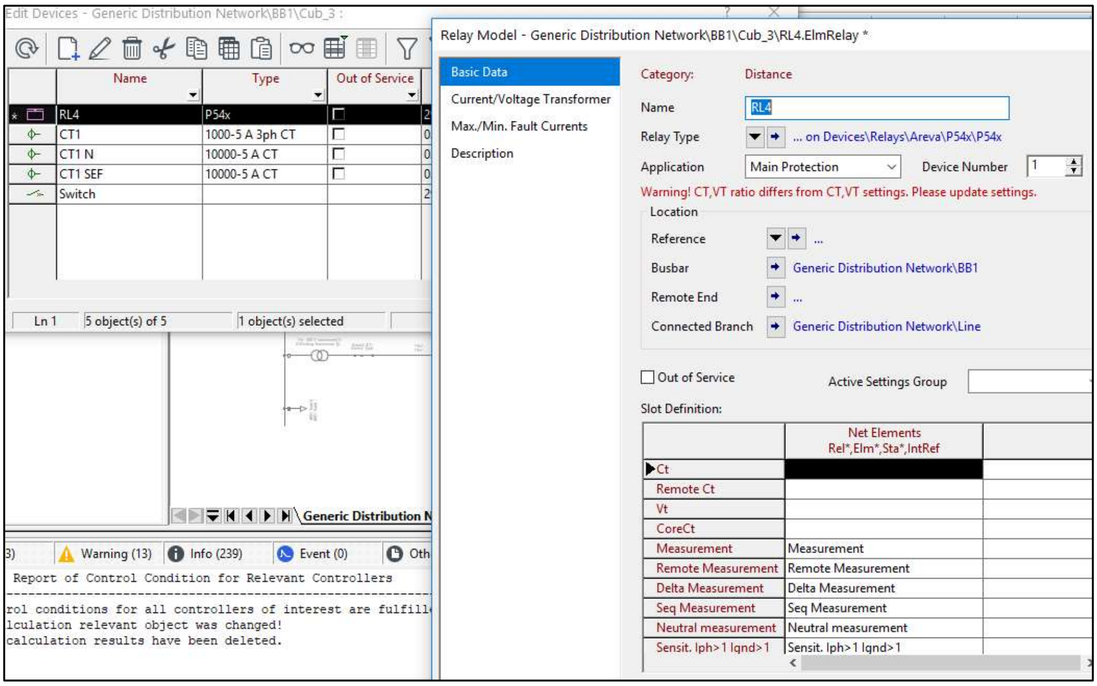
Please Select 'Relay Type' - \DIgSILENT Library\Protection Devices\Relays\Areva\P54x :

Name	Type	Objec
P54x	P54X	01/1

Figure 30: Allocating a Protection Relay in a DIgSILENT Model.

Similar to adding a CT, the procedure is to select the (CB) location of the intended Relay. Then 'add a new device' – Relay Model followed by 'Select' *Global Type*, or *Project Type* to re-use a model or 'Select' *New Project* to create one, as per the screenshot. In this case Select Global Type allows a predefined model of a MiCOM P545 (P54x) to be selected.

The relay inputs need to be configured to the CTs according to the relay configuration fields as demonstrated in Figure 31 and Figure 32.



Edit Devices - Generic Distribution Network\BB1\Cub_3 :

Name	Type	Out of Service
RL4	P54x	☐
CT1	1000-5 A 3ph CT	☐
CT1 N	10000-5 A CT	☐
CT1 SEF	10000-5 A CT	☐
Switch		

Ln 1 | 5 object(s) of 5 | 1 object(s) selected

```
Report of Control Condition for Relevant Controllers
-------------------------------------------------------
rol conditions for all controllers of interest are fulfill
lculation relevant object was changed!
calculation results have been deleted.
```

Relay Model - Generic Distribution Network\BB1\Cub_3\RL4.ElmRelay *

Category: Distance

Name: RL4

Relay Type: ... on Devices\Relays\Areva\P54x\P54x

Application: Main Protection   Device Number: 1

Warning! CT,VT ratio differs from CT,VT settings. Please update settings.

Location

Reference: ...

Busbar: Generic Distribution Network\BB1

Remote End: ...

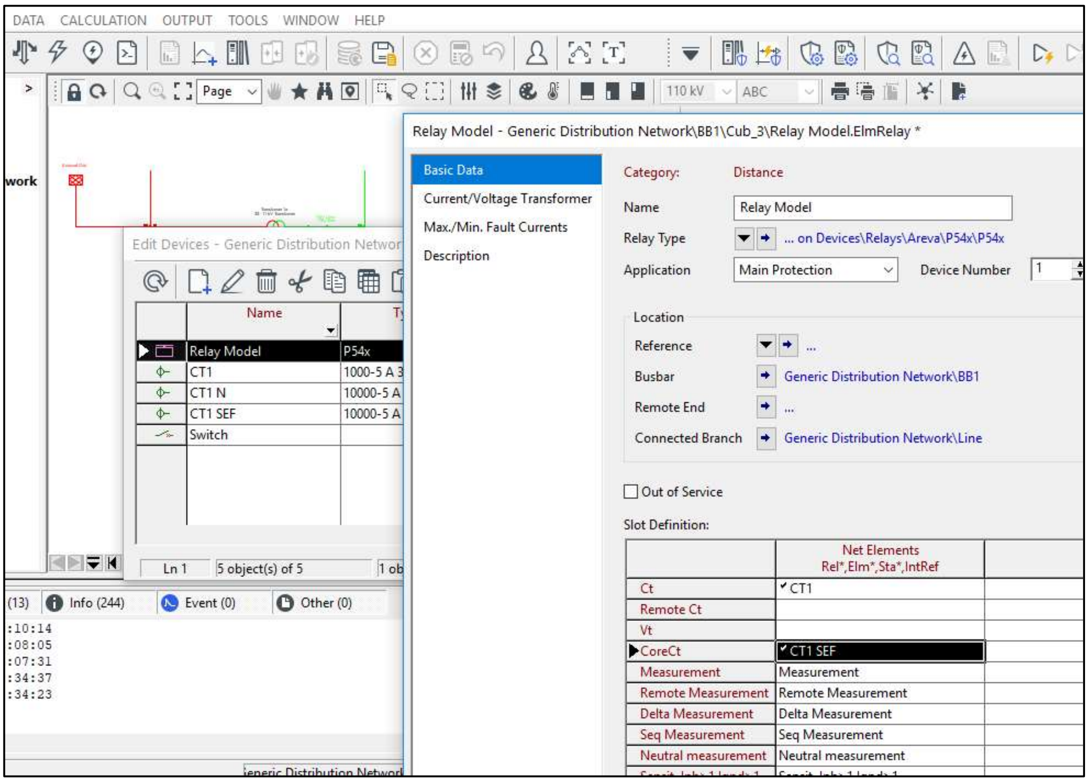
Connected Branch: Generic Distribution Network\Line

☐ Out of Service   Active Settings Group

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef
Ct	
Remote Ct	
Vt	
CoreCt	
Measurement	Measurement
Remote Measurement	Remote Measurement
Delta Measurement	Delta Measurement
Seq Measurement	Seq Measurement
Neutral measurement	Neutral measurement
Sensit. Iph>1 Ignd>1	Sensit. Iph>1 Ignd>1

Figure 31: Assigning CTs to Relay Inputs in a DIgSILENT Model.



Edit Devices - Generic Distribution Networ

Name	T
Relay Model	P54x
CT1	1000-5 A 3
CT1 N	10000-5 A
CT1 SEF	10000-5 A
Switch	

Ln 1 | 5 object(s) of 5 | 1 ob

```
:10:14
:08:05
:07:31
:34:37
:34:23
```

Relay Model - Generic Distribution Network\BB1\Cub_3\Relay Model.ElmRelay *

Category: Distance

Name: Relay Model

Relay Type: ... on Devices\Relays\Areva\P54x\P54x

Application: Main Protection   Device Number: 1

Location

Reference: ...

Busbar: Generic Distribution Network\BB1

Remote End: ...

Connected Branch: Generic Distribution Network\Line

☐ Out of Service

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef
Ct	✓CT1
Remote Ct	
Vt	
CoreCt	✓CT1 SEF
Measurement	Measurement
Remote Measurement	Remote Measurement
Delta Measurement	Delta Measurement
Seq Measurement	Seq Measurement
Neutral measurement	Neutral measurement

Figure 32: Assigning Individual CT Inputs According to Function.

The ‘Measurements’ field(s) then need to be set to reflect the 5A secondary windings of the CTs. In the case of a P545, measurement fields for ‘*Remote* –‘, *Delta*-‘, *Seq.*-‘, and ‘*Neutral*-‘, should all be changed to match the CT secondary nominal (5A in this case).

The relays can now be set. Setting the simulated relays is performed in a similar manner to setting those of a physical deice using an intuitive user interface. Precise details are not presented here, but it is necessary to ensure that those elements that are to be used should be enabled (*in service*) and correctly set. Any devices not being used should be disabled (*out of service*). Complex scheme logic is not required, but protection element outputs need mapping to tripping functions in order to integrate with the simulation software reporting and recording facilities.

As previously outlined, the simulator can be used to determine and report load currents and prospective short circuit currents. These and other reports available from the simulator can be used to examine and verify protection performance within the model as network parameters, relay settings, etc. are varied. Two useful features in this respect are the time-overcurrent plot and the fault sequencer.

The time overcurrent plot can be used to demonstrate the performance of the overcurrent relays on the network when fault conditions are simulated. Typically, faults might comprise simulated short circuits applied at the various busbars. The DIgSILENT software can be used to simulate faults across the network. By simulating short-circuit faults at various points on the network, therefore, it is possible to determine and report the corresponding fault current levels.

It is noted that DIgSILENT offers a choice of fault models that can be selected for performing short-circuit calculations. These can be categorised as ‘simplified’ or ‘complete’. A detailed description of the modus operandi of the ‘complete’ method, based on theory of superposition is available for information and reference in the DIgSILENT User Manual [119]. According to the manual, simplified models (such as that described by IEC 60909) are typically used for ‘planning’ considerations, whereas ‘complete’ methods are used for ‘operational’ studies as per Figure 33 below.

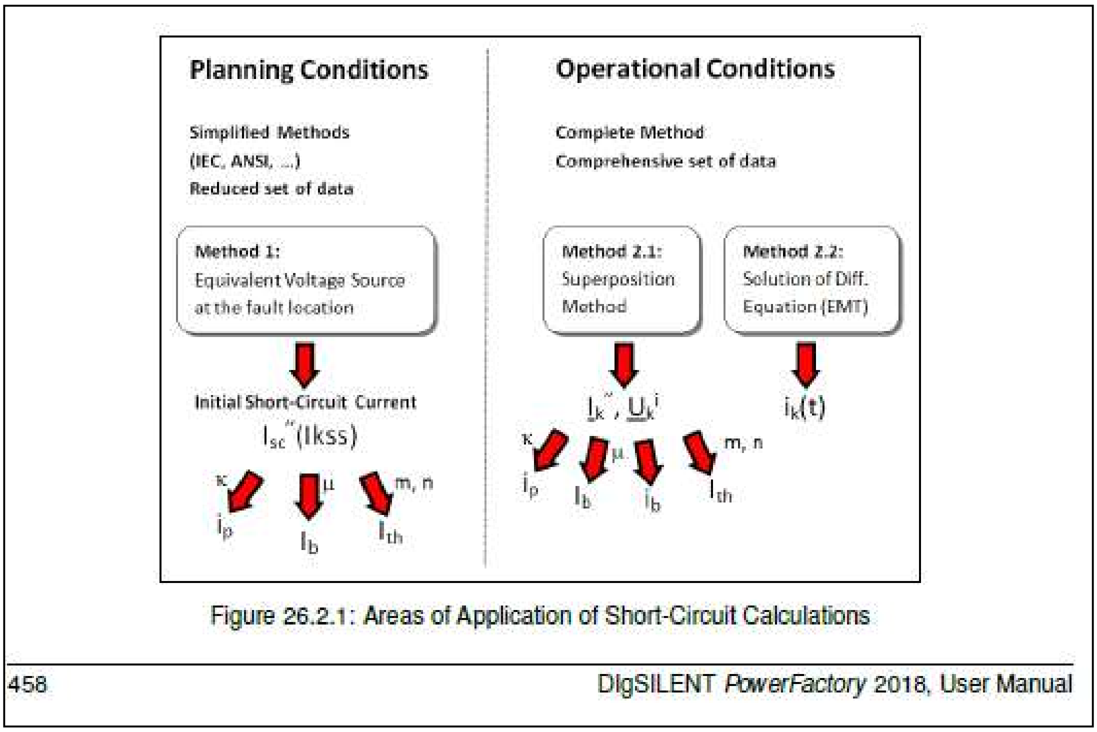


Figure 26.2.1: Areas of Application of Short-Circuit Calculations

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Figure 33: DIgSILENT Power Factory Short Circuit Calculation Model Summary.

Since the complete method is preferred for evaluating operational conditions, it is the model adopted for fault current calculations in this work.

So, unless otherwise stated, results and reports generated in response to faults will be in response to 'complete' method(s) of Figure 33.

7.1.3.1 DIgSILENT Time-Overcurrent Plots to Visualise Performance

The DIgSILENT software provides visual graphics to assist with protection studies, disturbance analyses, etc. Of particular interest in this time-graded overcurrent protection exercise is the facility to produce time-overcurrent plots. Time-overcurrent plots are outputs from the DIgSILENT simulator useful for visualising the operation of simulated overcurrent relays.

Considering a network models such as that presented in Figure 24, such time-overcurrent plots could be used to demonstrate overcurrent protection response for various fault scenarios (for example, F1 – F4).

The time overcurrent plot for a particular relay can be created (or added to an existing plot) by selecting the protected branch of the network and then choosing '*show*' (or '*add to existing*') *time-overcurrent plot* feature. With all the overcurrent protection characteristics combined onto a single plot, the credibility of a protection scheme can be assessed. This may be particularly useful to compare operation of similarly connected elements of a protection scheme.

7.1.3.2 Comparing *IN>1* and *ISEF>1* Elements to Verify Network Model Connection

To develop deeper understanding of the network simulation model and the operation of the internal protection elements, validation of the configured network model is to be partly scrutinised by connecting the *ISEF>* input to measure the actual current flowing in the neutral circuit and comparing this measured value with the derived value used by the *IN>* elements of the P545. Time-overcurrent plots can help compare performance of the (measured) sensitive current input (*ISEF>*) with that of the (derived) neutral current input (*IN>*) on RL1. Analysis of responses will help understanding of the subtle differences between the how the derived and measured quantities are managed within the network simulator and the relay models. An additional benefit arising from this exercise to compare two similar elements sourced from different measurement CTs is to gain exposure in allocating different instrument transformer sets to different relay inputs within the DIgSILENT environment. This facility will be required in simulation work to assess Directional Agents when CT and VT input signals are required to be acquired from different locations on the network.

Since the *IN>* function in the MiCOM P545 relay is derived from the phase current measurements, its input is shaped by the connection and configuration of the phase current inputs. There is no direct connection between the neutral circuit of the simulation model and the *IN>* elements of the MiCOM P545 relay. The relay does, however, have an additional current input that is typically used for sensitive earth-fault (SEF) protection. Thus, if the neutral current of the simulation model is used to drive the *ISEF>* input of the relay, the values of derived and measured neutral currents sensed by the relay can be extracted and compared.

Comparing *ISEF>* performance with *IN>* performance will provide opportunity to confirm that the elements can be correctly assigned to different inputs as well as facilitate an understanding of the limitations of the two approaches to provide neutral current protection.

For fault conditions that should generate a neutral current component, it might be reasonable to expect that if the *ISEF>1* and the *IN>1* elements are set with similar operating characteristics suitable for responding to the anticipated fault current, then both elements might operate.

An additional check on the validity of the network simulation model is performed using a comparison of the performance of the (measured) sensitive current input (*ISEF*>) with that of the (derived) neutral current input (*IN*>) on RL1.

By connecting both elements to use 'neutral current' as the operating quantity and by setting both elements similarly, the performances of the applied simulation relays can be compared with theoretically predicted expectations to indicate alignment between expected performance and model.

It might be expected that if two similar overcurrent elements were both set to operate on neutral current that they would both behave the same. This is not necessarily true. Performance depends upon how the neutral current is determined. Neutral current may either be measured, or it may be derived. When using a simulator to provide neutral current, or when using a measurement device, including protective relays, it is important to know exactly which quantity is being referred to, how it is being used, and what the implications are. To provide neutral/earth fault protection with the MiCOM P545, the user has a choice of using either a neutral current element (*IN*>), or a sensitive current input intended primarily to measure earth faults (*ISEF*>). Since these elements use different inputs to achieve similar functions, it might be assumed that they can be used interchangeably. This is not, however, the case since one element (*ISEF*>) uses measured quantities, whereas the other (*IN*>) uses derived quantities, their performances are not identical. To understand the implications of choosing to use the different elements, and to verify correct connectivity and configuration of the network model, both elements can be applied to respond to neutral current, and the differences in performances analysed. The *ISEF>1* element responds to the current that flows through the SEF input. In this case, that will be the current simulated by the DIgSILENT software and connected to the input circuit allocation designated 'CoreCt' in the DIgSILENT P545 model. Defining and connecting a CT connection from the SEF input to a neutral circuit at a relaying point in the network model should result in the SEF input measuring what the network model is simulating as neutral current at that point. The *IN>1* element derives its operating quantity from a summation of phase currents within the relay. The phase currents simulated at the relaying point by the DIgSILENT software are connected to the phase input circuit allocation designated 'Ct' in the DIgSILENT P545 model. The operating quantity for the *IN>1* element is derived internally by the MiCOM P545 relay from these simulated phase input currents at the relaying point. Hence the

IN> element of the relay effectively measures the imbalance in the phase currents generated by the DIgSILENT model. Since this IN current is derived inside the relay, it cannot be directly measured. Its performance must therefore be verified using a reference measurement. This exercise uses comparison of similarly configured *IN*> and *ISEF*> elements to confirm expected performance and further verify the model.

It should be recognised, however, that since one element uses measured quantities, and the other uses derived quantities, their expected performances are not necessarily identical. Predicting, explaining, and illustrating these differences demonstrates understanding, and provides confidence in the integrity of the model. Consider the two following scenarios:-

1. Connected to measure the neutral current generated by the fault simulator, the *ISEF>1* element will respond to the current that flows through the SEF input (designated '*CoreCt*' input in the DIgSILENT P545 model). In this case, that will be the neutral current simulated by the DIgSILENT simulator.
2. For the *IN>1* element, the current is internally derived by the relay from a summation of the phase currents generated by the simulator. The phase currents are simulated by the DIgSILENT software and connected to the input circuit allocation designated '*Ct*' in the DIgSILENT P545 model. Since the operating quantity for the *IN>1* element is derived internally by the MiCOM P545 relay, the *IN>1* effectively measures the imbalance between the phase currents generated by the DIgSILENT model.

The precise operation of the two elements will differ as earth paths become involved in the fault loops. Output reports from the DIgSILENT simulator will be used to compare the performance of *IN*> and the *ISEF*> elements. To enable this, they must be appropriately set. In this case, the first stage of overcurrent of each element will be used (*IN>1*, *ISEF>1*). For convenience, DT characteristics will be chosen for both, and the time settings will be arbitrarily set as instantaneous for *IN>1*, and 100 ms for *ISEF>1*. As will be observed later, setting a 100 ms delay on the SEF element will make it easy to differentiate the operation of the two elements in fault sequence reports.

According to the type of fault applied, and the circuit configuration, there will be a difference between the measured value of the current simulated in the neutral circuit (using *ISEF>1*), and the derived value (calculated by the relay as IN). The following fault scenarios predict the dominant components.

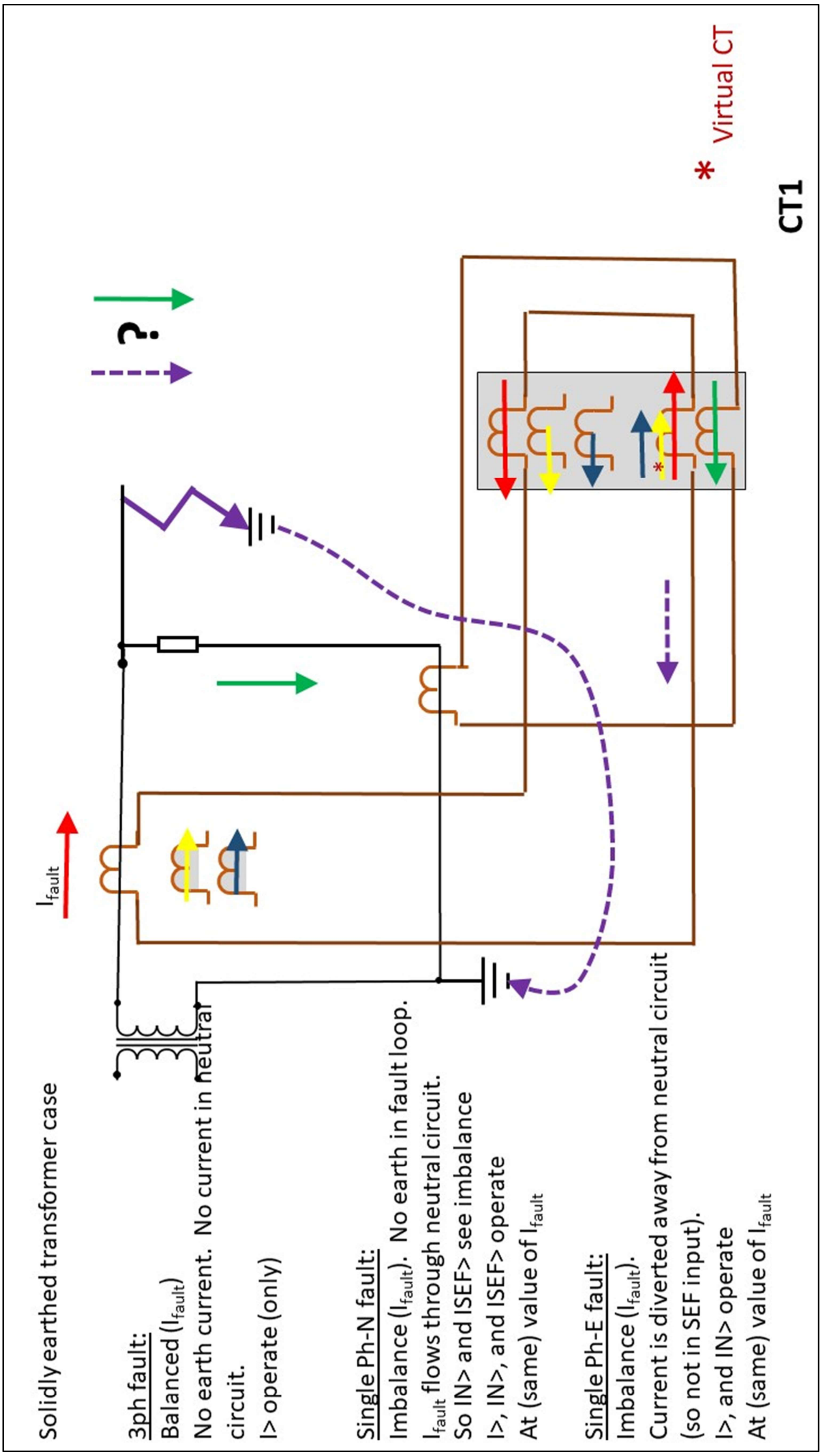
7.1.3.2.1 Comparing Measured vs Derived Neutral Current distributions for Single-Phase-Neutral Faults

In this case, the neutral current should be approximately the same as in the faulted phase element. No earth loop is involved in the fault current path and so all imbalance current should flow in the neutral current circuit. The true neutral current should be measured by the *ISEF>1* element. The *IN>1* element should measure the phase imbalance. These should both be approximately the same and should approximate to the phase current. The expected relay operation should therefore be that *I>1*, *IN>1*, and *ISEF>1* all trip.

7.1.3.2.2 Comparing Measured vs Derived Neutral Current distributions for Single-Phase-Earth Faults

In this case, the performance of the *IN*> and *ISEF*> elements may differ according to the earthing paths in the fault current circuit. The earthing paths will be affected by the earthing of the system transformer. Typically, the transformer secondary supplying the load circuits is of star/wye/Y winding. The neutral connection may be isolated, it may be solidly earthed, or it may be impedance earthed. Impedance earthing may be in the form of a simple resistor, or it may be in the form of a transformer such as a Petersen Coil [120]. Typically in the UK, the neutral point of the transformer winding is resistance earthed. A value of 1Ω is commonly chosen to restrict the maximum earth-fault current to around 60% of the expected phase current value.

The following four figures (Figure 34 - Figure 37) illustrate single-phase-earth fault scenarios for different transformer earthing arrangements.



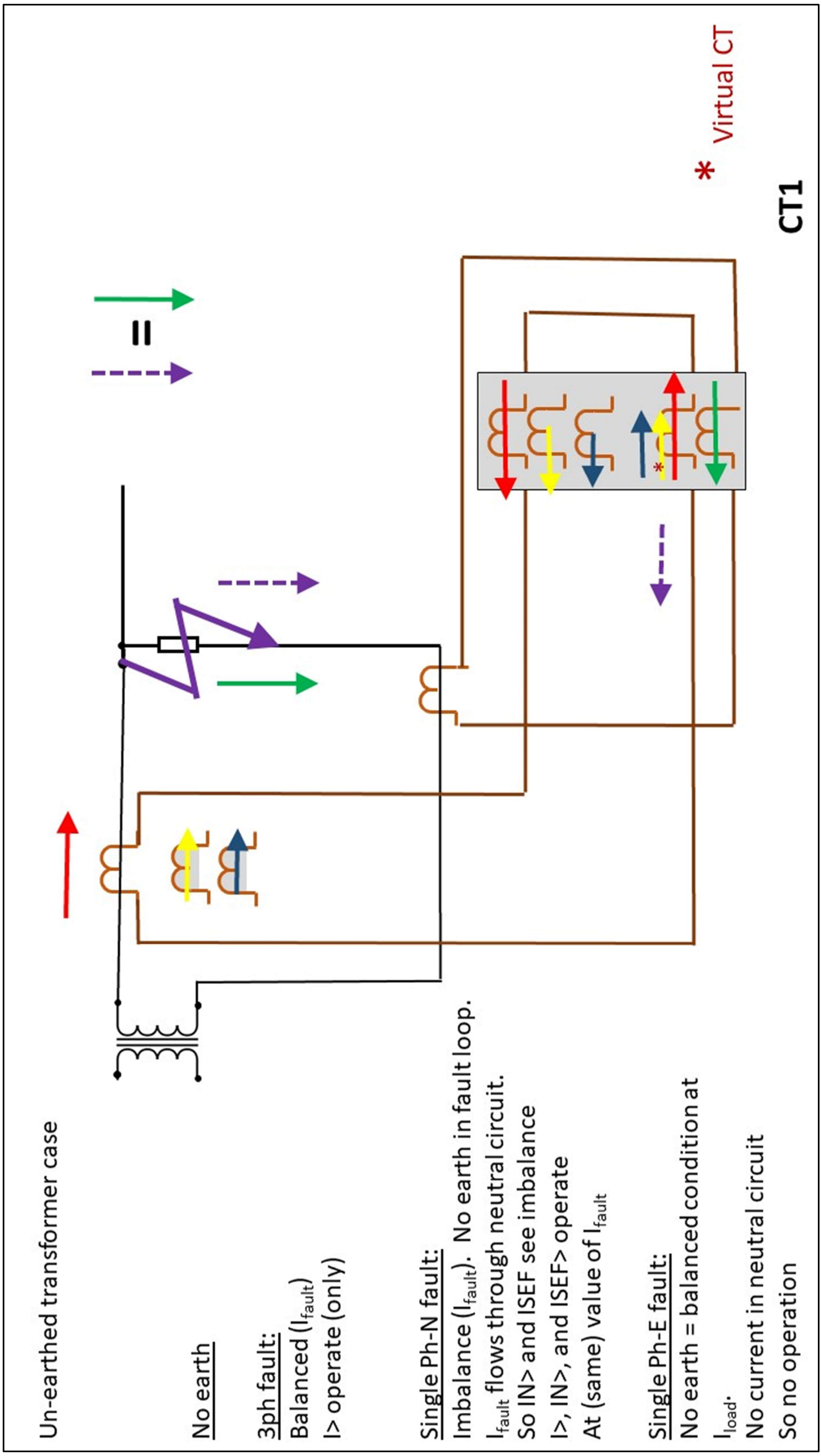
Solidly earthed transformer case

3ph fault:
Balanced (I_{fault})
No earth current. No current in neutral circuit.
I> operate (only)

Single Ph-N fault:
Imbalance (I_{fault}). No earth in fault loop.
I_{fault} flows through neutral circuit.
So IN> and ISEF> see imbalance
I>, IN>, and ISEF> operate
At (same) value of I_{fault}

Single Ph-E fault:
Imbalance (I_{fault}).
Current is diverted away from neutral circuit (so not in SEF input).
I>, and IN> operate
At (same) value of I_{fault}

Figure 34: Fault Current Scenarios for Solidly Earthed Transformer.



Un-earthed transformer case

No earth

3ph fault:
Balanced (I_{fault})
I> operate (only)

Single Ph-N fault:
Imbalance (I_{fault}). No earth in fault loop.
I_{fault} flows through neutral circuit.
So IN> and ISEF see imbalance
I>, IN>, and ISEF> operate
At (same) value of I_{fault}

Single Ph-E fault:
No earth = balanced condition at
I_{load}.
No current in neutral circuit
So no operation

Figure 35: Fault Current Scenarios for Un-Earthed (Isolated) Transformer.

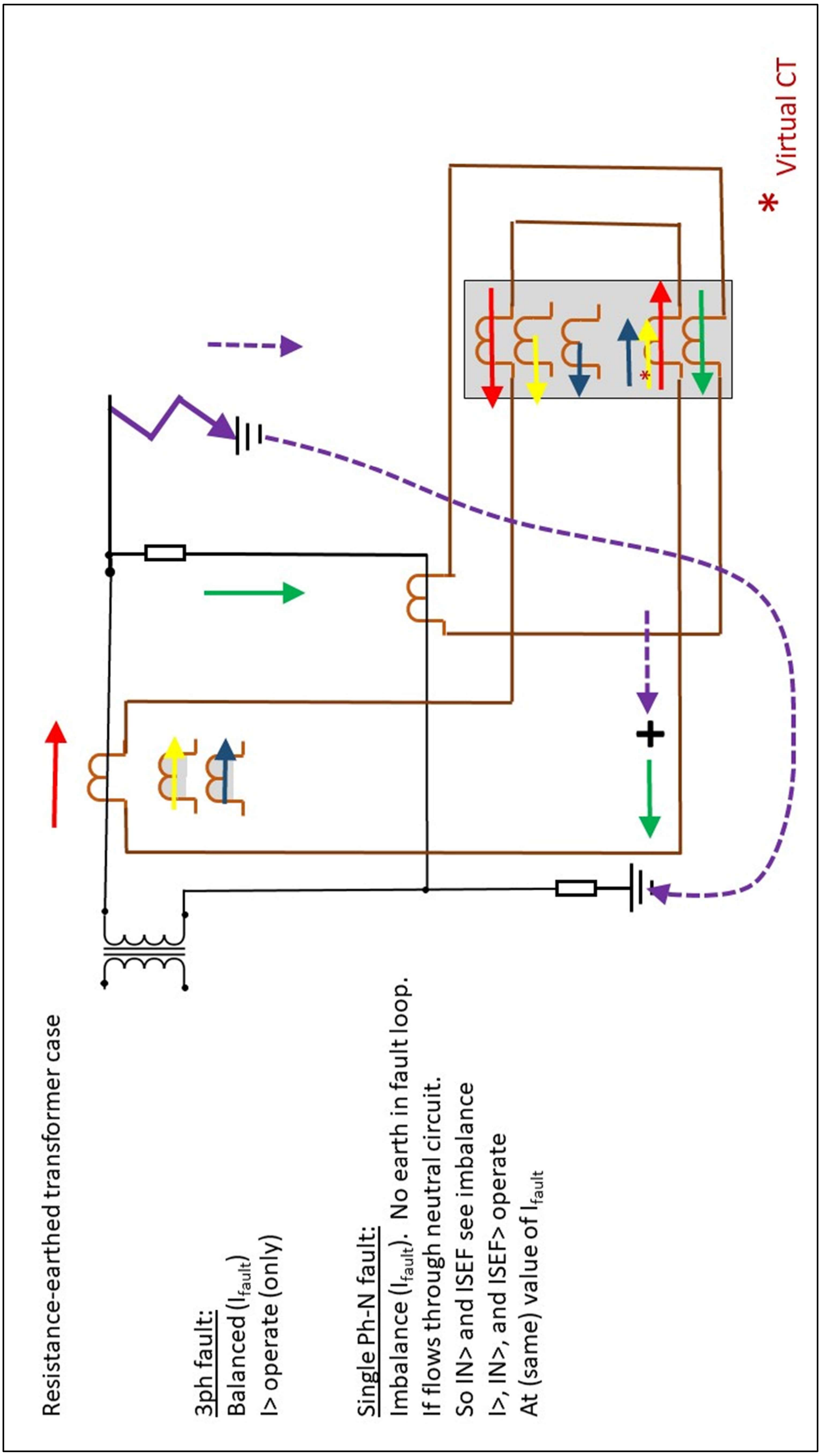
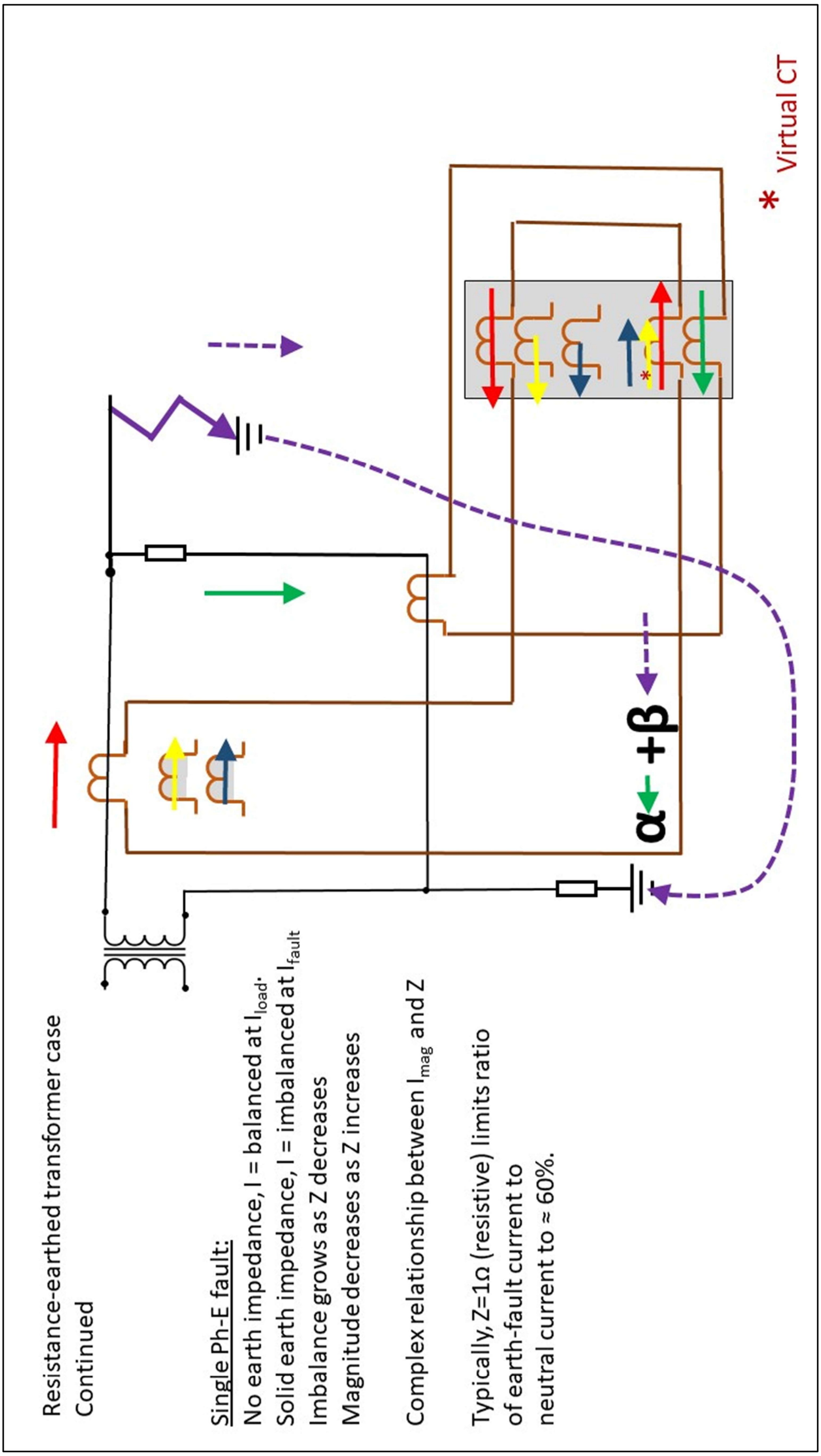


Figure 36: Non-Earth Fault Current Scenarios for Resistance-Earthed Transformer.



Resistance-earthed transformer case
Continued

Single Ph-E fault:
No earth impedance, I = balanced at I_{load}.
Solid earth impedance, I = imbalanced at I_{fault}
Imbalance grows as Z decreases
Magnitude decreases as Z increases

Complex relationship between I_{mag} and Z

Typically, Z=1Ω (resistive) limits ratio
of earth-fault current to
neutral current to ≈ 60%.

Figure 37: Single-phase-earth Fault Current Scenario for Resistance-Earthed Transformer.

7.1.3.2.3 Confirming *IN>1* and *ISEF>1* Elements Operation to Verify Network Model Connection

In this case, comparing simulator outputs with predicted tripping patterns for the *IN>1* and the *ISEF>1* elements for the different topologies and fault types described should confirm correct connections and configurations of the model, and hence verify that this aspect of the model is correct.

7.1.3.3 Using Fault Sequence Plot to Illustrate Protection Performance

It is possible within DIgSILENT to generate sequences of faults. The generated fault sequence waveforms, together with the corresponding relay tripping responses can be recorded for analysis. Subjecting the network to a fault sequence and examining the provoked protection response can provide a useful final verification of the network and applied protection.

7.1.4 Directional Agent Development

A fundamental part of this project is the deployment of Directional Agents to implement directional comparison protection schemes. Having verified the generic network simulation model (Figure 22), attention turns to using the model to evaluate the proposed protection approach. For this, suitable Directional Agent models will be required. Model selection should afford confidence that the directional protection functionality is tried and tested. Commercially available products will have undergone exhaustive testing to validate, homologate, and certify their performance. Testing based on these models is therefore most preferable. Due to limitations of resource availability, not all, if indeed, any, testing may be possible using such proven, commercially available, hardware models. In cases where model availability is compromised, the order of preference for selection of test models (behind certified devices) will be (i) already proven simulation models ahead of (ii) purpose-designed simulation models.

Evolving project constraints required that evaluation of directional elements be restricted to the use of a simulation environment. This precludes the use physical hardware models of relays. Further, during the course of the project, the DIgSILENT model of the MiCOM P545 was determined not to be faithfully representative of the directional protection provided by the MiCOM P545 relay and was therefore deemed to be unsuitable. It was also established that DIgSILENT did not support any teleprotection relay simulation models necessary to allow combinations of directional relay models to form directional comparison unit scheme models. Accordingly, the need for purpose-designed simulation models was exposed. Specifically, it became necessary to create and develop simulation models for Directional Agents, as well as for a teleprotection (communications interlink) relay in order to implement the required directional comparison unit protection scheme models.

The details of the simulation models created for this project are provided as Appendix I.

7.1.4.1 Applying Directional Overcurrent Protection to Protect Passive Radial Distribution Networks

The objective of this particular exercise is to introduce directional protection into the simulation model and to confirm correct connection of VT and CT inputs by verifying directional operation.

The overcurrent protection used to benchmark the configured distribution network model is swapped for directional overcurrent protection.

The performance of the directional overcurrent protection is to be evaluated using the DIgSILENT model.

Conventional voltage polarisation techniques are to be employed at this stage.

7.1.4.2 Directional Overcurrent Protection Applied to Distribution Networks featuring Embedded Generation

In this part of the study, embedded generation is introduced into the DIgSILENT network model. This affords the possibility to vary generation capacities across the network. Varying generation and load patterns across the network affects the power flows in the network affording opportunity to evaluate directional performance under conditions such as power flow reversal.

The performance of directional overcurrent protection is evaluated for different faulted and un-faulted network scenarios and with varying degrees of generating and load capacities. This can demonstrate the effectiveness of the network model to provide suitable stimulus for evaluating variations on the basic principle of directional protection, including wide-area directional comparison schemes.

At the centre of the DIgSILENT network model presented in Figure 21an 11 kV ring is formed from connectors BB3, Line 2a, BB2, and Line 2b. With loads and generators both upstream and downstream of the ring, the direction of power flow can be controlled by varying the loads and sources of generation. By varying the configuration of the network, and by varying fault positions within, and outside, this ring, power flow directionality can be altered. Doing this allows directional protection to be stimulated and analysed.

For concept evaluation, protection devices are applied to the ring and the rest of the network. For clarity and consistency, the protection devices are designated and referenced as shown in the following Figure 38.

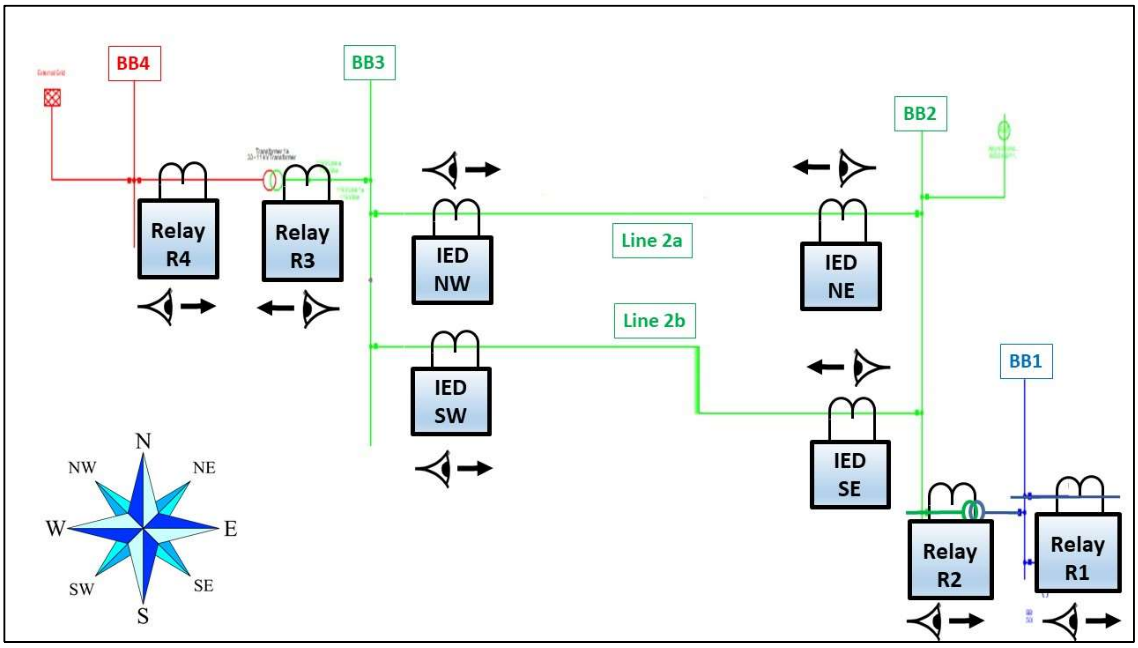


Figure 38: Application of Protection IEDs to Protect Generic Network Model.

In Figure 38 the IED Directional Agent protection devices associated with protecting the 11 kV ring are identified for convenience according to compass sub-ordinal points (NW, NE, SE, SW) as shown. Relays R1 through R4 reside at similar locations to those assigned in the previous overcurrent benchmarking exercise. The Directional Agents specifically assigned to protecting the 11 kV ring are deployed and configured to 'look into the ring'. For these devices the 'Forward' sense is as indicated in the graphic of Figure 38. The nominal sensing direction of the other relays is also indicated. Lines 2a and 2b form part of the 11 kV ring, and faults on these lines should normally be cleared by the four compass-point relays. Varying the contributions of generation, and the locations of faults should affect the directions of power flow around the ring, and hence influence the response of each Directional Agent. The other relays provide back-up, and protection for faults outside of the 11 kV ring. This configured model is the principle vehicle to be used for evaluating directional protection.

7.1.4.3 Comparison of Directional Protection Techniques

Directional comparison protection involves the determination of, and subsequent comparison of, directions of power flow at various measuring locations across a power system network. For networks featuring dispersed embedded generating resources, directional protection offers advantages over non-directional overcurrent protection [121], and Apostolov outlines the advantages that directional comparison protection can bring to the challenge [122].

An expressed intent of this work was to attempt a comparison of techniques used to implement directional comparison protection. However, this was pre-Covid19, and, as is apparent from scrutiny of the results, this became not possible. Access to suitable laboratory and hardware resources was unavailable, preventing secondary injection testing. Also, suitable proven software models to allow simulation testing were also not available. To overcome the obstacles and to facilitate (at least some) testing, it became necessary to undertake a resource consuming unplanned activity to design and implement a directional comparison protection simulation model with which to evaluate basic scheme performance.

Details of the Directional Agent simulation model and teleprotection (communications interlink) model, used to create directional comparison unit scheme models for performance evaluation in this exercise are presented in Appendix I as Appendix Figure 7, which is duplicated here as for convenience, as Figure 39.

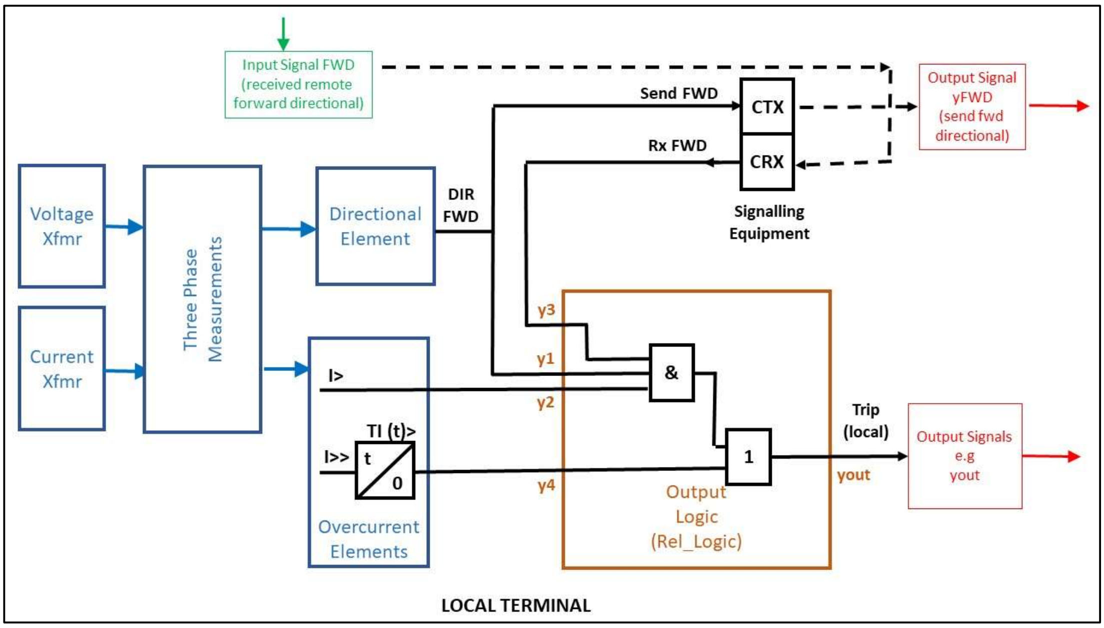


Figure 39: Functional Requirements for Directional Agent Block Element.

Appendix I, as well as outlining the design of the Directional Agents and teleprotection relays used to evaluate the directional comparison protection, also illustrates the process by which the models are created. Appendix I forms an instructional commentary on the procedure for creating a simulation model within a DIgSILENT environment. In this context, Appendix I is provided for the potential to serve as useful reference material for anyone facing the challenge of modelling a new relay in DIgSILENT.

7.1.5 Polarising Directional Protection

An objective of the project is to investigate the possibility to polarise directional protection from a remote signal. The focus of this work now turns to the topic of polarising the Directional Agents.

To make protection relays sensitive to the direction of flow of current on a network, directional control is added. The directional control is facilitated by the inclusion of polarising signal(s) which provide reference to which direction (as indicated by relative phase relationship), can be compared [25]. In the most common of implementations, the polarising signals are provided in the form of voltage references. Other options such as using current signals may also be considered.

The relationship between voltage and current in a circuit is defined by circuit impedance. Comparing the phase relationship of current and voltage imparts a sense of direction to the impedance quantity according to the lagging/leading relationship between the current and voltages. This determination of direction by consideration of the angle of the current signal with respect to the voltage signal is known as voltage polarisation.

When 'looking into' a healthy steady-state electrical network, a characteristic impedance can be measured. This impedance is characterised by the phase displacement between the voltage and current signals at the observation terminal(s). Since the observation is made looking into the network (i.e. looking forwards into the network), a relationship between current and voltage of <±90^0 around the characteristic angle can be used to suggest a forward sense for the impedance. Similarly, looking out from the network a relationship between current and voltage of >±90^0 around the characteristic angle can be used to suggest reverse sense to the impedance. Placing an axis on the complex impedance plane, perpendicular to the characteristic impedance, allows impedances to be conveniently divided between those that appear in the forward direction and those that appear in the reverse direction. This axis may be referred to as a directional line. The principle is illustrated in the following Figure 40.

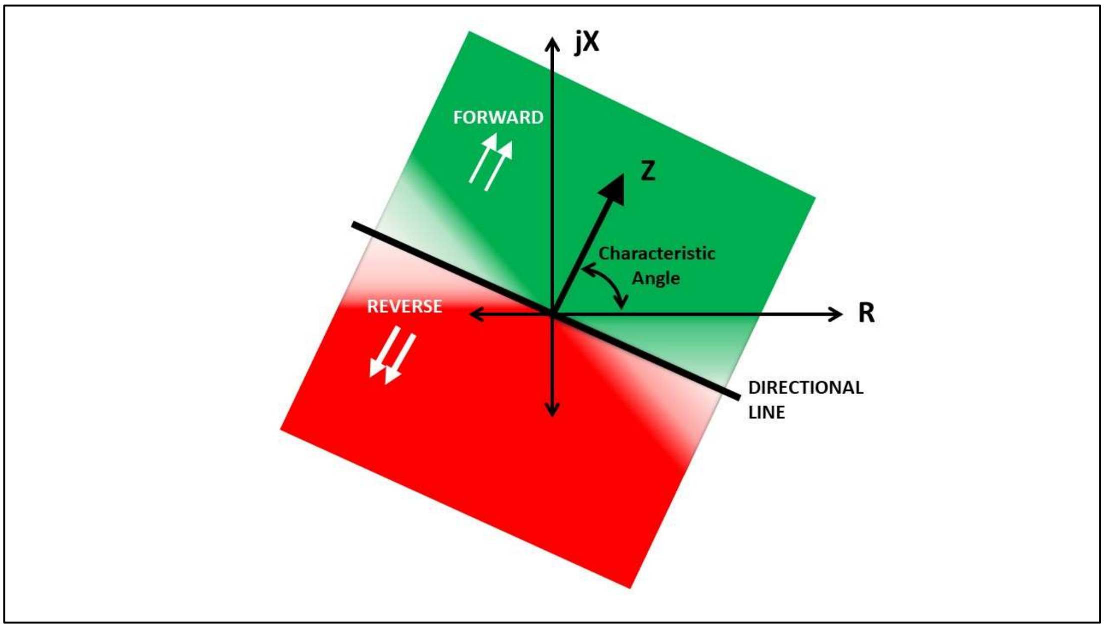


Figure 40: Outline of Directionality Principle.

The directionality elements of a relay need setting after taking consideration of the impedance that is expected to characterise the network and how it may change during fault conditions to become more inductive. With numerical relays implemented using computing techniques, the selection options are generally so flexible as to allow the 'forward' sense to be precisely matched to the characteristic impedance. The flexibility of numerical implementations may also afford discretion as to how the limits of directionality are applied to ensure certainty as illustrated in the following Figure 41.

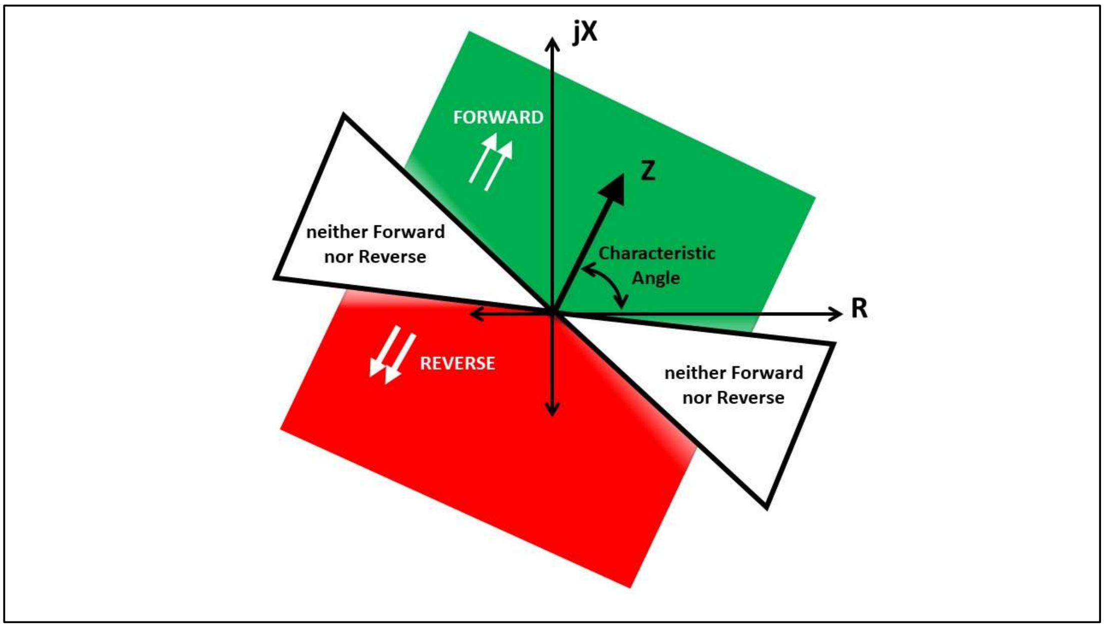
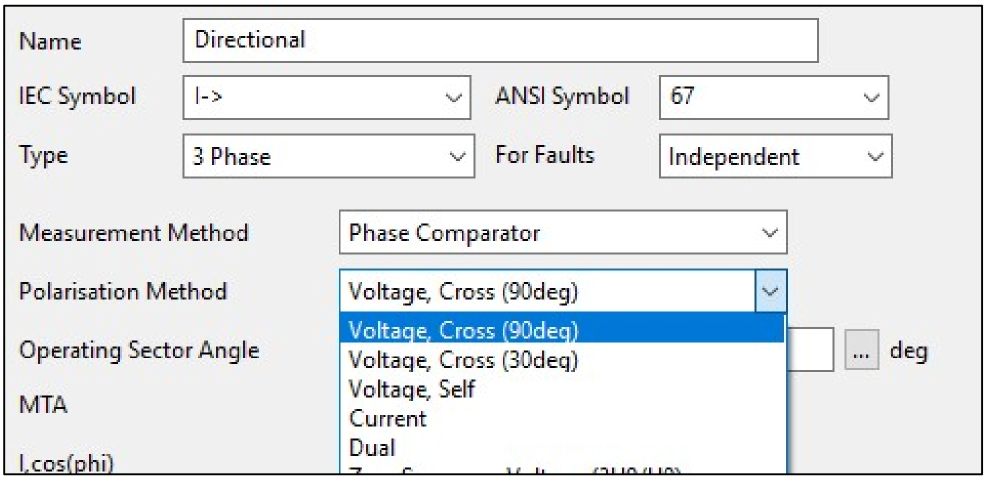


Figure 41: Qualified Directional Characteristic.

With implementations based on previous relaying technologies such as electromechanical, the same flexibility is not available. Relying on techniques to rotate polarising quantities to maximise torque angles by appropriate connections, relaying characteristics were restricted both in terms of settings, and operation to a limited range of angles that could be obtained by winding combinations. Typically, these angles are in increments of multiples of 30°, 45°, or 90°. Sonnermann provides a comprehensive appraisal of the possibilities [123].

The standard implementation of directional elements in DIgSILENT simulation accommodates a subset of standard configurations. Designated as '*Voltage, Cross (90deg)*', '*Voltage, Cross (30deg)*', and '*Voltage, Self*', three voltage-polarised, phase-comparator directionalising options are provided (as well as 'current' and 'dual' polarised options) from which the choice must be made as shown in the following Figure 42.



Name: Directional
IEC Symbol: I->
ANSI Symbol: 67
Type: 3 Phase
For Faults: Independent
Measurement Method: Phase Comparator
Polarisation Method: Voltage, Cross (90deg)

Figure 42: DIgSILENT Relay Model Directionalising Options.

7.1.5.1 Applying Directionality to Implement Unit Protection

The principle of a directional comparison protection scheme is most conveniently illustrated by reference to an example of a protected two-terminal line. Ignoring effects such as measurement inaccuracies and line charging current, then Kirchhoff's Law advises that, under healthy line conditions, the sum of the currents flowing into the line should equate to zero. Put another way, in the absence of a fault on the protected line, the current flowing in (i.e. forward current) at one end should be the same as the current flowing out (i.e. reverse current) at the other end. So, if the relay at one end sees forward current and the other relay sees reverse current, then it can be deduced either that the network is healthy or, if a fault is present, that the fault is external to the protected line. If both relays see current in the forward sense, then it is indicative of a fault internal to the protected line and tripping to isolate the fault should be initiated.

Whilst the choice of signals to determine directionality can be arbitrary, care needs to be taken to ensure the integrity of the polarising signals at the time when the measurement is most critical. For a protection principle based on directional measurements, correct measurement is most critical around the time of fault. Whilst determining direction using a phase voltage signal to (self-) polarise a current signal of the same phase provides discrimination under healthy conditions, under fault conditions, such as a single-phase-to-earth-fault, where the phase voltage may collapse to zero, other options (such as cross-polarised from healthy phases, sequence polarised, current polarised, or dual polarised) may provide a more robust method for determining direction. Further, in a directional comparison scheme where, the directions of two (or more) quantities are compared with each other, the quantities used to educate the directional decisions at the different terminals must be consistent. So, for example, if a particular voltage signal is used as reference to polarise a particular current at one end, a similar voltage signal must be used as reference to polarise a similar current connection at the other end(s). Since this work uses directional overcurrent elements as the basis of a directional comparison scheme, it is necessary that the comparisons are based on measurements of similar current quantities. Additionally, the quantity used to provide the polarisation at each terminal must have consistent referencing. This latter constraint requires that the polarising signals used at either end should be phase-aligned. If the sources of polarising reference signals reside on different parts of the protected network, the difference must be appropriately compensated. If the parts of the network from which the polarising signals are derived are linked by voltage transformation, the transformation process must be compensated in the polarising quantity before it is applied. For the purposes of this study, it is assumed that the polarising signals reside on the same network section, and testing is restricted to such cases.

7.1.5.2 Voltage Polarising Source for Directionality

A particular interest of this research is to investigate the use a different polarising voltage to determine the directionality. The use of a lower voltage polarising quantity offers potentially substantial cost savings benefits since expensive VTs may be avoided. For the example protected network Figure 38, the Eastern relays are connected downstream of the Western relays such that the Eastern relays have closer proximity to lower voltage (400 V) consumer connections than the Western relays. Revising the design of the Eastern relays and reassigning them to use a downstream 400 V connection, whilst retaining 11 kV voltage polarisation on the Western relays could allow a useful comparison to be made.

When considering the use of 400 V to polarise 11 kV CT connected Eastern relays, it must be recognised that the lower voltage signal is derived from the higher voltage one by means of a delta-wye connected 11 kV:400 V transformer. This means that, relative to the busbar/line voltage signal at the relaying point, the supplied relay polarising signal will be voltage-attenuated and phase-shifted. Additionally, whilst at 11 kV three-phase connections are more common, at the lower voltage level it is common for single-phase only connections to be provided.

Consequently, for the Western relays, three-phase 11 kV line voltage inputs are available, whereas, for the Eastern relays, a single-phase (400 V line-line equivalent) phase-shifted signal is preferable.

In a fully configurable numerical relay, it should be possible to design the relay to use software to internally compensate the polarising input to account for the differences. If the DIgSILENT simulated relay is to be used (for comparison purposes), then the configuration of the simulation model should, if possible, be adapted to compensate.

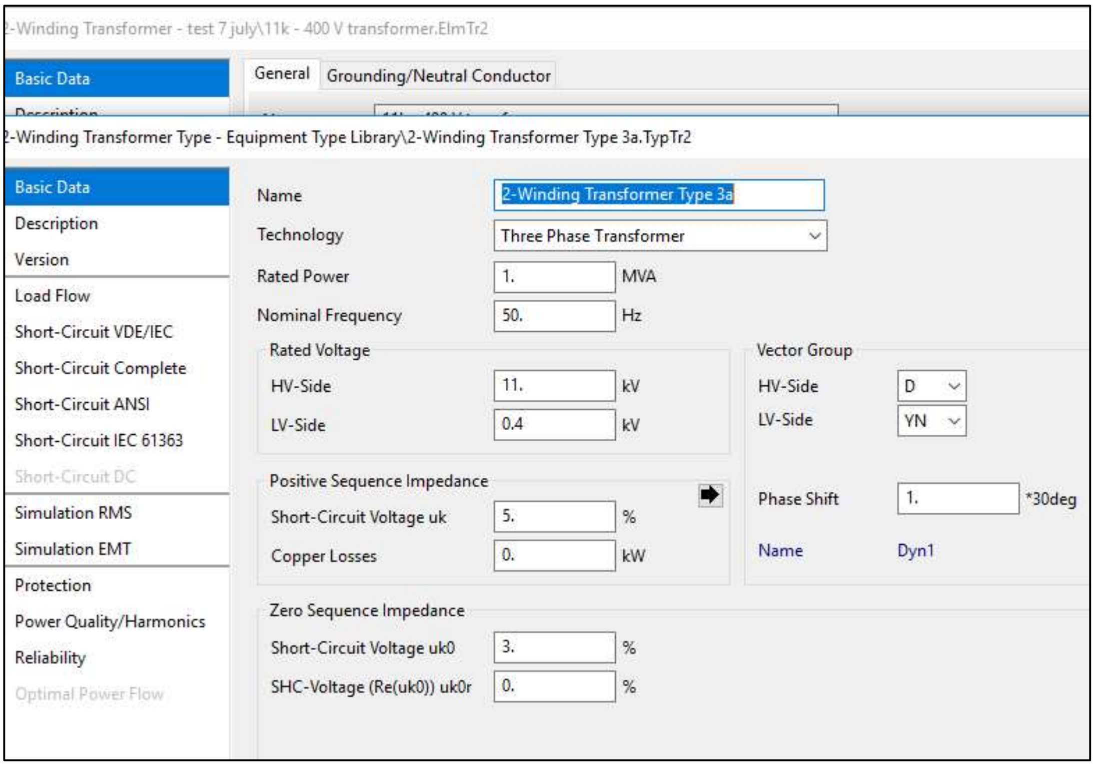
7.1.5.3 The Impact of Voltage Transformation on Polarising Quantities

In the example distribution network under test (Figure 38), two 11 kV busbars (BB3 and BB2) are connected by parallel lines (Line 2a and Line 2b). BB3 is located on the Western side of the network. BB2 is located on the Eastern side. Line 2a is located to the north of the network. Line 2b is located to the south. Directional overcurrent relays (referenced as NW, NE, SW, and SE according to their location on the network) are applied in the forward sense looking into each end of each line.

As detailed in Appendix I, purpose-designed relay simulation models have been created for use in conjunction with the network model of Figure 38 to evaluate directional comparison protection.

On the test network, the directional relays use CTs on the 11kV lines to which they are connected for current inputs. The relays on the Western side are configured to use 11 kV VTs connected to BB3 for the voltage-polarising (directional) inputs.

For the relays on the Eastern side (connected to BB2), the desire is to use a downstream lower voltage for the polarisation. LV downstream busbar BB1 connects to BB2 via an 11 kV:400 V power transformer providing the opportunity to supply the lower voltage to polarise the Eastern 11 kV relays. The design of the simulation models of these transformers are described within the DIgSILENT configuration menu as illustrated in the following screenshot (Figure 43).



-Winding Transformer - test 7 july\11k - 400 V transformer.ElmTr2

-Winding Transformer Type - Equipment Type Library\2-Winding Transformer Type 3a.TypTr2

Name: 2-Winding Transformer Type 3a
Technology: Three Phase Transformer
Rated Power: 1. MVA
Nominal Frequency: 50. Hz

Rated Voltage
HV-Side: 11. kV
LV-Side: 0.4 kV

Vector Group
HV-Side: D
LV-Side: YN

Positive Sequence Impedance
Short-Circuit Voltage uk: 5. %
Copper Losses: 0. kW

Phase Shift: 1. *30deg
Name: Dyn1

Zero Sequence Impedance
Short-Circuit Voltage uk0: 3. %
SHC-Voltage (Re(uk0)) uk0r: 0. %

Figure 43: DIgSILENT Relay Model 11 kV:400 V Transformer Details.

From the illustrative screenshot (Figure 43), it can be seen that the 11 kV:400 V transformer connecting between busbars BB2 and BB1 of Figure 38 is of the Dyn1 configuration. The implications of this Dyn1 configuration need to be accounted for when connections to relays need combining from both BB2 and BB1. For the NE and SE relays to use a 400 V polarising signal delivered from BB1, it is necessary to have suitably rated VT inputs on the relays which are then connected to appropriate voltage measurement connections on BB1. The directionalising block of the NE and SE relays must then be configured to use a voltage connection from BB1. The latter point requires that the configuration of the directionalising relay design should account for magnitude changes associated with the 11 kV:400 V Dyn1 transformer, and also the phase changes associated with the transformer.

Anticipating single-phase connection for the low-voltage polarisation signal, it would be advantageous for the directionalising blocks in the simulation model to support this too.

Attention needs to be paid to the consequences on polarisation of using signals related by such a delta-wye transformation.

An 11 kV:400 V transformer of the Dyn1 type connects between BB2 and BB1. The construction of this type of transformer is illustrated in the following Figure 44.

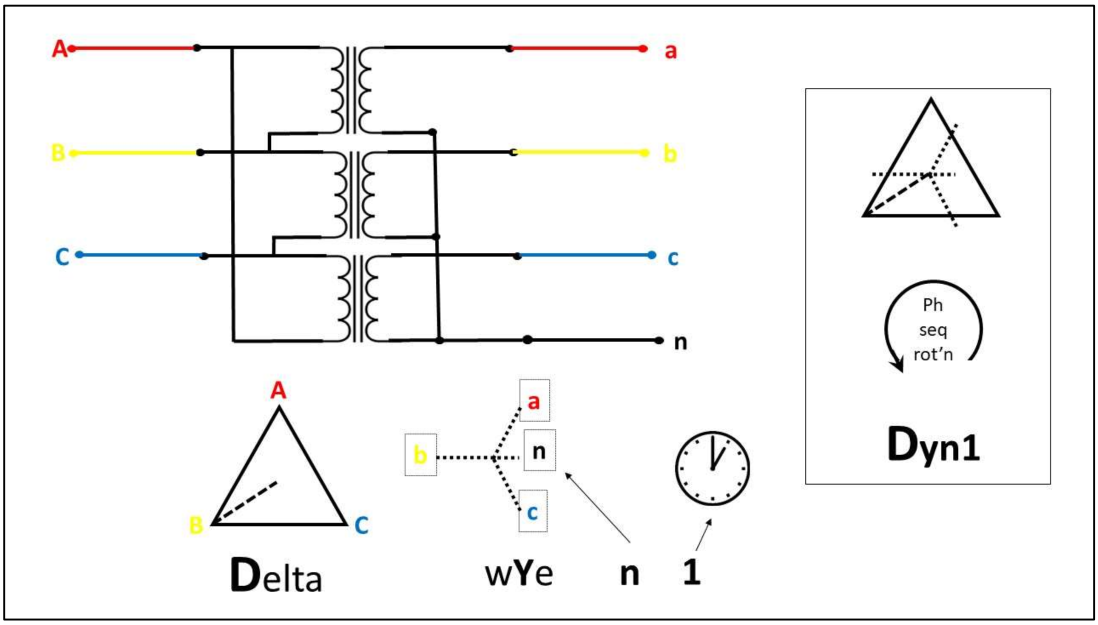


Figure 44: Dyn1 Transformer Winding Arrangement and Vector Transformation.

In Figure 44, A B and C represent the phases on the primary winding of a three-phase transformer. The winding arrangement is delta primary (D), wye (y), neutral connected secondary (n) with a 30^0 phase shift (1 (o'clock)) between the primary and secondary phase equivalents (a b and c).

The following Figure 45 shows a mapping of the transformer voltages overlaid onto a directional characteristic.

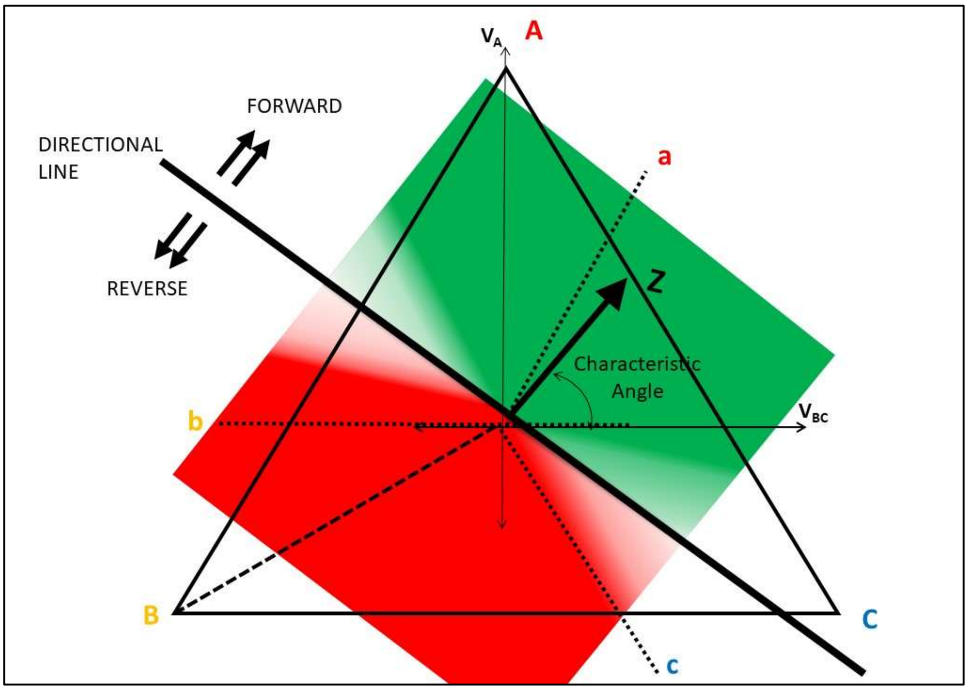


Figure 45: Single-phase directional characteristic with three-phase voltage transformer overlay.

In Figure 45, a characteristic impedance relative to current balanced three-phase voltage set is shown. It can be seen from the figure, that the same sense of direction for the a-phase voltage could be obtained from cross-polarised, quadrature-connected line-voltage primary side V_{BC}, or from self-polarised, phase connected, primary side V_A, or from 30º (leading) compensated, secondary side V_a. Directionality relative to a quadrature connected V_{BC} as shown has the advantage that V_{BC} ensures a polarising signal in the event of a voltage collapse on the measured phase $V_A = 0$.

From Figure 45, it can be seen that if a comparison of directional signals is to be made on measurements made by similar relays polarised from voltage signals taken from both the primary and secondary sides of a DYn1 transformer, then 30º (leading) compensation needs applying to the secondary voltage to assure ideal matching.

As an alternative, with some potential loss of selectivity, a modified characteristic like that shown in Figure 41 may be employed. By using a blinder[4] placed at ±60° to the characteristic impedance, this would ensure that any abnormal current producing an impedance within ±60° of the characteristic system impedance forward trajectory would be interpreted as a forward fault if polarised in the sense of the a-phase voltage of either winding. This arrangement should provide selective fault identification for fault impedances close to the characteristic angle, but selectivity may suffer as fault impedances increase and shift into the blind off-characteristic-impedance-axis regions. Since this option is available from the standard library of DIgSILENT relay model components, for initial evaluations, at least, this is the option that will be pursued.

It is worth noting that using a three-phase voltage cross-polarised directional element on the HV side of the protected zone, in conjunction with a single-phase LV polarising signal has advantages for the case of single phase-to-earth faults within the protected zone. This is because directional elements of the comparison scheme will receive polarising signals even in the event that the in-zone faulted phase voltage collapses. For the HV polarised relay, cross polarising from the two healthy phases should provide valid signals. Under these circumstances, for the LV polarised relay (single-phase self-polarised) there will always be a voltage signal on any of the phases (including the faulted polarising phase) due to the current distribution in the secondary windings of the Dyn1 transformer. The use of memory polarisation could be considered to improve performance for three-phase fault causing total voltage collapse. The potential benefits are recognised, but the topic is not researched in this work. The worthiness for investigation is noted for potential future work..

At the start of the project, an intent had been to experiment with providing the LV polarising input in the form of a digital VT interface conformant with IEC61850-9-2. Whilst this remains a most interesting and attractive aspect of the overall proposal, working within the constraints imposed by Covid19 renders evaluation not possible for now, and so that aspect of the development must be consigned to the category of potential future work. Nonetheless, whilst consequences of adopting a digital VT interface are not explored, it should be possible to explore

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[4] A blinder represents a portioning-off of a region of the normal operating characteristic in which, without the blinder, tripping would normally occur, but in which, by the presence of the blinder, tripping is prevented.

the predominant impacts of using remotely sources LV polarisation to achieve directionality for this type of application.

7.1.6 Directional Comparison Protection Scheme Performance

With distribution network models having been verified, and with suitably connected Directional Agent models and teleprotection models applied (refer Appendix I), directional comparison protection performance can be evaluated for a variety of network configurations in order to confirm suitability.

A suite of tests will be performed to determine this suitability based on applying the DIgSILENT created Directional Agents to the configurable generic distribution network model.

7.2 Distributed Low-Voltage Measurements Evaluation

A novel aspect of this research study is to provide a voltage polarising signal for applications such as the protection of distribution networks where traditional voltage transducers (voltage transformers) are not present. The prospect of taking LV voltage measurements, for use in combination with higher-voltage current measurands taken at traditional relaying points, is explored.

The concept of a ‘Voltage Cube’ is presented. A compact plug-in device for ‘mains’ voltage acquisition is introduced. The concept behind the Voltage Cube is that device (much smaller and cheaper than a conventional protection VT) could connect directly to the LV mains electricity at, for example, a consumer supply point. The Voltage Cube should measure the mains voltage, convert the voltage into a numerical value, and communicate it to subscribing devices such as a Directional Agent providing protection at a (potentially) higher voltage location on the protected network.

The objective of this element of research is to assess the feasibility of providing a compact, cost effective AC voltage measuring device that can be used to provide a polarising signal suitable for use be a Directional Agent IED. Identified research activities are literature review, candidate selection, and proof-of-concept testing.

7.2.1 Voltage Cube Literature Review

Literature review is used to research the dynamic performance requirements for protection VT inputs, as well as investigating the signal interfacing requirements for communications with Directional Agents.

7.2.2 Voltage Cube Candidate Proposals

Literature review guides identification of potential technologies for candidate solutions. Feasibility of the proposals is evaluated, and preferred candidate(s) are analysed for suitability. Preferred candidate solutions are selected.

7.2.3 Voltage Cube Proof-of-Concept Testing

Within imposed constraints, such proof-of-concept testing as may be useful to endorse feasibility/confirm selection will be performed.

6.3 Using Wireless Communications to Realise Directional Comparison Unit Protection from Directional Agents and Distributed Low-Voltage Measurements

The objective of this work package is to investigate the feasibility of using wireless communications to realise the interconnectivity of devices such as Directional Agents and Voltage Cubes to form wide-area unit protection schemes for smart electrical distribution networks.

Directional Agents have two potential wireless connections:-

1. Communication of directional information between connected Direction Agents to implement (potentially wide area) directional comparison unit protection schemes. This information transfer is suited to realisation with GOOSE messages conformant with IEC 61850-8-1.
2. Communication of Sampled Analogue Values (SAV) from (Voltage Cube) acquisition units to provide polarisation input to connected Direction Agents. This information transfer is suited to realisation with SAV messages conformant with IEC 61850-90-2.

Ideally this would both be implemented in a single interface port and since both IEC 61850-8-1 and IEC 61850-90-2 can co-exist on the same Ethernet bus, then sharing one common port should not be a problem.

Note: The original intent for this work was that literature review would give credence to conceptual ideas, and that proposals to engage the technology to deliver appropriate schemes would be reinforced by prototype work and rudimentary testing. Intended research practices for this work have, however, been disrupted by Covid19. The scope of study of this work package has, therefore, been limited to feasibility study informed by literature review.

Current 'state-of-the-art' concerning the use of wireless Ethernet communications for electrical power systems protection, automation, and control applications is assessed. Literature review guides a feasibility study to appraise the communications requirements to implement protection schemes based around Directional Agents exploiting the service provisions of IEC 61850. Particularly it looks at the implications of utilising the alternative medium of wireless Ethernet to realise substation communications rather than copper cables. To this end, an aim would be to assess the suitability of wireless Ethernet for servicing the requirements of GOOSE messaging as well as the suitability of wireless Ethernet for servicing the requirements of SAV transfer on a shared, combined interface. Technology maturity/readiness/availability is assessed, particularly with regards to demonstrating quality and associated potential compliance.

Chapter 8 Findings and Results

This chapter presents the results and findings of project research activities. The chapter's organisation aligns with the layout of the research methodologies and research activities described in Chapter 6 and Chapter 7.

Section 8.1 associates with evaluating the application of directional protection to distribution networks primarily by modelling and simulation testing. Results are presented to verify a generic distribution network model created to evaluate directional protection, to verify the development of purpose-designed Directional Agent simulation model, to verify the development of a purposed-designed directional comparison unit protection simulation scheme based on intercommunicating simulated Directional Agents, and to demonstrate the performance of the directional comparison unit protection scheme simulation model under various network configurations.

Section 8.2 associates with evaluating LV polarisation issues and delivers a feasibility study. Literature review is complimented by rudimentary field tests.

Section 8.3 associates with evaluating the use of wireless communications to implement the proposed directional comparison protection scheme. Feasibility assessment outcomes are presented. Observations from literature review mitigate in part the limitations on testing caused laboratory resource access restrictions consequent on Covid19.

8.1 Distribution Network Protection Evaluation Results

Results of a benchmarking exercise to verify a distribution network system model are presented within this section.

Consequential to successful demonstration of the model, the model is deployed as a vehicle to evaluate new protection for the network.

Results of testing protection based on directional principles is presented.

It should be noted that this is an exercise to verify a simulation model and demonstrate that it can validly be used to provide a test platform. Some the fault levels and durations that are discussed may not be practical/achievable on a real system. Further, assumptions such as the use of IDMT relays for overcurrent protection at 400V may be questioned. The purpose, however, is to demonstrate agreement between a theoretical analysis and simulator performance to provide a benchmark, rather than to provide an exact model of a specific network.

Note that these are maximum prospective fault levels from the simulation model (maximum sustained RMS values). They are far in excess of what would be experienced on a real network. In practice the maximum tolerable fault levels that can be experienced on the network are limited to lower values [124].

8.1.1 Distribution Network Protection - System Model Verification

The results of a benchmarking exercise to verify a distribution network system model are presented.

Results are presented for the following component activities of the benchmarking exercise:-

- Current flows are determined for the configured distribution network model.
  - Theoretical values are calculated.
  - A DIgSILENT model of the network is used to determine the values.
  - Theoretically derived values are compared with the output of the simulation model.
- A time-graded overcurrent protection scheme is designed and tested.
  - Performance of the simulated protection scheme is compared with predicted theory to verify the design.
  - Time-overcurrent plots are produced, allowing the performance to be visualised and checked.
  - Neutral current protection performance is analysed and evaluated to elaborate and verify network performance.
  - Fault sequence plots confirm the validity.

8.1.1.1 Network Impedances for Benchmark Configured Network Model

The calculations of the current flows for the configured network model being benchmark tested are based on the SLD presented in Figure 24 and in its simplified form in Figure 25.

To calculate the network currents, the impedance values are required. The impedances of the applicable SLD are defined by the parameters of the network components applied and are summarised in the following Table 4:-

Table 4: SLD Component Impedance Values.

Z_S	Z_{T3}	Z_{F3}	Z_{L3}	Z_{F2}	Z_{L2}	Z_{T1}	Z_{L1}	Z_{F1}	Z_{CL}
33 kV 8000-10000 MVA	33/11 kV 15 MVA 3 % 1 Ω N-E	1 km x 0.08+j0.1 Ω/km	33 kV 2 MW	10 km x 0.08+j.01 Ω/km	11 kV 1.75 MW	11k/400 V 1 MVA 5% 1 Ω N-E	400 V 500 kW	500 m x 0.02+j0.1288 Ω/km	400 V 100 kW

Noting that the 'Ohmic' impedance of a transformer is given by:-

$$Z_{T(V)} = \% \ x \ (V^2)/MVA$$

And that for a source/load the impedance is:-

$$Z_{S(V)} = V^2/MVA$$

Then the equivalent Ohmic impedance values can be determined. They are summarised in the following Table 5.

Table 5: Network Equivalent Impedance Values (Ω).

Z_S (33 kV)	Z_{T3} (33 kV)	Z_{F3} (11 kV)	Z_{L3} (11 kV)	Z_{F2} (11 kV)	Z_{L2} (11 kV)	Z_{T1} (11 kV)	Z_{L1} (400 V)	Z_{F1} (400 V)	Z_{CL} (400 V)
0.1089 to 0.136 (avg) 0.121	j2.178	0.08 + j0.1	60.5	0.8 + j1	69.1	j6.05	0.32	0.01 + j0.064	1.6

Where (referring to Figure 24 and Figure 25):

Z_S	is the 33 kV supply point source impedance,
Z_{T3}	is the (positive sequence) impedance of the 33 kV : 11 kV transformer between BB4 and BB3 [125],
Z_{F3}	is the (positive sequence) impedance of the feeder between the 33 kV : 11 kV transformer and BB3 [5] [126],
Z_{L3}	is the impedance of the loading at BB3,
Z_{F2}	is the (positive sequence) impedance of the feeder between BB3 and BB2,
Z_{L2}	is the impedance of the loading at BB2,
Z_{T1}	is the (positive sequence) impedance of the 11 kV : 400 V transformer between BB2 and BB1,
Z_{L1}	is the impedance of the loading at BB1,
Z_{F1}	is the (positive sequence) impedance of the feeder between BB2 and BB1,
Z_{CL}	is the impedance of the 400 V consumer load.

When analysing system quantities such as currents, it is convenient to work to a common base. The relationship between the impedances at the different base voltages is given by:-

$$Z_{V1} \equiv Z_{V2} \times (V1/V2)^2$$

So, using (in this case 33 kV) as a common base:-

---

[5] Values based on typical figures for BS6622/BS7835 three-core armoured 11 kV XLPE 400mm2 stranded copper conductors

- To covert from value at 400 V to equivalent on a 33 kV base, the value needs to be multiplied by $(33\text{ k}/400)^2 = 6806.25$
- To covert from value at 11 kV to equivalent on a 33 kV base, the value needs to be multiplied by $(33\text{ k}/11\text{ k})^2 = 9$.

Converting the impedance values of Table 5 to a common 33 kV base gives the following impedance table for the SLD Table 6.

Table 6: Network Equivalent Impedance Values normalised to 33kV Base (Ω).

Z_S (33 kV)	Z_{T3} (33 kV)	Z_{F3} (33 kV)	Z_{L3} (33 kV)	Z_{F2} (33 kV)	Z_{L2} (33 kV)	Z_{T1} (33 kV)	Z_{L1} (33 kV)	Z_{F1} (33 kV)	Z_{CL} (33 kV)
(avg) 0.121	j2.178	0.08 + j0.1	60.5	0.8 + j1	69.1	j6.05	2178	68.1 + j438.3	10.89 k

Note: Calculations assume mean source capacity, Zs, = 0.121 Ω.

Table 6 facilitates the calculation of prospective short-circuit fault currents for checking against the DIgSILENT derived simulation values.

8.1.1.2 Theoretical Determination of Zone Currents

Using the network equivalent impedances of Table 6, the theoretical values of the prospective short-circuit currents at the different busbars can be calculated as follows:-

For a short circuit fault at busbar BB4 (relative to 33 kV Base)

$Zs = 0.121\ \Omega$

So $I_{faultBB4} = (V/\sqrt{3}) / 0.121$

$= 157\text{ kA (33 kV base)}$

For a short circuit fault at busbar BB3 (relative to 33 kV Base)

$Z_{BB3@33} = Zs + Z_{T3} + Z_{F3} = 0.121 + j2.178 + 0.72 + j0.9\ \Omega$

$= 0.841 + j3.078\ \Omega$

$= 3.19 \text{ angle } 74.72^{o}\ \Omega$

So $I_{faultBB3} = (V/\sqrt{3}) / 3.19$

≈ 5.97 kA (33 kV base)

$\equiv 17.9$ kA (11 kV base)

For a short circuit fault at Busbar 2 (relative to 11 kV Base)

$Z_{BB2@33} = Zs + Z_{T3} + Z_{F3} + (Z_{F2} // Z_{L3})$

But, since

$Z_{F2} << Z_{L3}, (Z_{F2} // Z_{L3}) \approx Z_{F2}$

So,

$Z_{BB2@33} \approx Zs + Z_{T3} + Z_{F3} + Z_{F2}$

$= 0.841 + j3.078 + 7.2 + j9\ \Omega$

$= 8.041 + j12.078\ \Omega$

$= 14.51$ angle $56.35^{o}\ \Omega$

So $I_{faultBB2} = (V/\sqrt{3}) / 14.51$

$= 1.31$ kA (33 kV base)

$\equiv 3.93$ kA (11 kV base)

For a short circuit fault at Busbar 1:-

$Z_{BB1@33} \approx Zs + Z_{T3} + Z_{F3} + Z_{F2} + (Z_{T1} // Z_{L2})$

Again, since

$Z_{T1} << Z_{L2}, (Z_{T1} // Z_{L2}) \approx Z_{T1}$

So,

$Z_{BB1@33} \approx Zs + Z_{T3} + Z_{F3} + Z_{F2} + Z_{T1}$

$= 8.041 + j12.078 + + j54.45\ \Omega$

$= 8.041 + j66.528\ \Omega$

$= 67$ angle $83^{o}\ \Omega$

So $I_{faultBB1} = (V/\sqrt{3}) / 58.19$

$= 284$ A (33 kV base)

$\equiv 23.4$ kA (400 V base)

For completion, for a short circuit fault at the consumer load busbar:-

$$Z_{CLBB@33} \approx Zs + Z_{T3} + Z_{F3} + Z_{F2} + Z_{T1} + (Z_{F1} // Z_{L1})$$

Again, since

$$Z_{F1} << Z_{L1}, (Z_{F1} // Z_{L1}) \approx Z_{F1}$$

So

$$Z_{CLBB@33} = 8.041 + j66.528 + 68.1 + J438.3\ \Omega$$

$$= 76.291 + j504.8\ \Omega$$

$$= 510 \text{ angle } 81^{0}\ \Omega$$

So $I_{faultCLBB} = (V/\sqrt{3}) / 510$

$$= 37.4 \text{ A (33 kV base)}$$

$$\equiv 3.09 \text{ kA (400 V base)}$$

Calculating the load currents is not as straightforward as checking prospective short circuit currents due to the way the loads are represented and modelled in the simulator.

The short circuit calculations assumed that circuit elements are modelled as fixed impedance values (i.e. the impedance does not vary with, for example, applied voltage). A constant impedance model may not, however, be suitable for modelling all elements. In particular, terminal loads may be better modelled using a constant power model. That is the case in this exercise – with the simulator, loads are modelled as drawing constant power. In such cases, if the applied voltage varies, the current must adjust to maintain constant power. On a radial distribution network the voltage will drop as location on the network moves from the source to the network extremities and as loading increases. So a constant power model of a load presents a variable resistance, which is influenced by the applied voltage which in turn is influenced by the circuit loading and location. The relationship between power, voltage, and resistance is quadratic and so determining the load currents requires resolution of complex quadratic equations expressing the relationships of the variables. Avoiding such calculations is a major reason for employing system modelling software. So, rather than enter into a complex mathematical analysis to calculate the load currents and then use these calculations to the model outputs, a simpler check is proposed. Consumer load power expectations will be verified against the voltage and current deliveries predicted by the DIgSILENT PowerFactory model.

8.1.1.3 Fault Currents and Load Currents Determined using DIgSILENT Model of the Network

Using the 'Calculate Short-Circuit' and the 'Calculate Load Flow' functions provided by the DIgSILENT simulator prospective fault currents and load currents can be determined.

The prospective short-circuit fault currents for the network modelled in Figure 25 are determined as follows:-

Short-circuit current at BB4 =

159 kA (33 kV base)

Short-circuit current at BB3 =

17.4 kA (11 kV base)

Short-circuit current at BB2 =

3.92 kA (11 kV base)

Short-circuit current at BB1 =

23.2 kA (400 V base)

Short-circuit current at CLBB =

3.02 kA (400 V base)

Note that these are maximum prospective fault levels from the simulation model (maximum sustained RMS values). They are far in excess of what would be experienced on a real network. In practice the maximum tolerable fault levels that can be experienced on the network are limited to lower values [124].

Using the DIgSILENT function to predict load flows gives an output of the form shown in the following Figure 46.

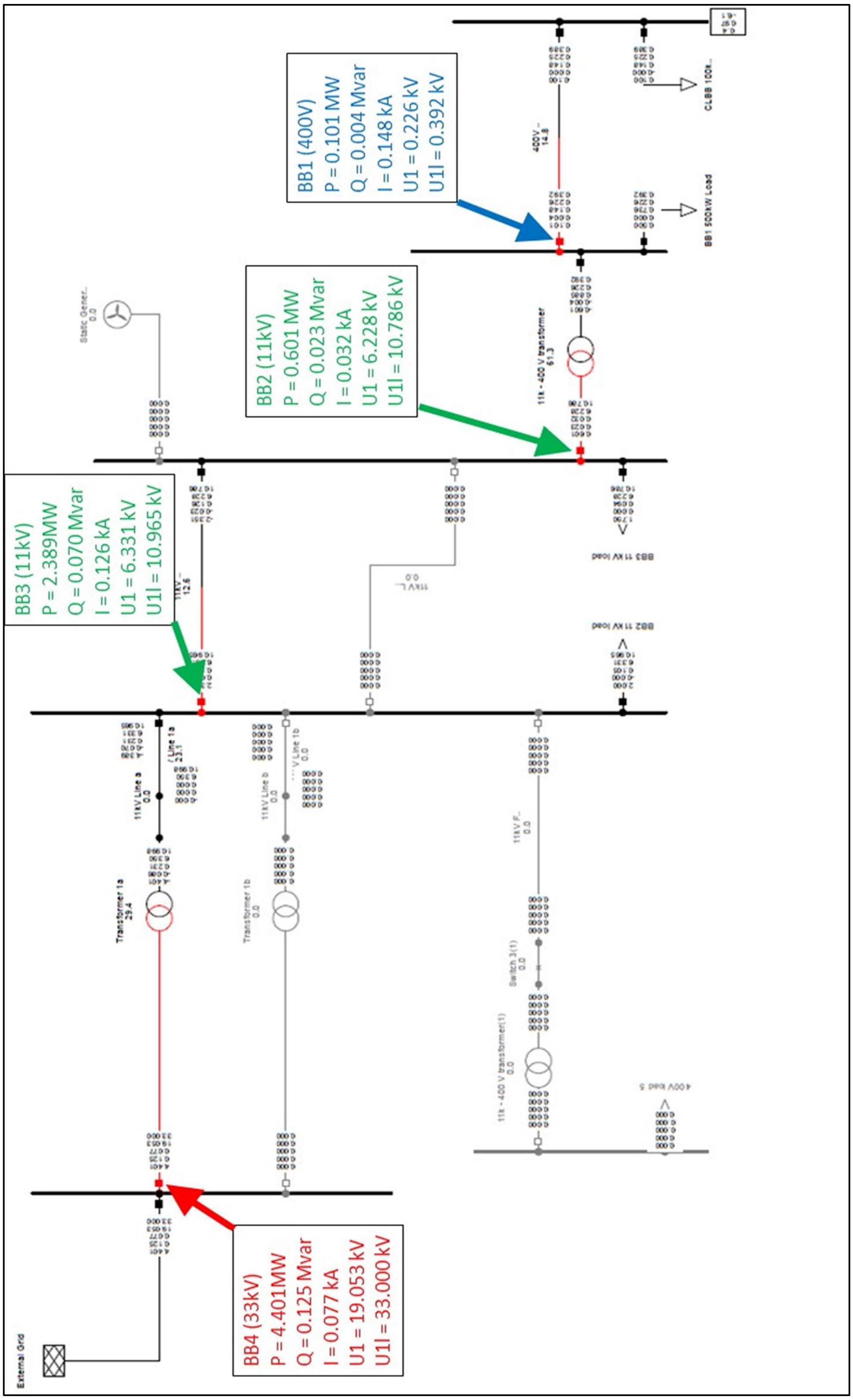


Figure 46: Load flow calculation output from DIgSILENT model for configured network of Figure 24.

Note: The diagram is annotated to clarify the calculated parameters for different busbars on the model. The annotation figures respect base voltages which are the nominal voltage of each busbar marked.

The summary of the load currents (determined from the simulator output of Figure 46) is:-

Load current measured by RL4 = 77.0 A (33 kV base)

Load current measured by RL3 = 126 A (11 kV base)

Load current measured by RL2 = 32 A (11 kV base)

Load current measured by RL1 = 148 A (400 V base)

8.1.1.4 Comparison of Calculated Zone Currents Compared with Equivalents Derived from DIgSILENT PowerFactory Simulation

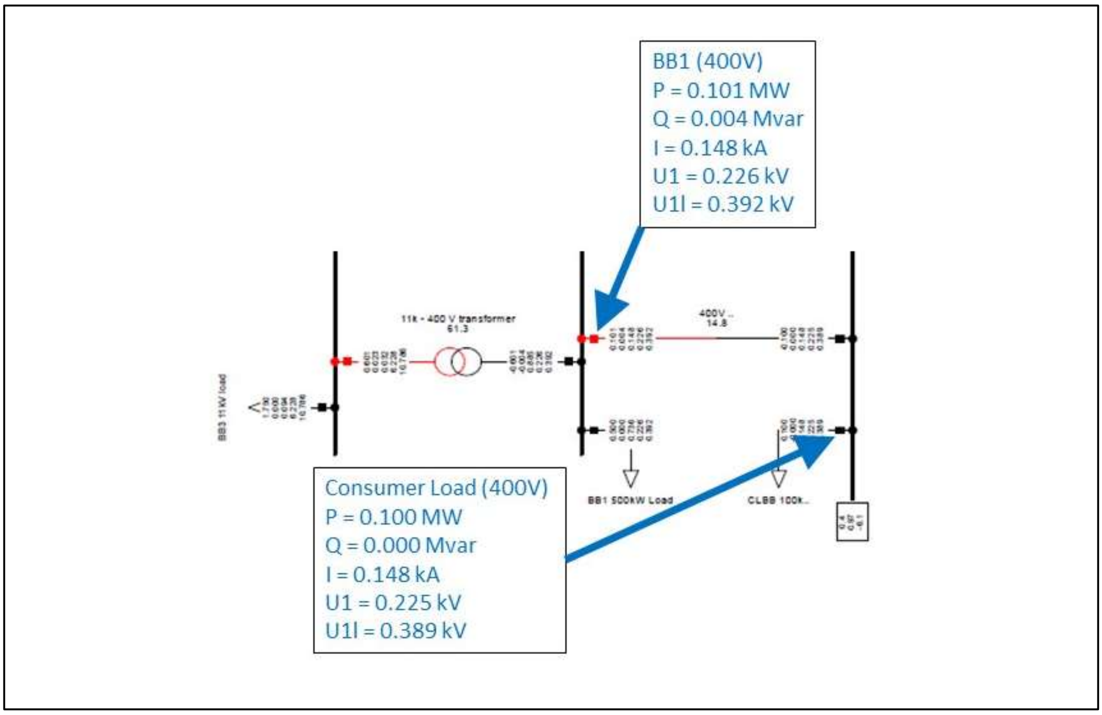
The calculated values for the prospective short circuit currents for the network shown in Figure 24 are presented, together with their equivalent values derived using the DIgSILENT model, in the following Table 7.

Table 7: Comparison of Theoretical vs Modelled Values of Fault Current for Configured Radial Distribution Network.

Busbar	Base Voltage	Short-Circuit Current	
		Calculated	Model-Derived
BB4	33 kV	157 kA	159 kA
BB3	11 kV	17.9 kA	17.4 kA
BB2	11 kV	3.93 kA	3.92 kA
BB1	400 V	23.4 kA	23.2 kA
CLBB	400 V	3.09 kA	3.02 kA

Clearly, there is alignment between the calculated, and model-derived, figures of Table 7, giving confidence in the model.

Because of the way the loads are modelled within the simulator, the simulator output values are taken in lieu of calculating the values. The credibility of these values should be checked in order to verify the simulation model. To do this, consider the network between BB1, the Consumer Load Bus, and the Load, as expanded in the following Figure 47.



BB1 (400V)
P = 0.101 MW
Q = 0.004 Mvar
I = 0.148 kA
U1 = 0.226 kV
U1l = 0.392 kV

Consumer Load (400V)
P = 0.100 MW
Q = 0.000 Mvar
I = 0.148 kA
U1 = 0.225 kV
U1l = 0.389 kV

Figure 47: Consumer Busbar Load Circuit Network Model.

If the network is correctly simulated, simple electric circuit laws should be respected. Verifying currents, voltages, and impedances at the loads should demonstrate this.

Terminating the network from BB1 is the line impedance (0.01 + j.066 Ω) and the load (100 kW). Note that the load is a three-phase balanced load, so that the load per phase is (100/3) = 33.3 kW.

The reported current flowing through the load is 148 A.

At the load, the voltage indicated by the output report is 225 V.

So the reported power consumed by the load in the model is 33.3 kW

Since the load is real, it must be a represented by a resistive load with an equivalent resistance being given by

$$R \equiv P/I^2$$

i.e.

$$R = 250 \ \ k / 3(148^2) = 1.52\ \Omega.$$

This can be used to check the validity of the reported voltage at BB1.

The impedance in the circuit from BB1 via the load is

$$1.52 + .01 + j.066\ \Omega$$

$$= 1.53 + j.066\ \Omega$$

$$\approx 1.53\ \Omega.$$

So, with a current of 148 A flowing, the voltage at BB1 would be 226 V.

This correlates with the 0.226 kV figure determined by the Newton Raphson algorithm used by the DIgSILENT PowerFactory software (convergence within three iterations). Similar exercises can be conducted for the other busbars, providing similar agreement.

Thus, given the correlation between modelled and predicted values of load and prospective fault currents, correct entry of modelling data is confirmed.

8.1.2 Distribution Network Benchmark Protection Testing Results

A time-graded overcurrent scheme is implemented to test the benchmark configuration of the network model. Time-overcurrent plots for the protection scheme performance are generated by the simulator, reported and analysed. Performance of the operation of the neutral overcurrent protection scheme is reported and analysed. Performance of the protection elements in response to a prescribed fault sequence is reported.

It should be noted that the settings used for the concept evaluation in this work are specific to the devices designed, configured, and applied to the generic distribution network model. In practice the settings (including for the crucial directional elements) would need to be tailorred to the specific topology and parameters of the actual system.

8.1.2.1 Configured Distribution Network Overcurrent Protection Scheme Settings Implementation

Recalling equation 1:- $I_S > 2I_S > 2I_{load\ \max}$

$$I_S > 2I_{load\ \max} \quad I_S < \frac{1}{2}I_S < \frac{1}{2}I_{\min-fault}$$

$$I_S < \frac{1}{2}I_{\min-fault}$$

and referring to the configured network model defined by the SLD presented in Figure 24 (and in its simplified form in Figure 25), current settings for relays RL1 – RL4 can be determined as follows:-

For RL1 of Figure 24

$(2 \times 148 \text{ A}) < I_S < (0.5 \times 23.2 \text{ kA})$

$296 \text{ A} < I_S < 11600 \text{ A}$, so

Choose $I_{S1} = 300 \text{ A}$

For RL2 of Figure 24

$(2 \times 32 \text{ A}) < I_S < (0.5 \times 3.92 \text{ kA})$

$64 \text{ A} < I_S < 1960 \text{ A}$, so

Choose $I_{S2} = 64 \text{ A}$

For RL3 of Figure 24

$(2 \times 126 \text{ A}) < I_S < (0.5 \times 17.4 \text{ kA})$

$252 \text{ A} < I_S < 8700 \text{ A}$, so

Choose $I_{S3} = 252 \text{ A}$

For RL4 of Figure 24

$(2 \times 77 \text{ A}) < I_S < (0.5 \times 159 \text{ kA})$

$154 \text{ A} < I_S < 79500 \text{ A}$, so

Choose $I_{S4} = 154 \text{ A}$

It should be noted that these settings are for the phase elements and are given in terms of primary system currents.

In primary values, the current settings required by the four relays are summarised for convenience in the following Table 8.

Table 8: Benchmark Relay Current Setting Values (in Primary Quantities).

Relay	Load Current	Fault Current	Setting Range	Chosen Value
RL1	148 A	23.2 kA	296 A < I_S < 11600 A	300 A
RL2	32 A	3.92 kA	64 A < I_S < 1960 A	64 A
RL3	126 A	17.4 kA	252 A < I_S < 8700 A	252 A
RL4	77 A	159 kA	154 A < I_S < 79500 A	154 A

The instrument CTs that interface between the primary plant and the relay current inputs are available in certain fixed values. Typically values such as 1000:5, 500:5, 250:5, 150:5, 100:5, 50:5, 1000:1, 500:1, 250:1, 150:1, 100:1, 50:1 etc. can be chosen [127]. The choice represents a balance between over-specification (excessive cost) and under-specification (overloading/stressing). Given that, for the phase elements (I>) of the P545, the current setting ranges are 0.08 – 4.00 (step) 0.1, then suitable chosen CT ratios and setting values could be as suggested in the following Table 9.

Table 9: Chosen CT Ratios and Current Settings.

Relay	Load	Target primary setting	Chosen CT Ratio	Equivalent Secondary Value	Available Setting Range	Setting Step Size	Applied Setting
RL1 (I>1)	148 A	300 A	500:5	3 A	0.08 – 4.00	0.01	0.6
RL2 (I>1)	32 A	64 A	100:5	6.4 A	0.08 – 4.00	0.01	0.64
RL3 (I>1)	126 A	252 A	250:5	5.04 A	0.08 – 4.00	0.01	1.01
RL4 (I>1)	77 A	154 A	150:5	5.1 A	0.08 – 4.00	0.01	1.03

With the current settings established, the *TMS* settings can be calculated. The following assumptions are made in calculating the *TMS* settings:-

1. All faults are solid three-phase balanced.
2. Faults beyond the consumer load busbar are assumed to be cleared instantaneously by fuse operation.
3. A grading margin of 400 ms is required between relay and fuse, and between relay and relay, to provide adequate time for downstream fault clearance before back-up protection acts.
4. *TMS* settings available are 0.025 – 1.200 in steps of 0.025.

Recalling equation 2:-

$$t_{characterist} \quad = TMS \times \frac{0.14}{(\frac{I}{PSM \times I_N})^{0.02} - 1}$$

and with the assumptions made, referring to the configured network model defined by the SLD presented in Figure 24 (and in its simplified form in Figure 25), the *TMS* settings for relays RL1 – RL4 can be determined as follows:-

For a fault at CLBB

RL1 should operate in 400 ms.

The short-circuit current level (at CLBB) is 3.02 kA (@400 V), and the setting is 300 A (@ 400 V).

From equation (2)

$$TMS_{RL1} = (0.4 \times ((3020/300)^{0.02} - 1))/0.14$$

$$= 0.135$$

So chosen TMS_{RL1} is 0.15

With TMS_{RL1} set to 0.15, using equation (2), t_{op} is calculated as 444 ms.

At BB1 the short-circuit current is 23.2 kA (@400 V), so with TMS_{RL1} = 0.15, using equation (2), at this current, RL1 should operate in

$$(0.15 \times 0.14) / (((23200/300)^{0.02}) - 1)$$

$$= 0.231 \text{ s}$$

$$\approx 230 \text{ ms}$$

Note, however, that the simulation model of the overcurrent element reverts to definite time (DT) operation when the current, I, exceeds 20x setting. Since the ratio 23200/300 > 20, then the operate time will be fixed. The time will be equivalent to an IDMT evaluation at based on a current of

$20 \times I_{Set}$ (252.5)

= 5050A.

So, the operate time for RL1 (calculated using equation (2)) will be

$= (TMS \times 0.14) / (20^{0.02} - 1)$

$= TMS \times 2.267$ s

= 0.15 x 2.267 s = 340 ms.

As will be reported later, this value is confirmed by the simulator output presented in Figure 51, and so is the value used for the grading study.

For a fault at BB1

To grade with RL1, RL2 should operate in with a margin of 400 ms at the grading point (BB1).

The short-circuit current level at BB1 is 23.2 kA (@400 V) ≡ 843 A (@11 kV), and the setting is 64 A (@11 kV).

From equation (2)

$TMS_{RL2} = ((0.4 + 0.34) \times ((843/64)^{0.02} - 1))/0.14$

= 0.279

So chosen TMS_{RL2} is 0.275

With TMS_{RL2} set to 0.275, using equation (2), t_{op} is calculated as 728 ms.

At BB2 the short-circuit current is 3.92 kA (@11 kV), so with TMS_{RL2} = 0.275, using equation (2), RL2 operates in

$0.275 \times 0.14) / (((3920/64)^{0.02}) - 1)$

= 0.449 s

≈ 450 ms

As noted previously, the simulation model of the overcurrent element reverts to definite time (DT) operation when the current exceeds 20x setting. Since the ratio 3920/64 > 20, then the limit will apply.

So, the operate time for RL2 (calculated from equation (2)) will be

= TMS x 2.267 s

= 0.275 x 2.267 s = 623 ms.

For a fault at BB2

To grade with RL2, RL3 should operate in with a margin of 400 ms at the grading point (BB2), so RL3 should operate in 0.623 + 0.400 = 1.023 s.

The short-circuit current level is 3.92 kA (@ 11kV), and the setting is 252 A (@11 kV).

From equation (2)

TMS_{RL3} = (1.023 x ((3920/252.5)$^{0.02}$ – 1))/0.14

= 0.412

So chosen TMS_{RL3} is 0.425

With TMS_{RL3} set to 0.425, using equation (2), t_{op} is calculated as 1.05 s.

At BB3 the short-circuit current is 17.4 kA (@11 kV), so with TMS_{RL3} = 0.425, using equation (2), RL3 should operate in

(0.425 x 0.14) / (((17400/252.5)$^{0.02}$) - 1)

= 0.673

≈ 675 ms

As noted previously, the simulation model of the overcurrent element reverts to definite time (DT) operation when the current exceeds 20x setting. Since the ratio 17400/252.5 > 20, then the limit will apply.

So, the operate time for RL3 (calculated from equation (2)) will be

= TMS x 2.267 s

= 0.425 x 2.267 s = 964 ms.

For a fault at BB3

To grade with RL3, RL4 should operate in with a margin of 400 ms at the grading point (BB3), so RL4 should operate in 0.963 + 0.400 = 1.363 s.

The short-circuit current level is 17.4 kA (@11 kV) ≡ 5800 A (@33 kV), and the setting is 154.5 A (@33 kV).

From equation (2)

TMS_{RL4} $= (1.363 \times ((5800/154.5)^{0.02} - 1))/0.14$

$= 0.732$

So chosen TMS_{RL4} is 0.725

With TMS_{RL4} set to 0.725, t_{op} is calculated as 1.35 s.

As noted previously, the simulation model of the overcurrent element reverts to definite time (DT) operation when the current exceeds 20x setting. Since the ratio 5800/252.5 > 20, then the limit will apply.

So, the operate time for RL4 (using equation (2)) will be

$= TMS \times 2.267$ s

$= 0.725 \times 2.267$ s = 1.64 s.

At BB4 the short-circuit current is 159 kA.

Since the ratio 159000/252.5 > 20, then the operate time will be also be fixed at

$= 0.725 \times 2.267$s = 1.64 s.

As previously noted, these are theoretical values from a simulator. On a real system, a fault level of ≈ 160kA would not be experienced, and certainly such fault levels would not be tolerated for durations of 1.64 s. Design practicalities would restrict current levels to maybe 10% of this, and IDMT relays are likely to be complemented by instantaneous high-set elements to provide rapid clearance for dangerously high fault levels.

For convenience, the calculated relay settings for relays RL1 – RL4 are summarised into the following Table 10.

Table 10: Settings for Configured Radial Distribution Network of Figure 24.

Relay	CT Ratio	*PSM*	I_{Set}	*TMS*
RL1 ($I>1$)	500:5	0.6	300 A	0.15
RL2 ($I>1$)	100:5	0.64	64 A	0.275
RL3 ($I>1$)	250:5	1.01	252.5 A	0.425
RL4 ($I>1$)	150:5	1.03	154.5 A	0.725

8.1.2.2 DIgSILENT Simulator Overcurrent Protection Output Reports used to Benchmark Distribution Network Model

Figure 48 through Figure 55show different network fault scenarios and associated time plots created in DIgSILENT (some annotated to aid clarity), for use in the benchmarking exercise to validate the network model presented in Figure 24.

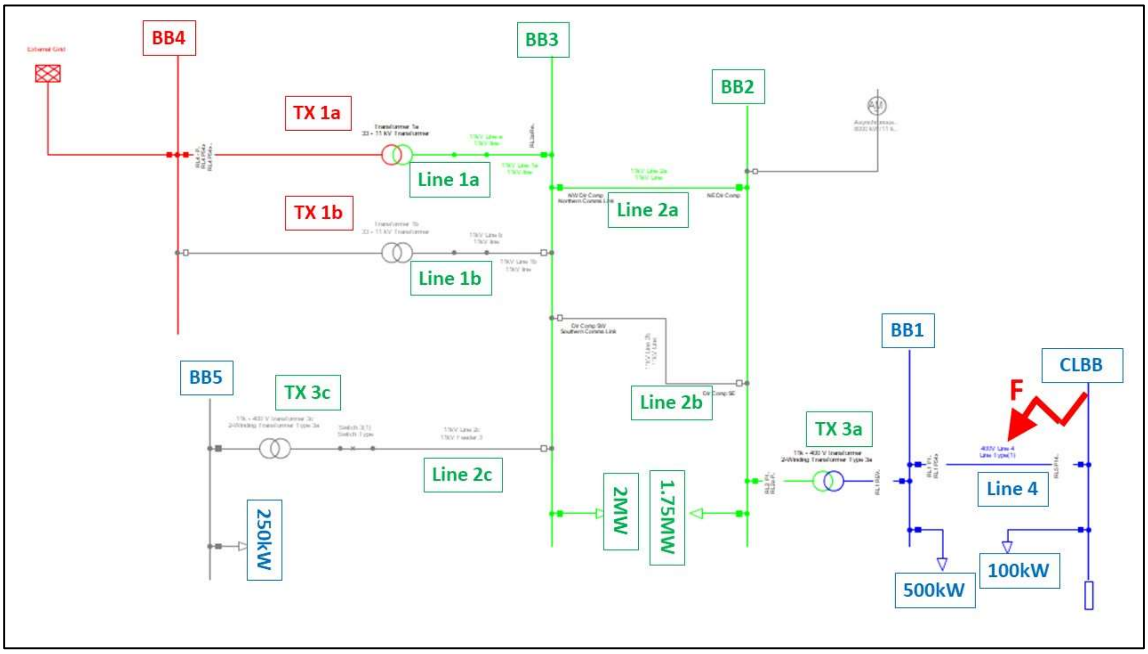


Figure 48: Network Diagram Illustrating Benchmark Short-Circuit Fault Simulation at CLBB.

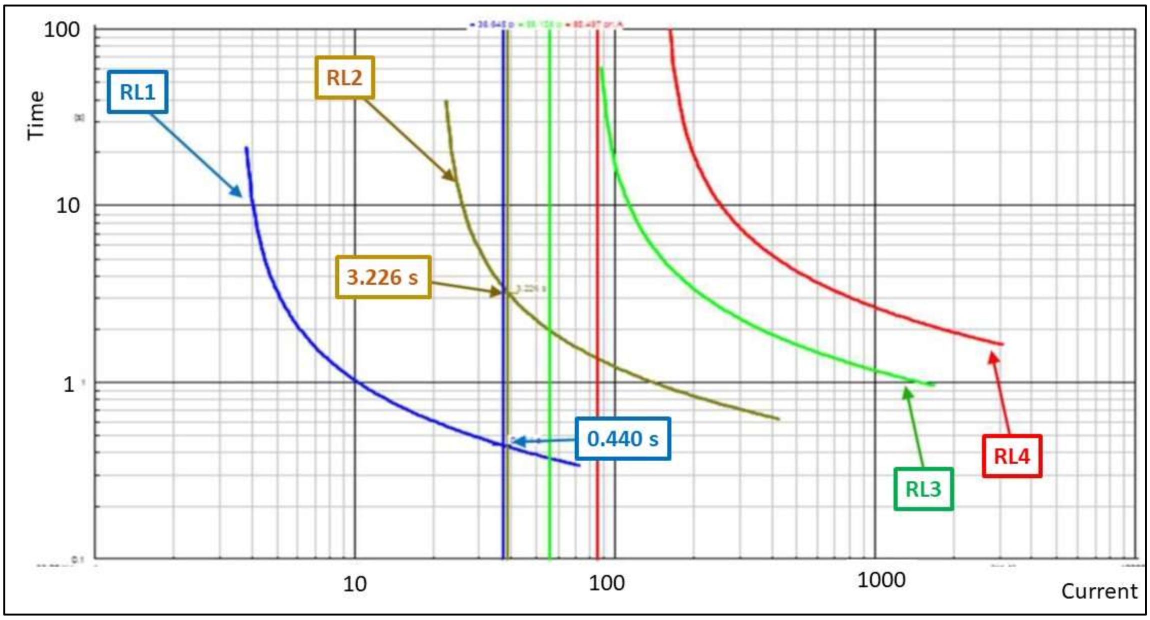


Figure 49: Time-Overcurrent Plot for Benchmark Simulated Short-Circuit Fault at CLBB.

Figure 49 shows that RL1 operates in 444 ms for a short circuit fault at CLBB. This confirms the value calculated for a TMS_{RL1} setting of 0.15.

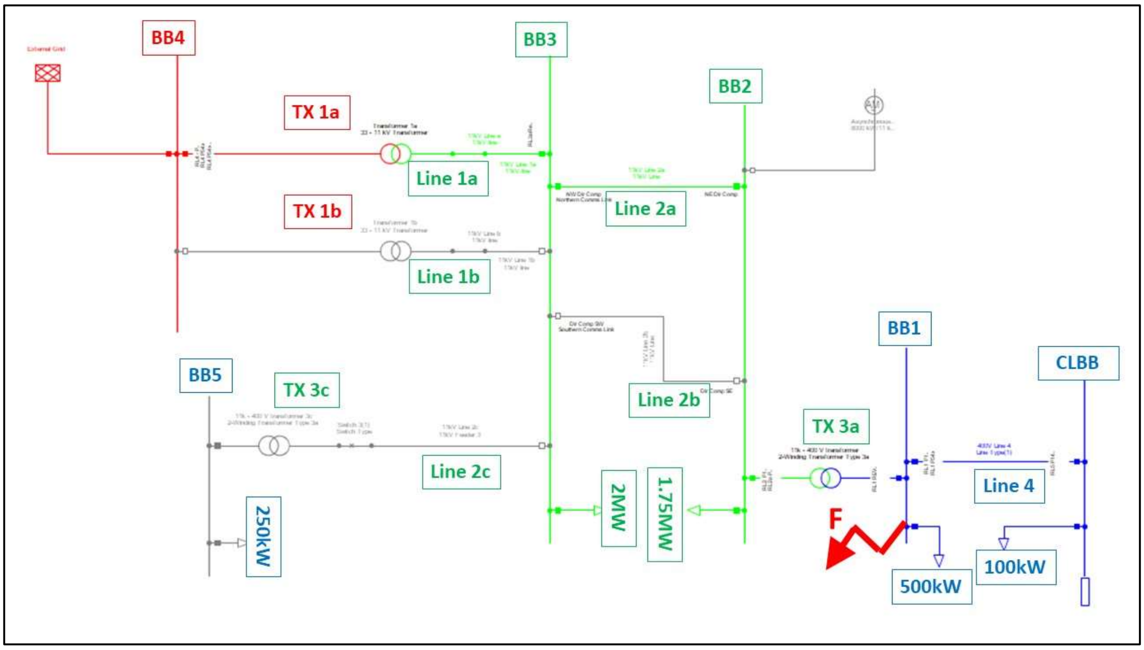


Figure 50: Network Diagram Illustrating Benchmark Short-Circuit Fault Simulation at BB1.

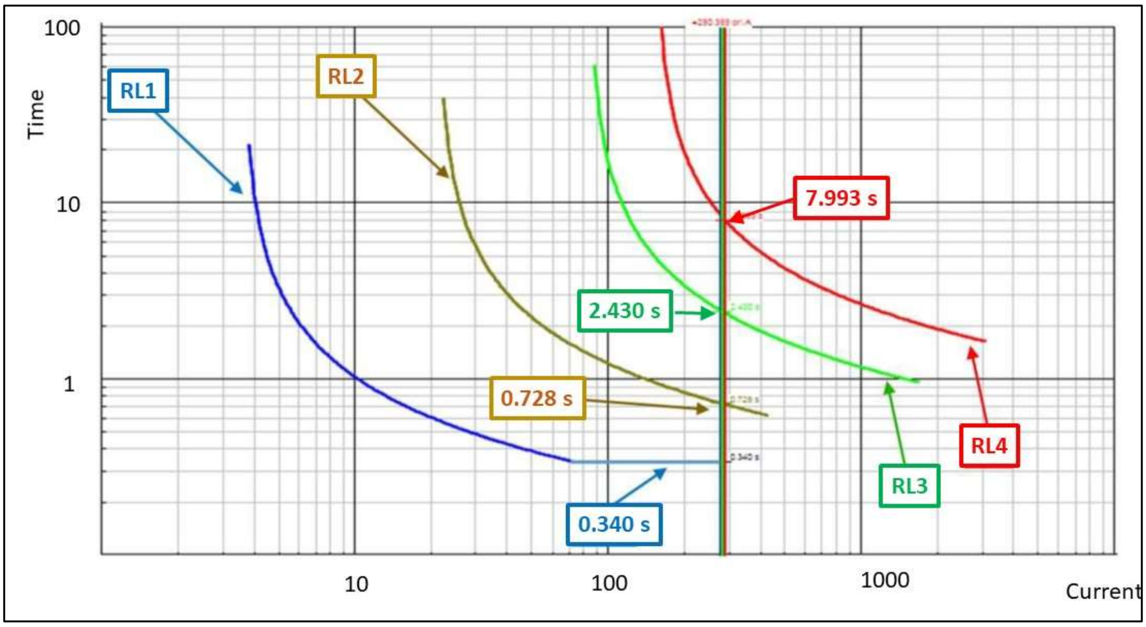


Figure 51: Time-Overcurrent Plot for Benchmark Simulated Short-Circuit Fault at BB1.

Figure 51 shows that RL1 operates in 340 ms for a short circuit fault at BB1. This confirms the value calculated for a TMS_{RL1} setting of 0.15. The figure also shows that RL2 operates in 728 ms, also confirming the calculated value obtained for a TMS_{RL2} setting of 0.275.

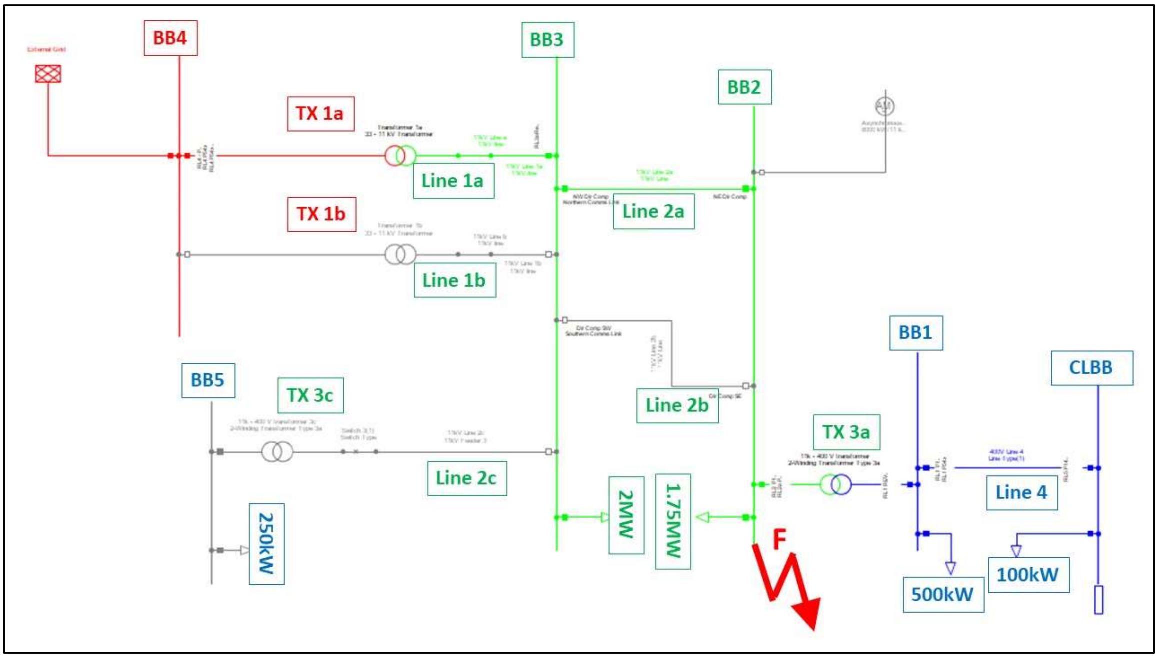


Figure 52: Network Diagram Illustrating Benchmark Short-Circuit Fault Simulation at BB2.

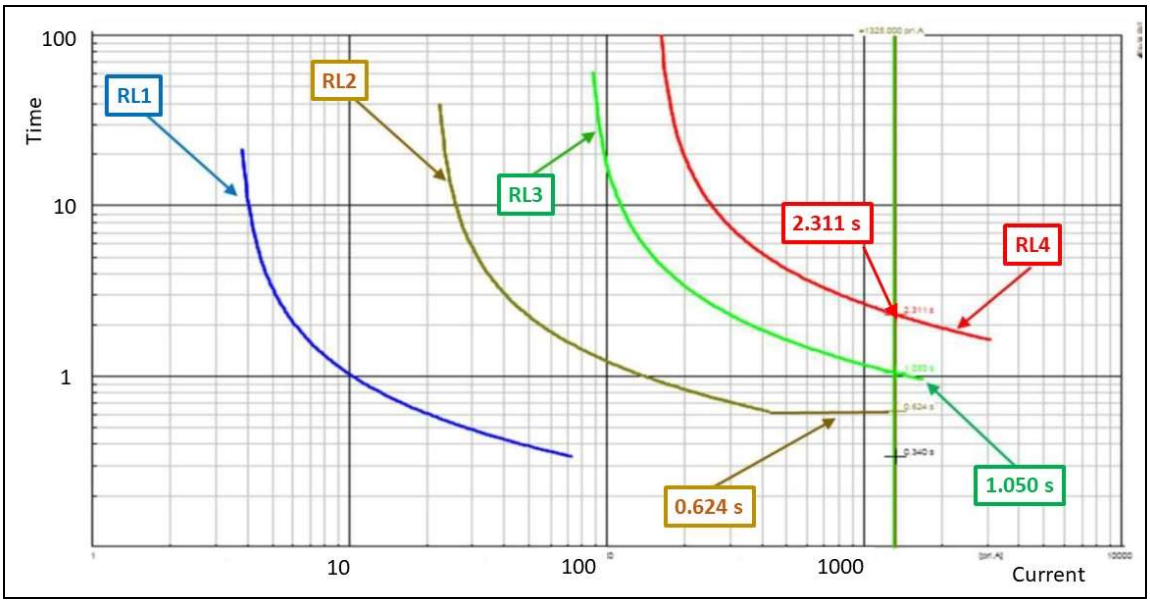


Figure 53: Time-Overcurrent Plot for Benchmark Simulated Short-Circuit Fault at BB2.

Figure 53 shows that RL2 operates in 624ms for a short circuit fault at BB2. This confirms the value calculated for a *TMS*_{RL2} setting of 0.275. The figure also shows that RL3 operates in 1.05s, also confirming the calculated value obtained for a *TMS*_{RL3} setting of 0.425.

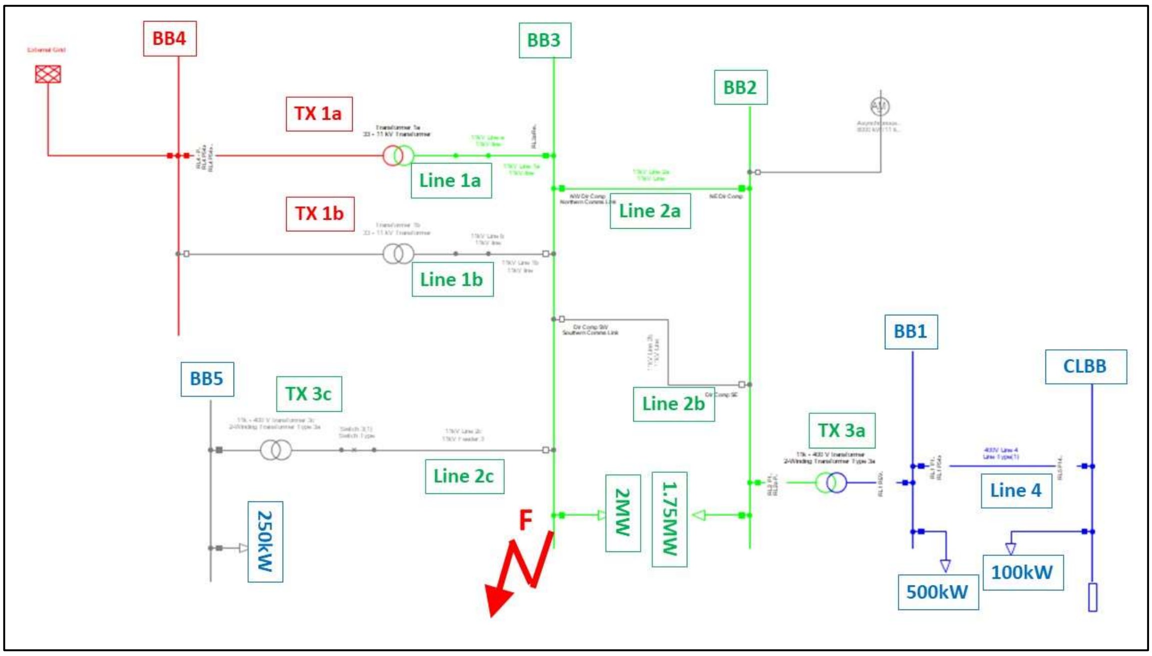


Figure 54: Network Diagram Illustrating Benchmark Short-Circuit Fault Simulation at BB3.

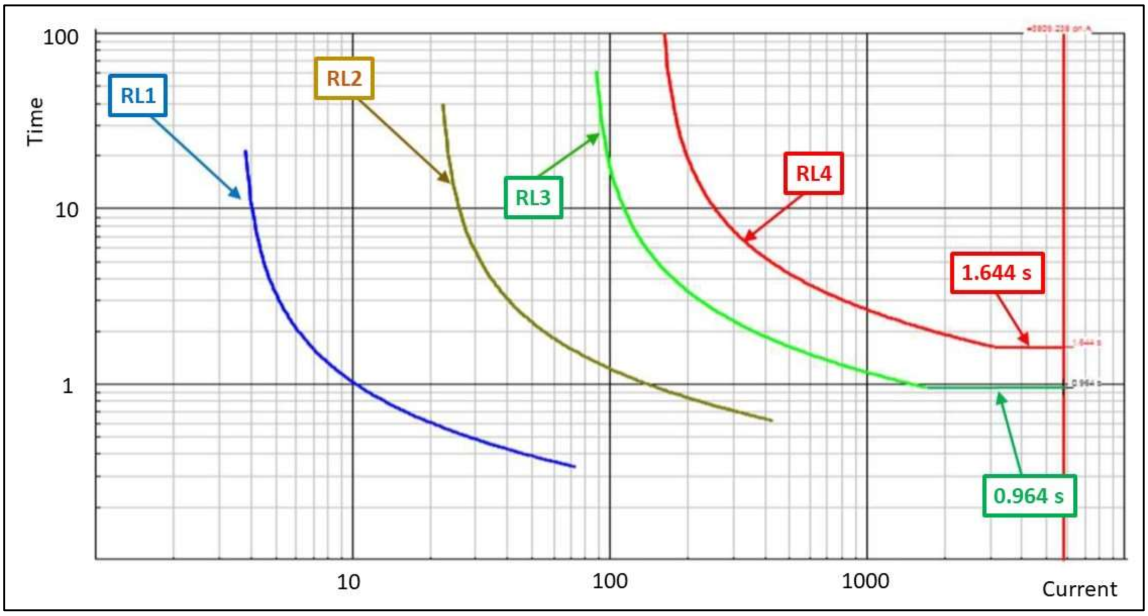


Figure 55: Time-Overcurrent Plot for Benchmark Simulated Short-Circuit Fault at BB3.

Figure 55 shows that RL3 operates in 964 ms for a short circuit fault at BB2. This confirms the value calculated for a TMS_{RL3} setting of 0.425. The figure also shows that RL4 operates in 1.64 s, also confirming the calculated value obtained for a TMS_{RL4} setting of 0.725.

8.1.2.3 Comparison of *IN>1* and *ISEF>1* Elements Results for Benchmark Model

This testing is performed on RL1 which protects the connected 4-wire 400 V system. By connecting the 'CoreCt' input to measure the current in the neutral circuit, a measurement of neutral current will stimulate the *ISEF>* input of the simulation model. If correctly connected, configured, and appropriately set, and understood, performance of the *IN>1* element compared with that of the *ISEF>1* element can be used to demonstrate correctness of the connection and configuration. Operation to demonstrate correct connection and configuration is established by application of severe single-phase-to-neutral faults with the relaying elements configured as follows:-

- The first stage of overcurrent of each element is used (*IN>1*, *ISEF>1*).
- For convenience, DT characteristics are chosen for both.
- Time settings are set at:-

    - instantaneous (*IN>1*) and
    - 100ms (*ISEF>1*)
- Applied current setting values need to be different for the different elements because of the different input quantities.
    - Since the *IN>1* element uses currents derived from phase currents, under single-phase short circuit conditions the imbalance will tend towards the phase current and so current settings for the *IN>1* element should be similar to those of the phase elements.
    - Concerning the *ISEF>1* element they will be lower.

Expected operation of the elements, against which performance should be verified is:-

(i) For a single-phase-neutral fault

The neutral current should be approximately the same as in the faulted phase element.

No earth loop is involved in the fault current path and so all imbalance current should flow in the neutral current circuit.

- The true neutral current should be measured by the *ISEF>1* element.
- The *IN>1* element should measure the phase imbalance.

For a single-phase to neutral fault, these should both be approximately the same and should approximate to the phase current. The expected relay operation should, therefore, be

I>1 TRIP,

IN>1 TRIP,

ISEF>1 TRIP.

(ii) For a single-phase-earth fault

The performance of the *IN>* and *ISEF>* elements differ according to the earthing paths in the fault current circuit. The earthing paths are affected by the earthing of the system transformer. For this exercise, the transformer secondary supplying the load circuits is of star/wye/Y winding. The neutral point of the transformer winding can either be isolated, solidly earthed, or earthed via a suitable 1 Ω resistor.

The simulator model can be used to demonstrate typical current values associated with earth-faults and hence guide current setting selection. Consider the following Figure 56 which shows the fault currents associated with a short-circuit single-phase-to-earth fault at CLBB.

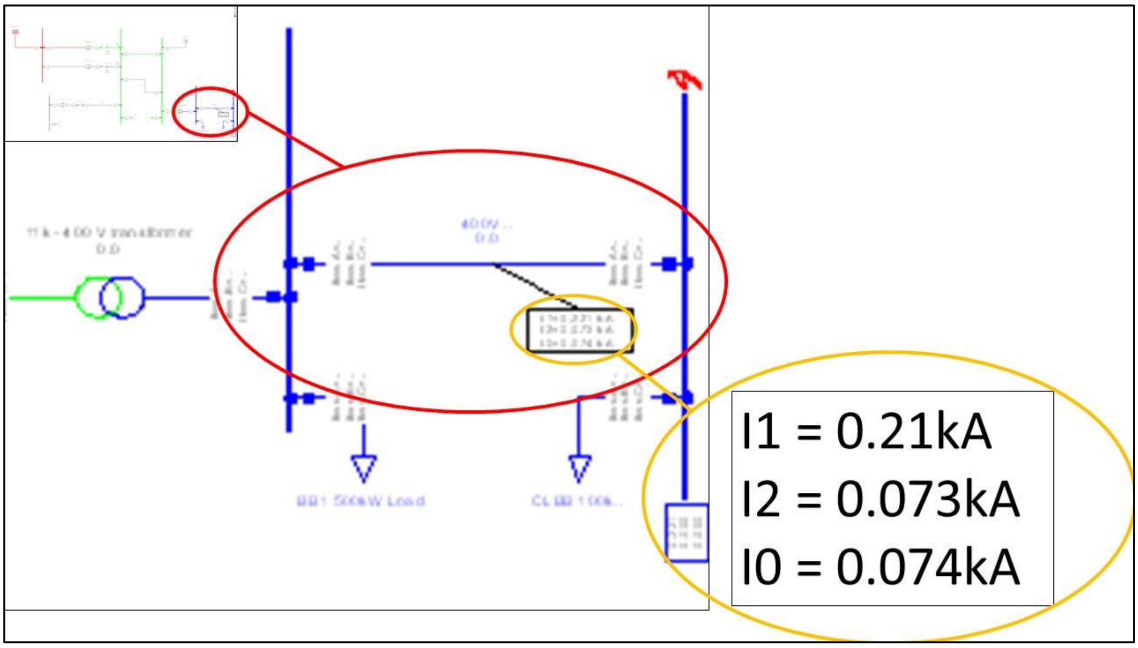


Figure 56: Current Measurement for Benchmark Simulated Single-Phase-Earth Short-Circuit Fault at CLBB.

Using the fault current rule-of-thumb of equation (1) for setting overcurrent protection, from Figure 56, it can be reasoned that an overcurrent element for *ISEF>1* with a setting above 100 A would be appropriate. 150 A is chosen to provide separation from load current values.

Since the neutral elements (*IN*>) of the P545 are derived from the phase measurements (*I*>), it should be clear that whatever CT ratios and settings are chosen for the phase elements, similar should apply to the derived neutral elements. For the phase elements (*I*>) and the neutral elements (*IN*>) of the P545, the current setting ranges are 0.08 – 4.00 (step) 0.1. So, with a CT ratio of 500:5 A, a target value of 300 A can be set for *IN>1*.

The setting range of the SEF input, however, is limited to 0.005 – 0.1, step 0.0025 so that, with a 500:5 A CT, 100 A cannot be set. Choosing a CT with a ratio of

5000:5 changes the target value to 0.030 which allows a 150 A setting for the *ISEF>1* element.

For the exercise, *ISEF>1* is configured as DT with a CT ratio of 5000:5 (via *CoreCt* input), a current setting of 0.030 (150 A) and an arbitrary time setting of 100 ms. *IN>1* is configured as DT with a CT ratio of 500:5 (via Ct input), a current setting of 0.6 (300 A) and instantaneous operation. In summary, the *IN>1* and the *ISEF>1* elements are set as per the following Table 11 for the benchmark verification exercise.

Table 11: *IN>1* and *ISEF>1* settings for benchmark exercise.

Relay	CT Ratio	*PSM*	I_{Set}	*TMS*
RL1 (*IN>1*)	500:5	0.6	300 A	0
RL1 (*ISEF>1*)	5000:5	0.03	150 A	0.1

A summary of the protection operation for the three scenarios (solidly-earthed, isolated, and resistance-earthed) is summarised in the following three subsections (8.1.2.3.1 - 8.1.2.3.3).

8.1.2.3.1 *IN>* and *ISEF>* Operation for the Single-Phase-to-Earth Fault with a Solidly-Earthed Transformer

In this case (as described in Figure 34), the true neutral current should be close to zero since the fault current should be flowing via earth not via neutral. The true neutral current should be measured by the *ISEF>1* input. The *IN>1* element should measure the phase imbalance which in this case should be equivalent to the earth fault current.

So, in summary, for the case of a phase-earth fault, with a solidly earthed transformer, the phase element (I>1) should measure fault current, the neutral element (*IN>1*) should measure phase imbalance and the SEF element should measure true neutral current (nominally zero). The relay operation should, therefore be

I>1 TRIP,

IN>1 TRIP,

ISEF>1 No operation.

This is clearly illustrated in the following Figure 57.

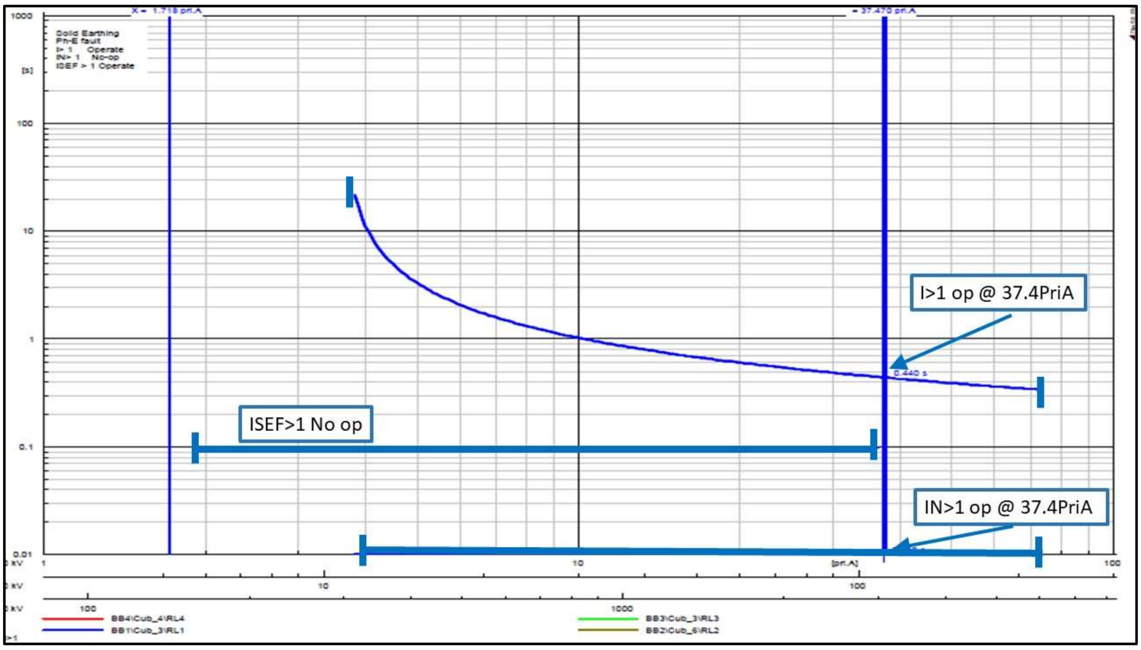


Figure 57: Overcurrent Operation for Single-Phase-Earth Fault Current Scenario with Solidly-Earthed Transformer.

The operation illustrated in Figure 57 confirms the expected operation and verifies both the understanding of the network model with respect to neutral current simulation, and connection and configuration of the relay simulation model with respect to *IN*> and *ISEF*> operation for this case.

8.1.2.3.2 IN> and *ISEF*> Operation for the Single-Phase-to-Earth Fault with Isolated (Un-Earthed) Transformer

In this case presented in Figure 35 with no earth path in the current loop, there is no imbalance, and the phase currents will maintain balanced load. So, provided the balanced phase currents remain below setting, none of the elements should operate. This is clearly illustrated in the following Figure 58.

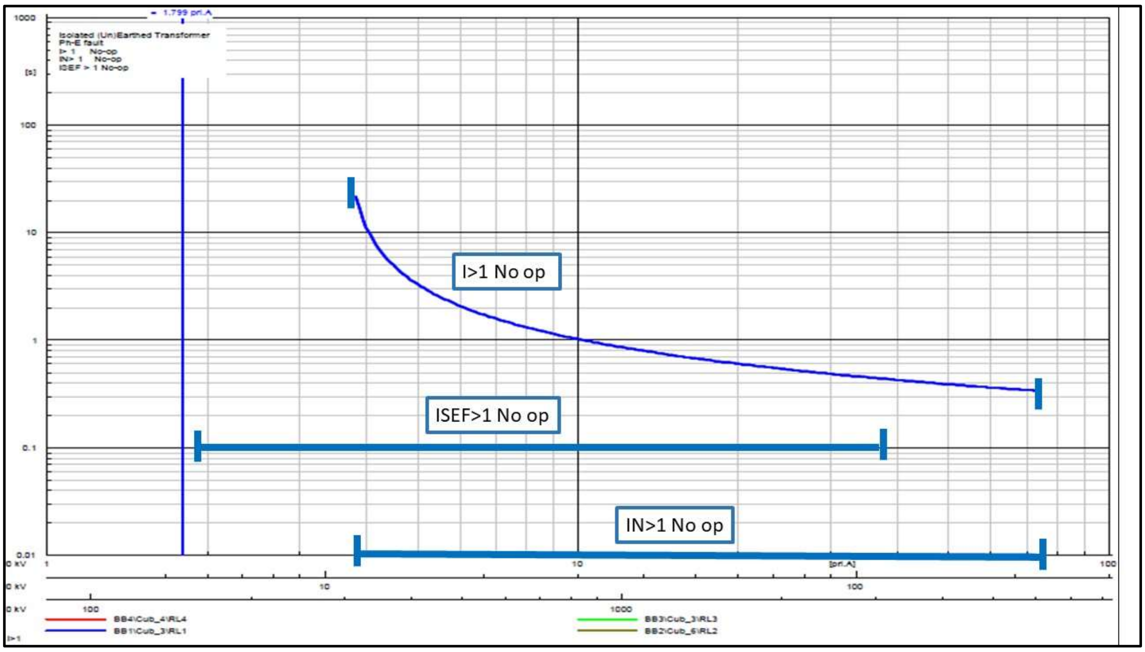


Figure 58: Overcurrent Operation for Single-phase-earth Fault Current Scenario with Isolated (Un-Earthed) Transformer.

The operation illustrated in Figure 58 confirms the expected operation and verifies both the understanding of the network model with respect to neutral current simulation, and connection and configuration of the relay simulation model with respect to *IN*> and *ISEF*> operation for this case.

8.1.2.3.3 *IN*> and *ISEF*> Operation for the Single-Phase-to-Earth Fault with Resistance-Earthed Transformer

In this case illustrated in Figure 36, the true neutral current (measured by the SEF input in this case) is described by a relationship between the imbalance ratio and the imbalance magnitude. The imbalance increases as the resistance decreases, whereas as the resistance increases, the magnitude decreases. The relationship is therefore complex. A resistance value of 1 Ω is typically used in the UK. This value is chosen since it limits the earth fault value to approximately 60% of the phase current value. Selecting a 1 Ω resistance value, the performance of the protection elements are as illustrated in the following Figure 59.

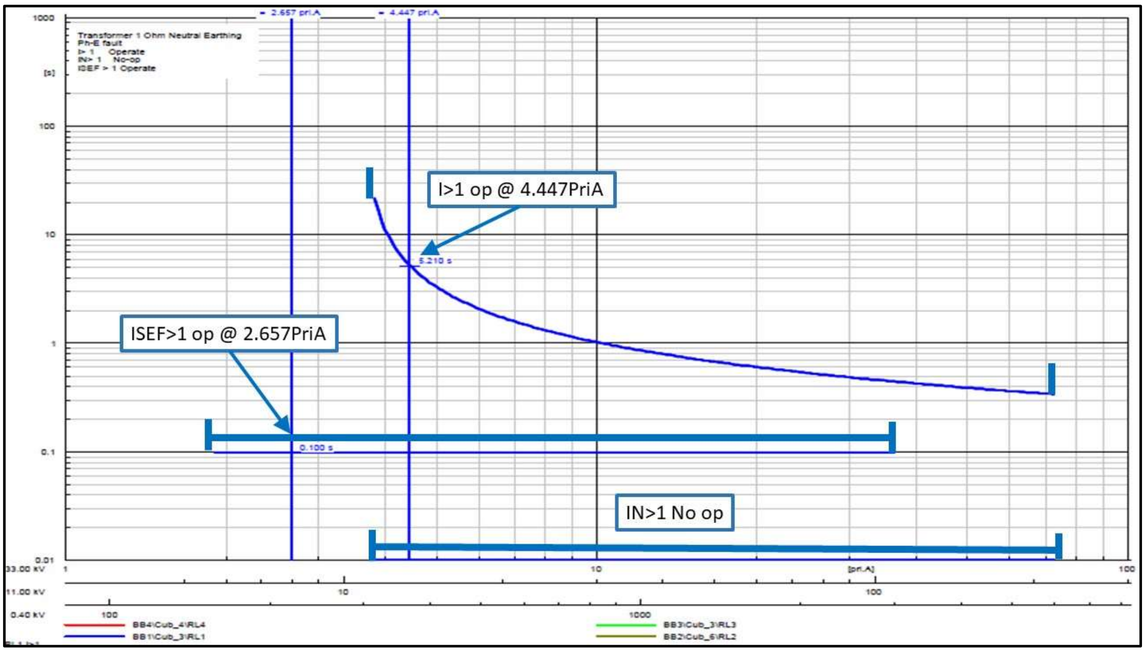


Figure 59: Overcurrent Operation for Single-Phase-Earth Fault Current Scenario for 1Ω Resistance-Earthed Transformer.

Figure 59 shows the operation of the *ISEF>1* and *I>1* elements which are as expected. Also, as expected, *IN>1* does not operate. *ISEF>1* operates at approximately 220 A @ 400 V (≡2.657 A @primary level).

I>1 elements operate at approximately 367 A @400 V (≡4.447 A @primary level).

Inclusion of the earthing resistor limits the earth fault current value to 2.657/4.447 (approximately 60%) of the phase current value as expected.

The operation illustrated in Figure 59 confirms the expected operation and verifies both the understanding of the network model with respect to neutral current simulation, and connection and configuration of the relay simulation model with respect to *IN>* and *ISEF>* operation for this case

8.1.2.3.4 Summary of *IN>* and *ISEF>* Verification of the Network Model

Simulation model performance of the overcurrent elements in the cases examined in section 8.1.2.3 (and included subsections) is in line with predicted performance. With that agreement, the objective of this suite of tests to further verify the network model and to demonstrate understanding of the differences in operation of alternatively stimulated neutral-current measuring protection elements is successfully met and concluded.

8.1.2.4 Fault Sequence Reports for Benchmark Model Performance

Application of a suitable fault sequence and analysis of protection performance provides final verification of the validity of the network model and the correctness of the applying protection models.

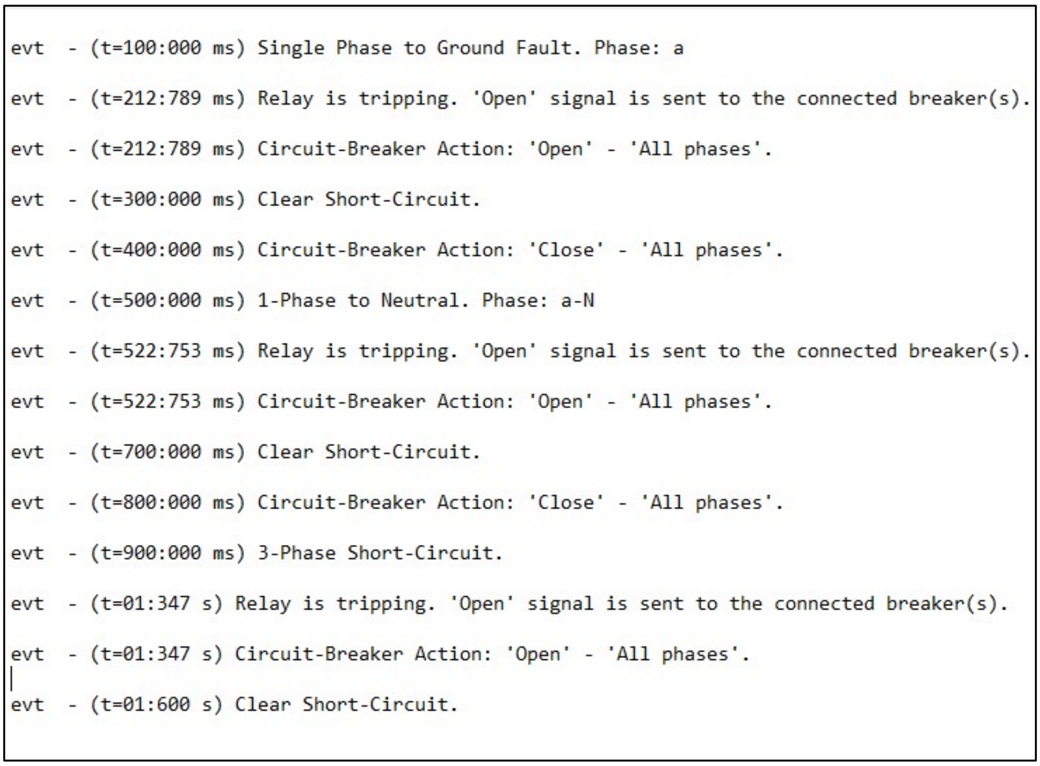
The following sequence of faults is applied to the network for evaluation using the DIgSILENT fault sequencer:-

1. Single-phase to earth fault, followed by
2. Single-phase to neutral fault, followed by
3. Three-phase short-circuit.

The following Figure 60 and Figure 61 illustrate the sequence.

The screenshot presented as Figure 60 provides a (contracted) self-explanatory summary of the events created to generate the fault sequence at the consumer load busbar, CLBB, on the network model described by Figure 24. The faults stimulate the protection provided by RL1.

Figure 61 shows the corresponding system waveforms, demonstrating the protection performance. Note that this figure is provided to illustrate the relay operation. It is not provided to display precise waveform values. Rather, it is the ON/OFF nature of the signals that has significance in reflecting the relay performance.



```
evt  - (t=100:000 ms) Single Phase to Ground Fault. Phase: a

evt  - (t=212:789 ms) Relay is tripping. 'Open' signal is sent to the connected breaker(s).

evt  - (t=212:789 ms) Circuit-Breaker Action: 'Open' - 'All phases'.

evt  - (t=300:000 ms) Clear Short-Circuit.

evt  - (t=400:000 ms) Circuit-Breaker Action: 'Close' - 'All phases'.

evt  - (t=500:000 ms) 1-Phase to Neutral. Phase: a-N

evt  - (t=522:753 ms) Relay is tripping. 'Open' signal is sent to the connected breaker(s).

evt  - (t=522:753 ms) Circuit-Breaker Action: 'Open' - 'All phases'.

evt  - (t=700:000 ms) Clear Short-Circuit.

evt  - (t=800:000 ms) Circuit-Breaker Action: 'Close' - 'All phases'.

evt  - (t=900:000 ms) 3-Phase Short-Circuit.

evt  - (t=01:347 s) Relay is tripping. 'Open' signal is sent to the connected breaker(s).

evt  - (t=01:347 s) Circuit-Breaker Action: 'Open' - 'All phases'.

evt  - (t=01:600 s) Clear Short-Circuit.
```

Figure 60: Events Defining DIgSILENT Example Fault Sequence for Generic Network Benchmark Exercise.

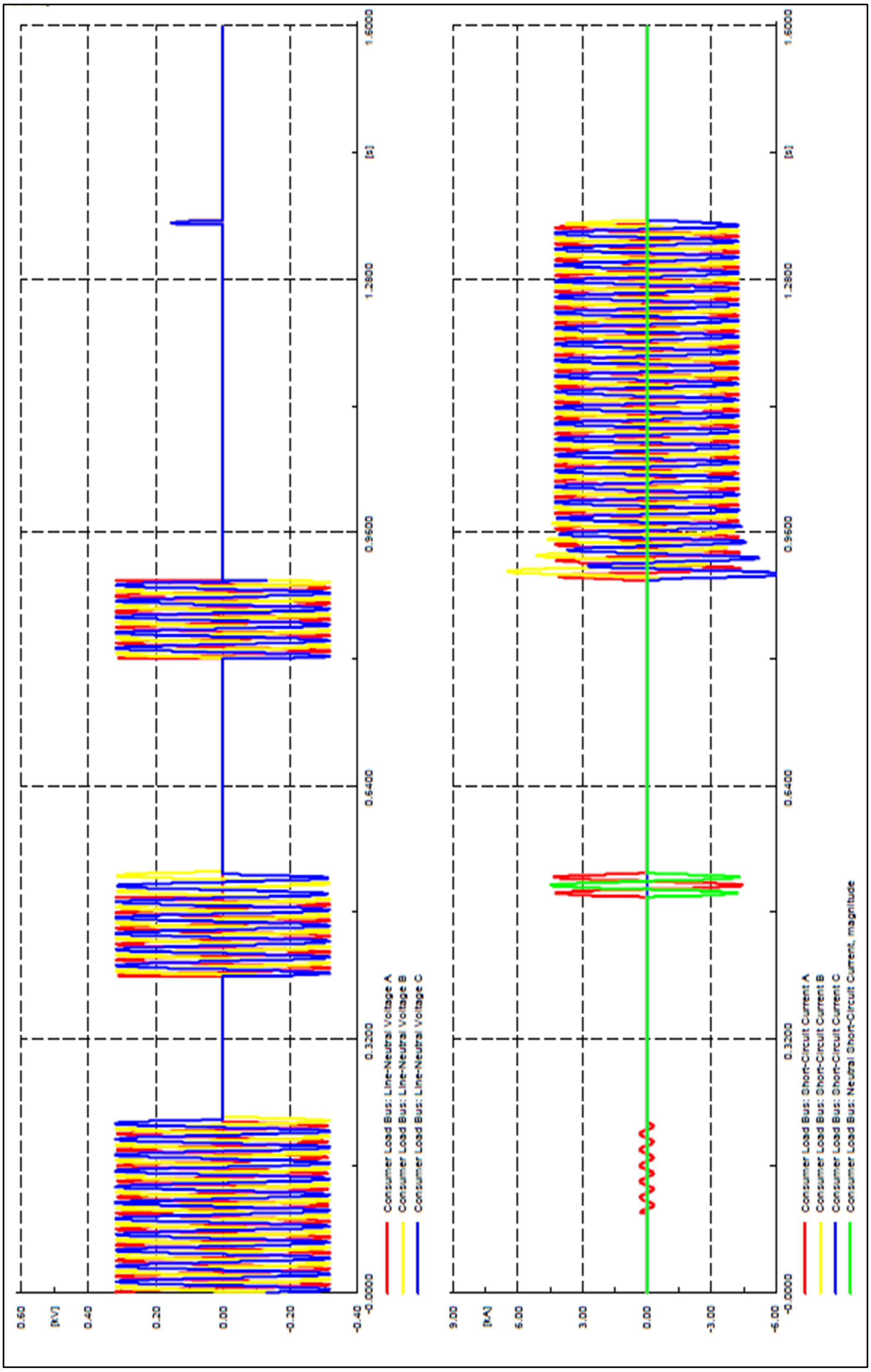
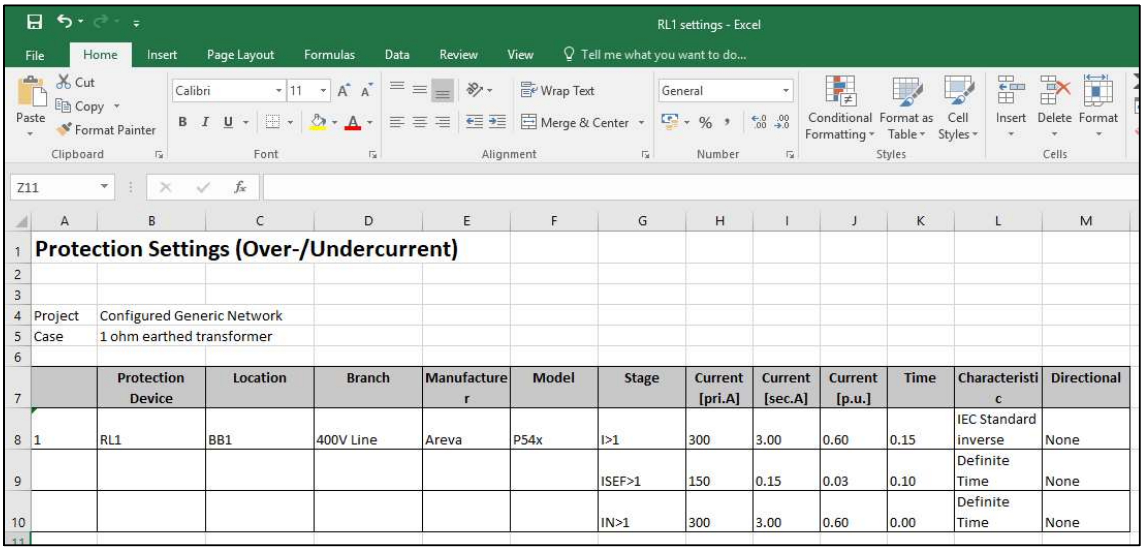


Figure 61: DIgSILENT Example Fault Sequence for Generic Network Benchmark Exercise.

For the exercise, the generic network is configured as per the benchmarking exercise with a 1Ω resistor earthing the 400V transformer neutral. The chosen value was based on a rule of thumb - 'The 1 Ohm Rule'. Whilst this rule is now recognised as being out of date [128], 1 Ω remains the value that was used for testing. The network zone enclosing CLBB is protected by RL1. The applied settings are as described previously. For convenience, and completeness, the final settings applied to RL1 are exported from the DIgSILENT model and are summarised in the following Figure 62.



Protection Settings (Over-/Undercurrent)

Project Configured Generic Network
Case 1 ohm earthed transformer

	Protection Device	Location	Branch	Manufacturer	Model	Stage	Current [pri.A]	Current [sec.A]	Current [p.u.]	Time	Characteristic	Directional
1	RL1	BB1	400V Line	Areva	P54x	I>1	300	3.00	0.60	0.15	IEC Standard inverse	None
						ISEF>1	150	0.15	0.03	0.10	Definite Time	None
						IN>1	300	3.00	0.60	0.00	Definite Time	None

Figure 62: Benchmark Overcurrent Settings Extracted from DIgSILENT Simulator.

Considering the protection settings applied, it should be clear that for a fault affecting all elements

- *IN>1* would trip first (instantaneously) followed by
- *ISEF>1* with a (Definite Time) delay of 100 ms, followed by
- *I>1* with a (IDMT) delay appropriate to a *TMS* of 150%

This time-grading of elements can be used to distinguish operations.

The response of the relay RL1 protecting against simulated faults at the consumer load busbar, CLBB, according to the sequence defined by Figure 60 is presented in Figure 61 and characterised by

- At t=100 ms, A-E fault is applied

- At t=213 ms RL1 operates. It is confirmed as *ISEF>1* since the operating time is approximately 100 ms. *I>1* has the potential to operate (in approximately 5.2 s, but is pre-empted by *ISEF>1*
- At t=500 ms, A-N fault is applied
- At t=522 ms RL1 operates. It is confirmed as *IN>1* since the operating time is instantaneous (22 ms). *I>1* has the potential to operate (in approximately 0.44 s, but is pre-empted by *IN>1*
- At t=900 ms, 3-ph fault is applied
- At t=1.35 s RL1 operates. It is confirmed as *I>1* due to the operating time of approximately 0.45 s.

The sequence of events confirms the predicted behaviour and serves to validate the configured generic network.

It should be recognised that a (rather lengthy) iterative process was involved to conclude in a correctly configured network and associated network protection scheme. The importance of checking results from the simulator against expected outputs to verify a simulation model before using the model to evaluate new ideas is highlighted by the necessity for these iterations.

8.1.3 Distribution Network Model Verification Summary

A benchmarking exercise involving the application of overcurrent elements provided by simulated MiCOM P545 relays has been undertaken in the development of a distribution network model within a DIgSILENT PowerFactory environment.

Many iterations of the DIgSILENT model were required before a convergence between these results and the simulation results was observed. For the author, it has provided a useful, demanding exposure to, and experience of, the tool. It has demonstrated the importance of verifying the performance of a simulation model to understand its behaviour before accepting its worth as a valid tool to further investigate system performance.

The model developed is now considered sufficiently developed, verified, and proven to be eligible to serve as a platform for the evaluation of directional techniques for the protection of smart electrical distribution networks.

8.1.4 Directional Protection Testing Results of Using the DIgSILENT Distribution Network Model to Evaluate Different Protection Techniques

Having been suitably verified and qualified in a benchmark configuration, the generic network simulation model of Figure 24 is considered appropriate to evaluate the performance of Directional Agents.

8.1.4.1 Results of Applying Directional Overcurrent Protection to Passive Radial Distribution Networks

The objective of this exercise is to introduce directional protection into the simulation model and to confirm correct connection of VT and CT inputs by verifying directional operation.

The overcurrent protection used to benchmark the configured distribution network model is swapped for directional overcurrent protection. The performance of the directional overcurrent protection is evaluated using the DIgSILENT network model presented in Figure 24.

As for the previous model verification exercise, overcurrent elements in the MiCOM P545 devices were used. These overcurrent elements can be set as non-directional (as was used previously), or as directional 'FORWARD' or directional 'REVERSE' (as are the intended cases here).

To provide the directional dimension to the protection a so-called polarising quantity is needed to act as a reference for the directional qualification. So, for the overcurrent elements to provide directional tripping, they must be set for the appropriate direction of operation (forward, reverse, or non-directional) and the appropriate polarising signal must be correctly presented.

In this part of the exercise, the influences of the polarising technique are not being evaluated, and it is sufficient to use the default phase polarising signals and characteristic settings provided by the protection element. On the three-phase protection elements used here, polarisation involves making a conventional (three-phase voltage) connection between the line VTs and the protection VT inputs. Within DIgSILENT this is achieved by assigning a VT connection to the relay model in a similar manner to that described previously for making the CT connections (refer Figure 31 and Figure 32).

Referring to the network model presented in Figure 24, to check the directional functionality, three-phase measurement VTs (11 kV:110 V) are assigned as protection VT inputs to the MiCOM P545 relays. The relays are configured to match the CT and VT input connections and the overcurrent elements are set for FORWARD operation (in the sense of forward meaning looking towards the load from the source on a radial network. A suitable fault applied at F2 should appear in the forward direction for relay RL2 (connected at BB2) so that RL2 should initiate tripping if set to non-directional or directional forward, but should not operate if set to directional reverse.

Such a fault was applied. Whilst the protection operated when set to non-directional (as expected), and did not operate for reverse operation (as expected), when set to operate for forward faults, it failed to operate.

This was not as expected.

The unexpected result warranted investigation/explanation before progressing. This is provided in the following section 8.1.4.1.1.

8.1.4.1.1 Unexpected Results of Applying Directional Overcurrent Protection to Passive Radial Distribution Networks with MiCOM P545 Relays

When being used to evaluate directional protection on the verified test platform, a DIgSILENT simulation model of a MiCOM P545 relay failed to trip as expected. Since the intention had been to use the simulation model of the P545 as a Directional Agent with the verified test platform, for performance evaluation of directional comparison unit protection scheme, it is clear that the reason for the unexpected behaviour needs to be established, and appropriate action taken, before the evaluation continues.

Limited access to laboratory space and resources, makes ‘fault finding’ for such unexpected scenarios difficult. After investigation, involving significant help from DIgSILENT Technical Support Service, the following issues, critical to the Directional Agents’ study are noted.

- Applied as an ‘off-the-shelf’ model (i.e., in the default configuration), the overcurrent elements of the DIgSILENT simulation model of the MiCOM P545 relays applied to the network described by Figure 24, do not respond as anticipated for a fault applied at F2.
- With the same default configuration of the MiCOM P545 model, as well as the directional overcurrent elements, the distance elements did not work as anticipated either.

- Applied as an 'off-the-shelf' model (i.e. in the default configuration), the distance elements of the DIgSILENT simulation model of an SEL 421 relay did work as anticipated.
- Correct operation of the SEL 421 was taken as indication that the method of connecting the VTs was correct.
- Applied as an 'off-the-shelf' model (i.e. in the default configuration), the overcurrent elements of the DIgSILENT simulation model of a MiCOM P141 relay also worked as anticipated.
- Correct operation of the MiCOM P141 was also taken as verification that the VT connections were correct, that directionality was being exhibited, and that the problem lay either with the implementation, or application, of directionality in the P545 model.
- DIgSILENT relay simulation models are constructed from standard DIgSILENT simulation library components.

Whilst a support ticket concerning the issues with the P545 was raised against DIgSILENT for investigation, in order to progress with the research, a decision was taken to try to use a different protection device to the preferred MiCOM P545. The original device selection was influenced by the fact that the MiCOM P545 device has both conventional directional overcurrent elements and, the somewhat less widely applied, directional comparison protection elements based on (Delta) Superimposed Components. Noting that the MiCOM P443/P446 relays also feature the (delta) directional comparison protection elements, the use of these was investigated. MiCOM P44x distance protection devices are a range of devices which employ two distinct and different impedance measuring techniques. The P441, P442, and P444 use a convergent numerical technique to determine impedance values and hence determine in-zone/out-of-zone conditions. The P443 and P446 employ phase comparator elements (similar to those used in conventional analogue distance protection devices) to differentiate in-zone/out-of-zone conditions. The phase comparison method employed in P443/P446 lends itself to producing the superimposed (delta) components used in the directional comparison elements. The implementation of the P441/P442/P444 does not, and so delta directional comparison is not provided by these devices.

Investigation into the DIgSILENT P40 distance protection simulation models (including P443 and P446) reveals that they are based on the P441/P442/P444 variants, and hence do not afford the opportunity to evaluate the delta directional comparison elements. A check on the DIgSILENT implementation of the P14x Feeder Management relays confirmed that directional overcurrent elements are included in the simulation model. The DIgSILENT simulation model for the MiCOM P141 is built from the standard library and provides a directional element that could be used for some of the intended evaluation. Noting that the model of MiCOM P141 relay uses standard library components to realise overcurrent and directional functionality, and that this functionality is required to evaluate the implementation of Directional Agents (and hence directional comparison unit protection), then, in the interests of efficacy, it was decided to temporarily use MiCOM P141 models in place of MiCOM P545 models. Pending resolution of the issues with the MiCOM P545 models[6], MiCOM P141 models replace them as test vehicles.

Whilst the support ticket raised against DIgSILENT, was investigated, the models of MiCOM P545 protecting the test network were replaced with MiCOM P141 (similar overcurrent protection to P545 but without distance, differential, and (delta) superimposed directional comparison protection).

The directionality tests, which had originally started with the MiCOM P545 models, resumed and concluded as expected using the replacement MiCOM P141 models. Accordingly, it is determined that the deployment of simulated MiCOM P141 relays on the test network of Figure 24.

- Demonstrate correct connection of the relays, in order to
- Demonstrate correct directional overcurrent operation

The latter was confirmed by setting the $I>1$ element of RL2 in turn to

- Non-directional
- Directional FORWARD
- Directional REVERSE

And observing correct fault responses to stimuli designed to provoke

- Operation for (forward) fault F2 when set ‘non-directional’
- Operation for (forward) fault F2 when set ‘FORWARD’
- Restraint (no operation) for (forward) fault F2 when set ‘REVERSE’

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[6] It was subsequently determined that the implementation of directionality in the P141 and P545 are similar. Principal difference is in the internal configuration of the protection kernels. Further issues arising later with DIgSILENT relay simulation models (refer 7.1.4.3), led to a decision to create a bespoke Directional Agent model. Commonality of library component building blocks however, affords these tests ongoing validity and they are not subsequently repeated.

Thus, the exercise has confirmed the capability for the selected MiCOM P141 simulation relays (built from standard DIgSILENT library model components) to provide directional overcurrent protection on a radial feeder network. By complement, the network is confirmed to appropriately simulate suitable faults to stimulate correctly designed directional overcurrent protection.

8.1.4.2 Results of Applying Directional Overcurrent Protection to Active Distribution Networks featuring Embedded Generation (Windfarm)

The generic network model that had previously being configured as a passive radial distribution network is now reconfigured as an active network for testing. The intention being to demonstrate that directional principles can be selective for fault detection for changing directionality of power flows across the network such as might be caused by the integration of embedded generation (windfarm) into the network. Note the intended purpose to demonstrate the selectivity of the directional principles. Time-delayed overcurrent characteristics are used in this project to provide a common performance reference across different tests. This coordinated time-delayed overcurrent protection is not being proposed as the most effective means to protect this network. Operating times and fault levels are excessive in many cases. The unrealistic nature of some of these values is recognised. They are accepted as a consequence of applying a ‘one-size-fits-all’ approach to protection across such a network. Although lacking in realism, the approach is useful for illustration purposes since it exaggerates operation, and clearly highlights desirable responses.

The configured network model shown in Figure 24 is now reconfigured to allow protection for the effects of connecting a source of embedded generation (windfarm) at BB2. To provide the necessary additional protection, extra directional relays are added as shown in Figure 38.

As shown in Figure 38, directional overcurrent protection is provided for an 11kV ‘ring’ zone bounded by four MiCOM P141. This extra protection is in the form of four relays. Using compass sub-ordinal points to locate their position on the schematic of the protected ring, they are designated IEDs NW, SW, NE, and SE. All four are connected and configured with the convention of seeing a FORWARD direction when ‘looking into’ the 11 kV ring.

The same relay settings as were applied for Relays 1, 2, and 4 in the benchmarking exercise, and as described by Table 10, are used. In effect Relay 3 is replaced in this exercise by the four relays protecting the 11 kV ring. For the devices designated IEDs NW, SW, NE, and SE, settings similar to those previously applied to Relay 3 are employed. The settings are, however, slightly displaced to facilitate clear differentiation on the resulting DIgSILENT output plots.

For this series of tests, the settings for the overcurrent ($I>1$) elements for these four relays are as presented in the following Table 12.

Table 12: Directional $I>1$ settings for IEDs NW, NE, SE, and SW for directionality verification tests.

Relay	CT Ratio	*PSM*	I_{Set} *(secondary)*	*TMS*	*Directional Setting*
IED NW ($I>$)	250:5	1.0	5 A	0.425	Per test
IED NE ($I>$)	250:5	1.1	5.5 A	0.425	Per test
IED SE ($I>$)	250:5	1.2	6 A	0.425	Per test
IED SW ($I>$)	250:5	0.9	4.5 A	0.425	Per test

Using a similar methodology to that used to benchmark the network model (introduced in section 7.1.2.2), short circuit faults may be applied to evaluate protection response.

To stimulate a variety of fault current flow paths through the different 11 kV relaying points, faults are applied to a range of network topologies. With lines 2a and 2b both energised on the network, and for scenarios of both windfarm disconnected and windfarm connected, three-phase short-circuit faults are applied according to the following summary:-

- At BB1 with IEDs NW, NE, SE, and SW set FORWARD looking,
- At 33 kV/11 kV transformer with IEDs NW, NE, SE, and SW set FORWARD looking,
- At mid-point of Line 2a with IEDs NW, NE, SE, and SW set FORWARD looking,
- At mid-point of Line 2a with IEDs NW, NE, SE, and SW set REVERSE looking.

Throughout these tests, when connected, the (windfarm) generator is configured to dispatch 2 MW.

As is demonstrated in the following subsections 8.1.4.2.1 - 8.1.4.2.9, the test scenarios produced expected results. This verifies the validity of network model and the suitability of the deployment of directional protection deployment to detect expected fault current flow scenarios.

8.1.4.2.1 Protection Directionality Verification for 11 kV ring for Fault at BB1, Windfarm Disconnected and Relays set to Forward Direction

The DIgSILENT network for the fault scenario is shown in the following Figure 63.

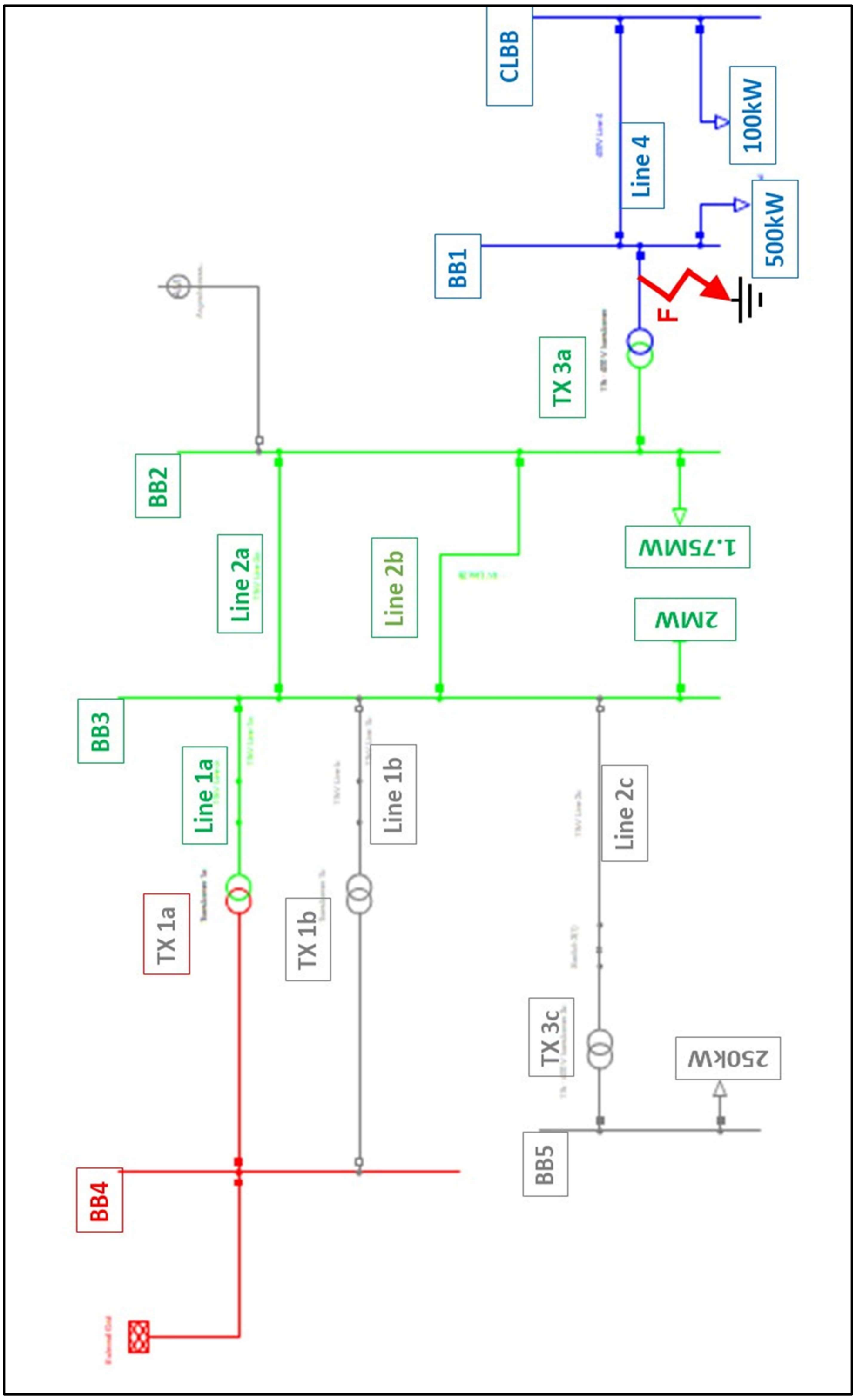

Figure 63: Network Configuration for Protection Directionality Verification for 11 kV ring for Fault at BB2, Windfarm Disconnected and Relays set to Forward Direction.

A magnified section of the resulting output time-overcurrent plot is shown in the following Figure 64.

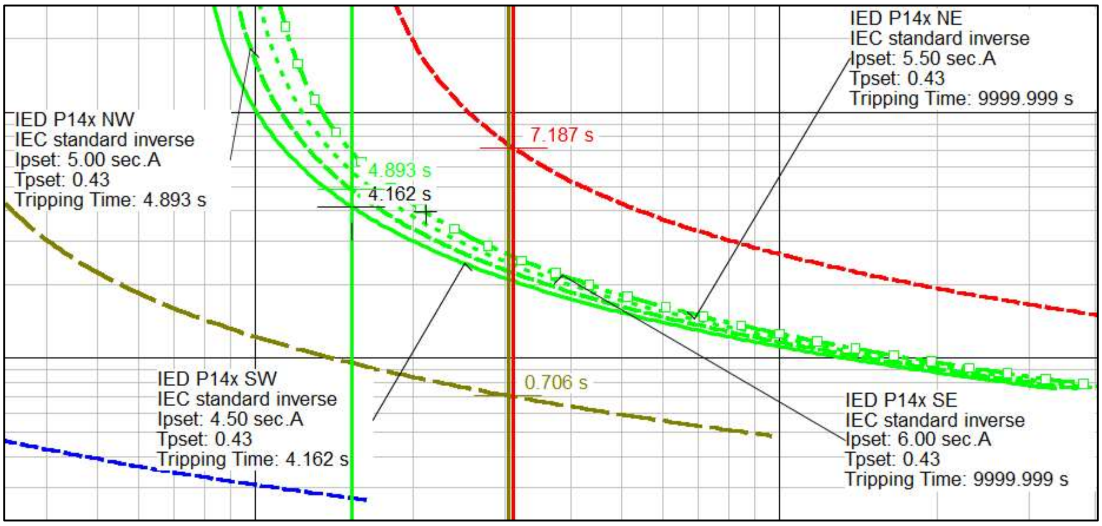

Figure 64: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at BB2, Windfarm Disconnected and Relays set to Forward Direction.

Note the separation of the four P14x *I>1* curves which is achieved by slight displacement of settings (Δ 0.5secA). Without this slight difference in settings, the curves of all four IEDs would be co-incident and they would appear as one. With the small difference, each curve is slightly different and they appear, therefore, independently on the plot.

It can be seen from the plot that the two Western relays sense current flow in their forward sense and operate. The two Eastern relays sense current flow in their reverse sense and restrain.

This is as expected as the network configuration is radial (no embedded generation is connected), resulting in unidirectional flows from the grid supply generation (in the west) to load (in the east). The fault is ‘in front’ of the Western relays, and ‘behind’ the Eastern ones.

8.1.4.2.2 Protection Directionality Verification for 11 kV ring for Fault at BB1, Windfarm Connected and Relays set to Forward Direction

This represents a similar scenario to that of Figure 63, but with the windfarm connected and configured to dispatch 2 MW.

A magnified section of the resulting output time-overcurrent plot is shown in the following Figure 65.

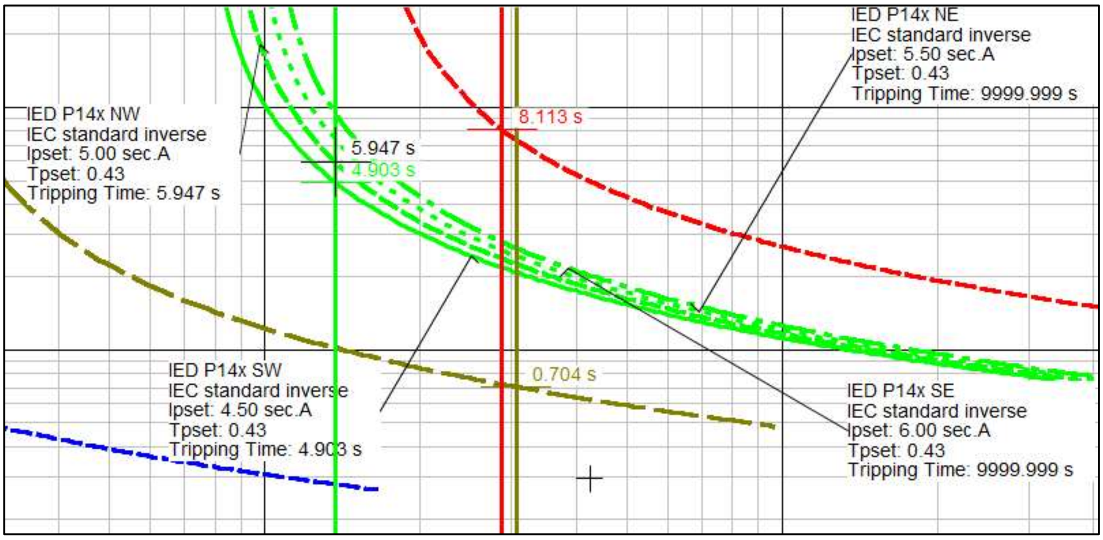

Figure 65: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at BB2, Windfarm Connected and Relays set to Forward Direction.

The plot is similar to that produced for the previous case (reported in Figure 64). Again, the fault is ‘in front’ of the Western relays, and ‘behind’ the Eastern ones, and the relays correctly operate or restrain according to the directional settings, but the operating times of the Western relays are slightly slower. This is due to the windfarm sharing part of the fault current contribution, hence reducing the fault current available to the two Western relays.

The operation is in this case is as expected.

8.1.4.2.3 Protection Directionality Verification for 11 kV ring for Fault at 33 kV/11 kV Transformer, Windfarm Disconnected and Relays set to Forward Direction

This case is similar to that described by Figure 63, but the fault is upstream of (behind) the Western relays. There is no generation and hence no fault current contribution from the windfarm. Since the network is now radial, and the fault is upstream of the four IEDs NW, NE, SE, and SW, no current should flow through any of the four relaying points of interest. Accordingly, they would not be expected to operate (irrespective of the directionality setting). This is confirmed by a magnified section of the resulting output time-overcurrent plot shown in the following Figure 66.

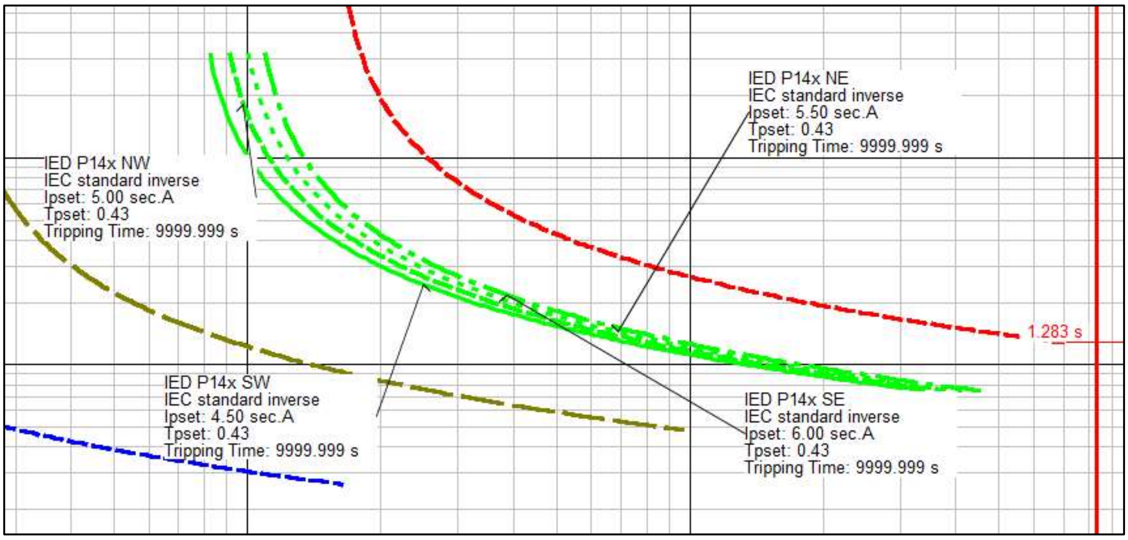

Figure 66: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at 33 kV/11 kV Transformer, Windfarm Disconnected and Relays set to Forward Direction.

For completeness, the test was repeated with the four relays set to non-directional. The results, as expected, confirmed the same hypothesis.

8.1.4.2.4 Protection Directionality Verification for 11 kV ring for Fault at 33 kV/11 kV Transformer, Windfarm Connected and Relays set to Forward Direction

This case is similar to that described by Figure 63, but the fault is upstream of (behind) the Western relays and 2 MW of generation is connected at BB2. In this case, the Western relays should see fault current in the reverse sense and restrain. If part of the current from the generator feeds the fault, then the Eastern relays may be expected to operate. A magnified section of the resulting output time-overcurrent plot is presented in the following Figure 67.

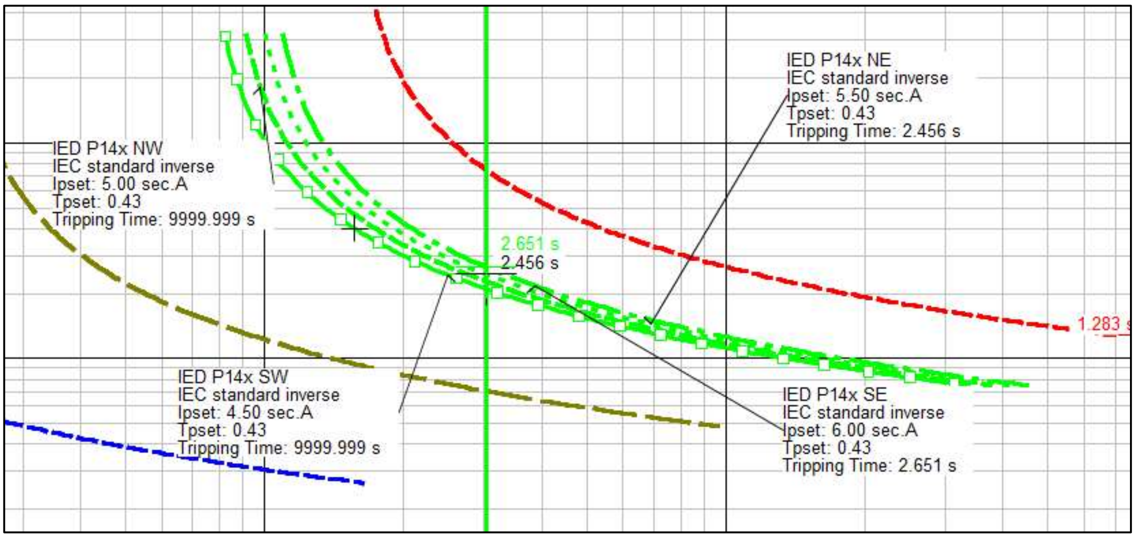

Figure 67: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at 33 kV/11 kV Transformer, Windfarm Connected and Relays set to Forward Direction.

It can be seen from the plot that the two Eastern relays operate (in approximately two and a half seconds) whilst the two Eastern relays restrain.

This operation is as expected since the windfarm contributes to the fault current, and the Eastern relays see the fault current in their forward sense. For the two Western relays, the fault is behind and so, the forward sensing elements do not detect it.

8.1.4.2.5 Protection Directionality Verification for 11 kV ring for Fault at Mid-Point of Line 2b, Windfarm Disconnected and Relays set to FORWARD Direction

The network configuration for this case is presented in Figure 68. Similar to the case of Figure 63, no embedded generation is connected, but here the fault is now applied at the mid-point of Line 2b. That places it in the protected 11 kV ring zone between the two ‘Northern’ relays. The network configuration and applied fault is shown in the following Figure 68.

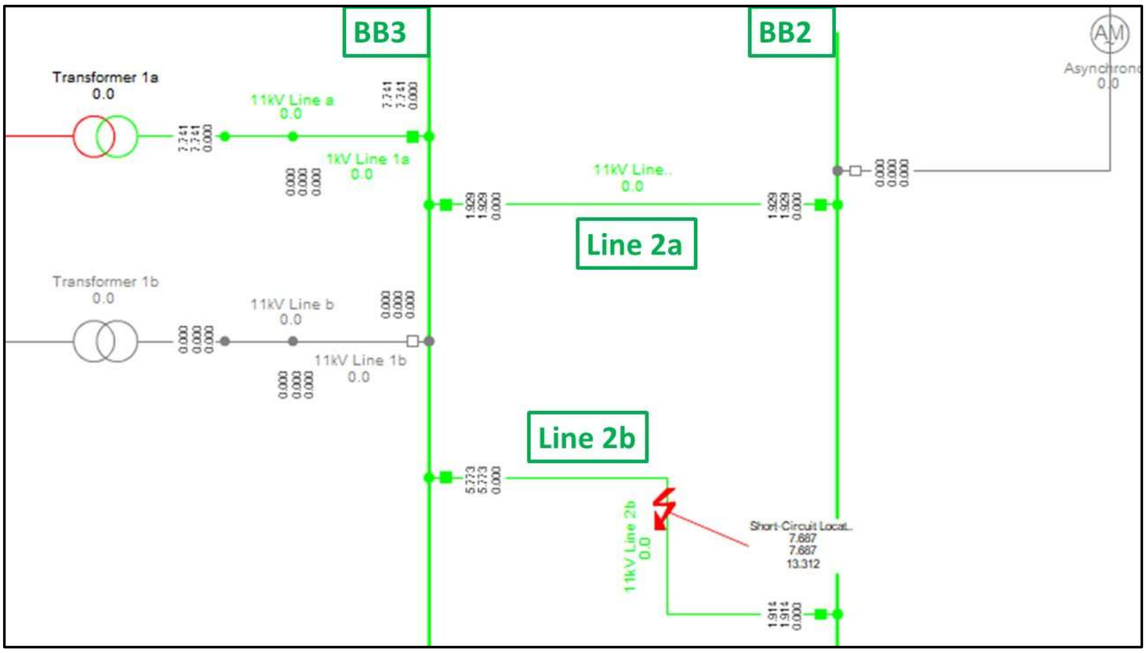

Figure 68: Network Configuration for Protection Directionality Verification for 11 kV ring for Fault at Line2b (mid-point), Windfarm Disconnected and Relays set to Forward Direction.

A magnified section of the resulting output time-overcurrent plot is shown in the following Figure 69.

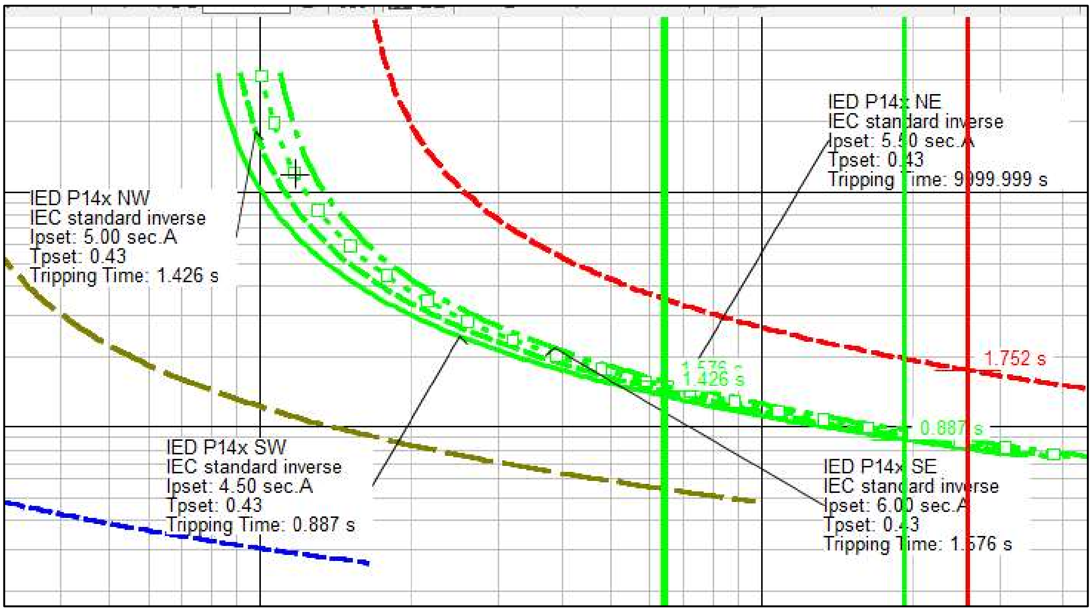

Figure 69: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at Line2b (mid-point), Windfarm Disconnected and Relays set to Forward Direction.

It can be seen that with the exception of IED NE, the relays protecting the 11 kV ring operate in the forward sense. The following Figure 70 features an overlay of the fault current paths derived from the faults currents values embedded in the report. The fault current path and the operation of the IEDS correlate. IEDS NW, SW, and SE see fault current in the forward sense and operate, IED NE sees it in the reverse sense and restrains.

This operation is as expected.

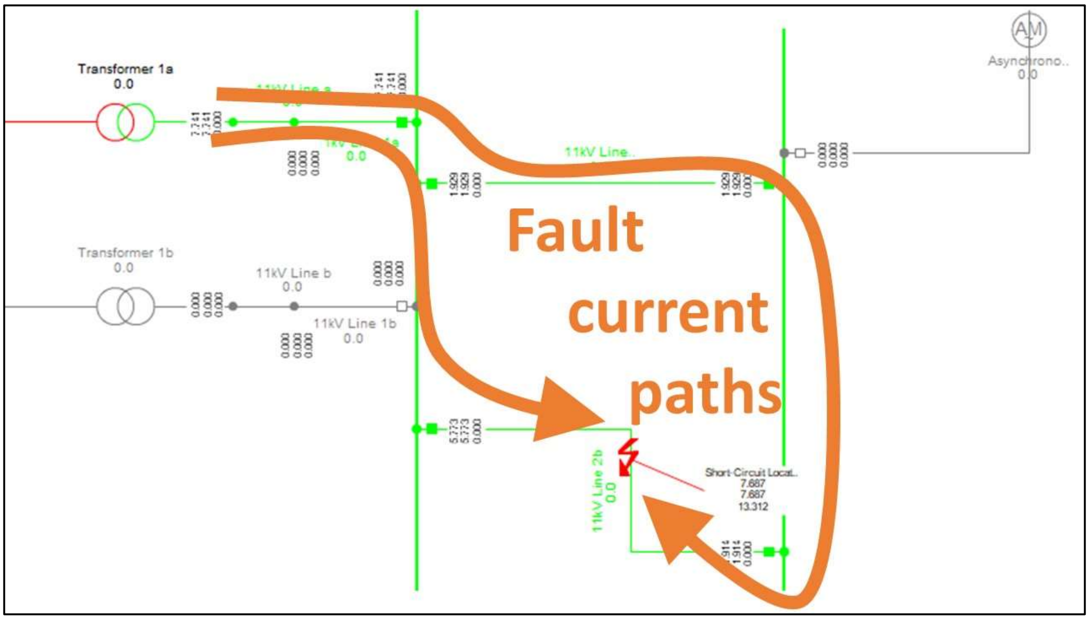

Figure 70: Fault Current Path Illustration Verification for Fault at Line2b (mid-point) with Windfarm Disconnected.

8.1.4.2.6 Protection Directionality Verification for 11 kV ring for Fault at Mid-Point of Line 2b, Windfarm Disconnected and Relays set to REVERSE Direction

This represents a similar scenario to that presented in Figure 68, with the difference that the relays NW, NE, SE, and SW are set for reverse operation.

A magnified section of the resulting output time-overcurrent plot is shown in the following Figure 71.

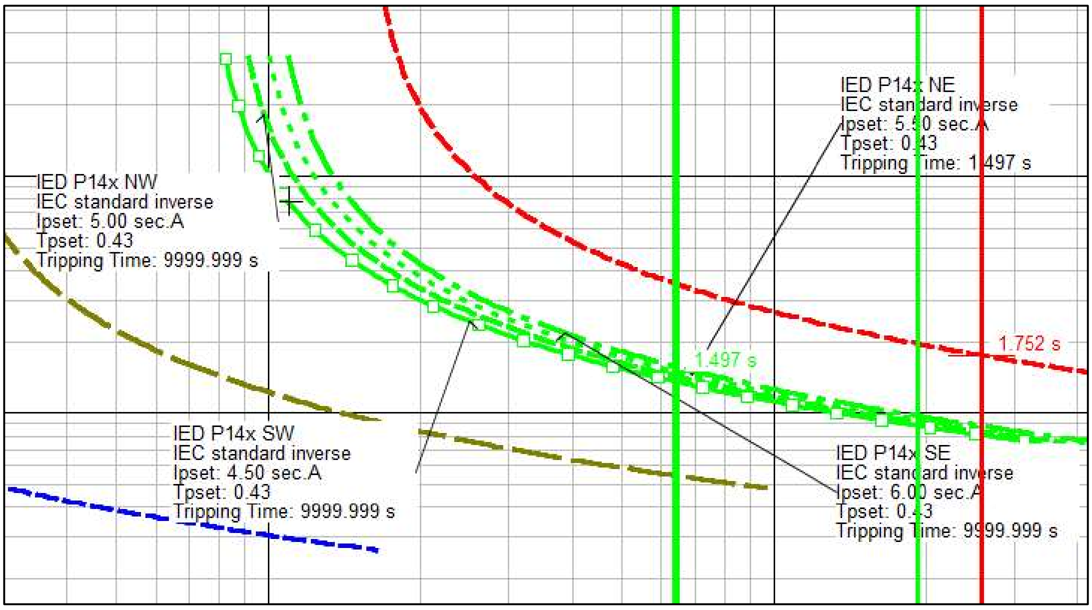

Figure 71: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at Line2b (mid-point), Windfarm Disconnected and Relays set to Reverse Direction.

It can be seen that with the exception of IED NE, the relays protecting the 11 kV restrain. Referring to the current flow path highlighted Figure 70 this is as expected since they 'see' current in the forward sense but are set for reverse operation. IED NE sees current associated with the fault in the reverse sense and also correctly operates.

8.1.4.2.7 Protection Directionality Verification for 11 kV ring for Fault at Mid-Point of Line 2b, Windfarm Connected and Relays set to FORWARD Direction

The network configuration for this case is presented in Figure 72. It is similar to the case of Figure 70, with the relays of interest set for forward operation and fault applied at the mid-point of Line2b, but the embedded generation is connected in Figure 72.

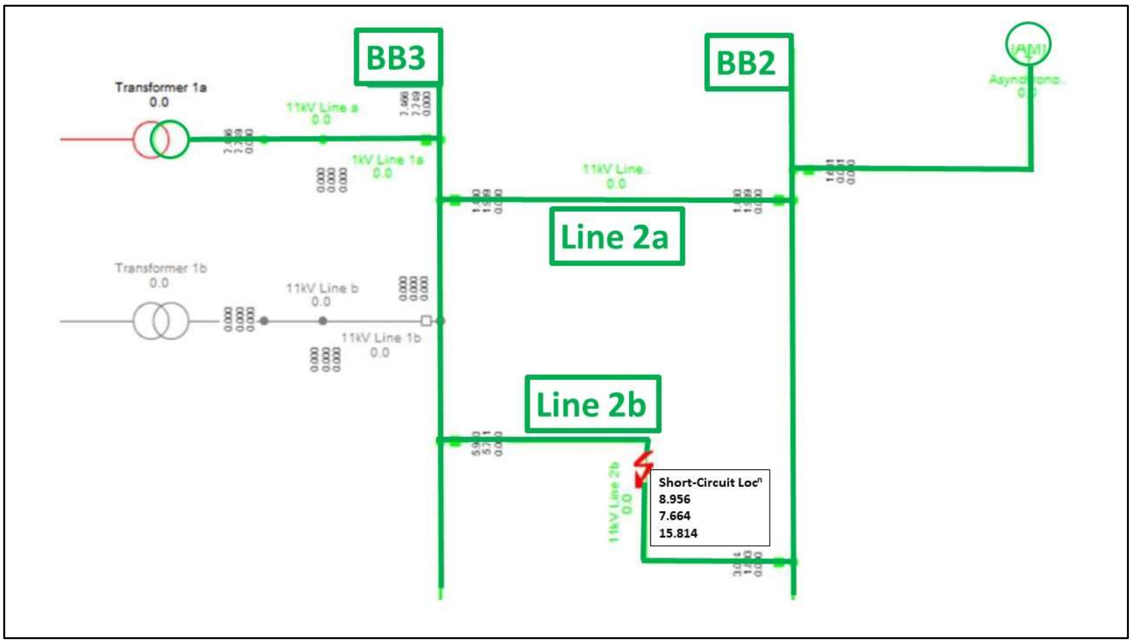

Figure 72: Network Configuration for Protection Directionality Verification for 11 kV ring for Fault at Line2b (mid-point), Windfarm Connected and Relays set to Forward Direction

The connected windfarm contributes to the fault current levels, but does not fundamentally change the fault current directions. As such, it represents an evolutionary scenario of a network into which a moderate amount of renewable resource has been integrated, rather than a revolutionary (potential future) scenario where embedded distributed resources dominate. The fault current levels are reflected in a magnified section of the resulting output time-overcurrent plot shown in the following Figure 73.

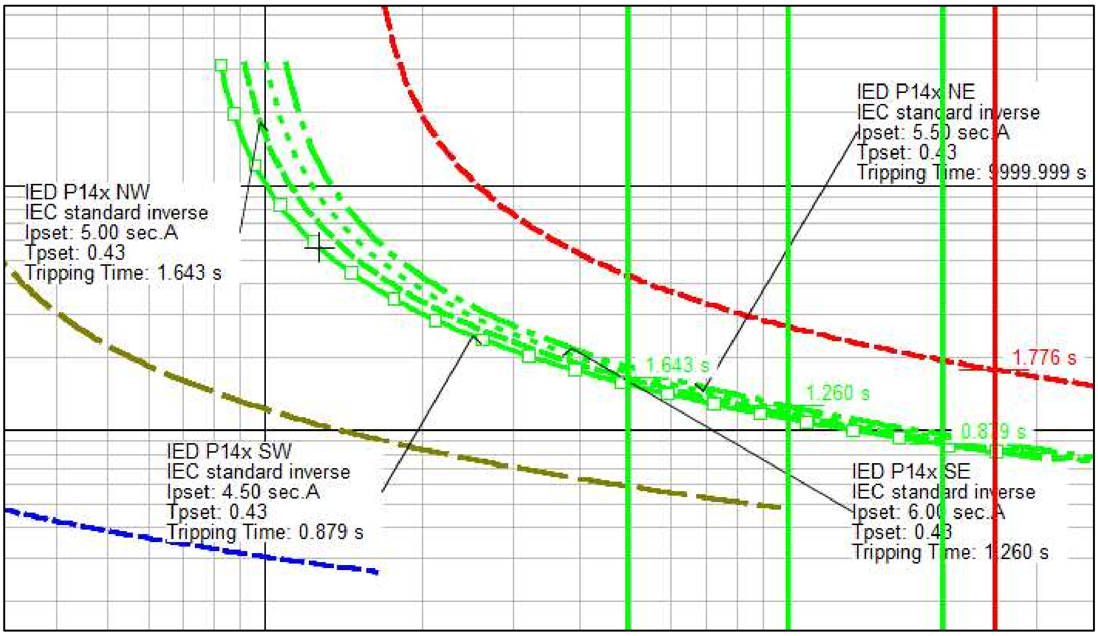

Figure 73: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at Line2b (mid-point), Windfarm Connected and Relays set to Forward Direction.

As for the case for described by Figure 70, it can be seen that with the exception of IED NE, the relays protecting the 11 kV ring see fault current in the forward sense and operate. IED NE sees fault current in the reverse sense and restrains.

8.1.4.2.8 Protection Directionality Verification for 11 kV ring for Fault at Mid-Point of Line 2b, Windfarm Connected and Relays set to REVERSE Direction

This represents a similar scenario to that of

Figure 72, with the windfarm connected and a fault applied at the mid-point of Line 2b, but with IEDs NW, NE, SW, and SE set for reverse operation. This test can confirm the directionality decision making of the IEDs as they each should demonstrate opposite behaviour compared with the previous test.

A magnified section of the resulting output time-overcurrent plot is shown in the following Figure 74.

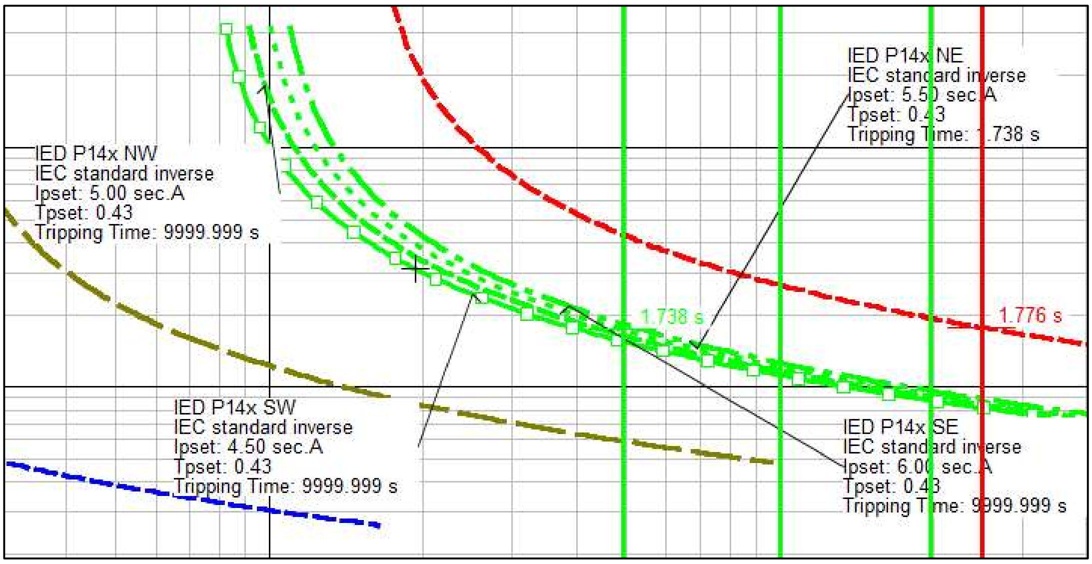

Figure 74: Time-Overcurrent Plot for Protection Directionality Verification for 11 kV ring for Fault at Line2a (mid-point), Windfarm Connected and Relays set to Reverse Direction.

The operation of the IEDs is as expected.

8.1.4.2.9 Protection Directionality Verification for 11 kV ring for Fault at Mid-Point of Line 2b, Windfarm Connected and Relays set for Definite Time Operation

The behaviour recorded in previous sections 8.1.4.2.1 through 8.1.4.2.8 is as predicted, and serves to demonstrate correct connection and deployment of directional overcurrent protection to the 11 kV ring at the heart of the protected generic network model. As is common practice on UK distribution networks, time graded overcurrent (IDMT) protection has been applied. With IDMT, the operate time varies according to fault current level. As the study moves into connecting directional elements together to form unit protection schemes, IDMT elements become less appropriate. For unit protection, discrimination does not need to rely on time, and so a combination of ‘instantaneous’ directional decision making, coupled with high speed communications, can provide 'near instantaneous[7]' unit protection.

To facilitate evaluation of Directional Agents as constituent parts of directional comparison unit protection schemes, therefore, it can be appropriate to replace the directional IDMT protection with (DT) instantaneous directional protection. To form unit protection schemes, both forward- and reverse- sensing elements will be required, for each Directional Agent located at each relaying point. A lack of forward operation should not necessarily imply reverse operation (and vice-versa). Using both signals can provide interlocking security against (for example) wiring faults. It may be appropriate, therefore, to indicate both forward and reverse operation at each relaying point.

Although, in practice, the DT elements of all Directional Agents might reasonably be set to instantaneous, when presenting the results of multiple Directional Agents acting upon the same fault condition clarity may be afforded by configuring each Agent with different operational characteristics. Similar to cases involving IDMT characteristics therefore (as explained in 8.1.4.2.1) to aid analysis of operations, therefore, distinction of the operation of the individual Directional Agents is achieved by separating the characteristics. Each Directional Agent is set with a slightly different operation time, and with a slightly different operating current. In a real-world scenario, it should be anticipated that all elements would be set the same to achieve highest sensitivity with fastest operating times.

The purpose of this test now is to show coincident correct operation of the four relays for a fault mid-point on line 2b. In this case relays NW, SW, and NE should see the fault in the forward sense (so relay elements NWF, SWF, and NEF should operate, and relay elements NWR, SWR, and NER should restrain). Relay SW should see the fault in the reverse sense (so relay element SER operates, whilst relay element SEF restrains).

To demonstrate, in this test, different operating characteristics are applied to the relay elements, and a fault is applied mid-point on line 2b. Time-overcurrent plots

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[7] Near instantaneous operation is used to indicate un-delayed definite-time (instantaneous) overcurrent operation incorporated into a communications-aided teleprotection scheme. Delays associated with communications propagation and processing need to be included into the prediction and measurement of actual operating times.

are shown for both forward and reverse looking Definite Time elements of the Directional Agents. The elements are set identically except for:-

- Directional setting (forward/reverse),
- Time settings (they increase in 10 ms increments from instantaneous),
- Current settings (they increase in +.25 A increments from {2x max load current (≈ 3 A) = 6 A} – secondary).

For reference purposes, the settings applied are as presented in the following Table 13.

Table 13: DT time settings applied to 11kV Directional Protection for Illustrations.

Relay	NWF (fwd)	NWR (rev)	NEF (fwd)	NER (rev)	SWF (fwd)	SWR (rev)	SEF (fwd)	SER (rev)
Current Setting (sec A)	6	6.25	6.5	6.75	7	7.25	7.5	7.75
Time setting (ms)	0 See Note *	20	30	40	50	60	70	80

Note: * Appears as 10/20 ms on plot/record due to contact mimic.

Note also, that as previously stated, in a real-world scenario, it should be anticipated that all elements would be set the same to achieve highest sensitivity with fastest operating times (instantaneous).

The following

Figure 75 shows the current distribution for a short-circuit fault applied at the mid-point of Line2b.

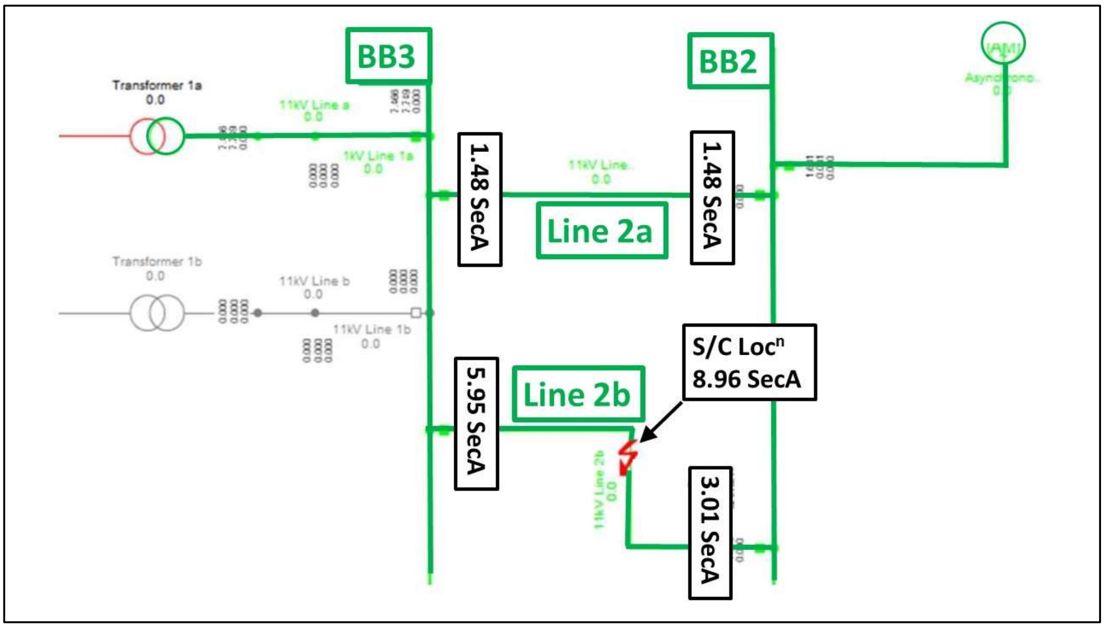
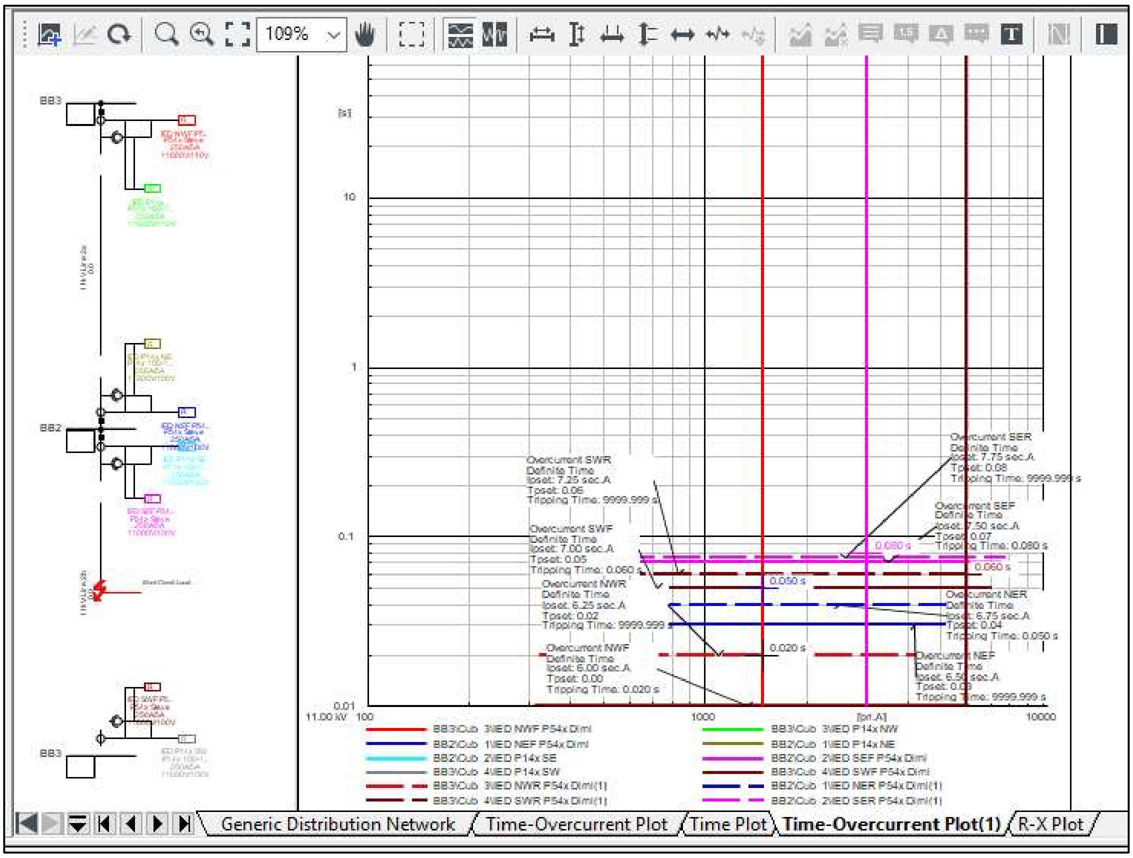


Figure 75: Faulted Network DT Directional Overcurrent Protection Example.

The responses of the relays located at NW, NE, SW, and SE terminals of the 11kV Sub-Network are shown in the following Figure 76 which is provided for illustrative purposes and for which magnification of salient parameters is provided in the subsequent Figure 77.



Overcurrent SWR
Definite Time
Ipset: 7.25 sec.A
Tpset: 0.06
Tripping Time: 9999.999 s

Overcurrent SWF
Definite Time
Ipset: 7.00 sec.A
Tpset: 0.05
Tripping Time: 0.060 s

Overcurrent NWR
Definite Time
Ipset: 6.25 sec.A
Tpset: 0.02
Tripping Time: 9999.999 s

Overcurrent NWF
Definite Time
Ipset: 6.00 sec.A
Tpset: 0.00
Tripping Time: 0.020 s

Overcurrent SER
Definite Time
Ipset: 7.75 sec.A
Tpset: 0.08
Tripping Time: 9999.999 s

Overcurrent SEF
Definite Time
Ipset: 7.50 sec.A
Tpset: 0.07
Tripping Time: 0.080 s

Overcurrent NER
Definite Time
Ipset: 6.75 sec.A
Tpset: 0.04
Tripping Time: 0.050 s

Overcurrent NEF
Definite Time
Ipset: 6.50 sec.A
Tpset: 0.03
Tripping Time: 9999.999 s

BB3\Cub 3\IED NWF P54x Diml
BB2\Cub 1\IED NEF P54x Diml
BB2\Cub 2\IED P14x SE
BB3\Cub 4\IED P14x SW
BB3\Cub 3\IED NWR P54x Diml(1)
BB3\Cub 4\IED SWR P54x Diml(1)
BB3\Cub 3\IED P14x NW
BB2\Cub 1\IED P14x NE
BB2\Cub 2\IED SEF P54x Diml
BB3\Cub 4\IED SWF P54x Diml
BB2\Cub 1\IED NER P54x Diml(1)
BB2\Cub 2\IED SER P54x Diml(1)

Figure 76: Relay Response to Network DT Directional Overcurrent Protection Example.

Clarity of the tripping operation of the relays is enhanced in the following Figure 77 which features an enlarged excerpt of the previous Figure 76.

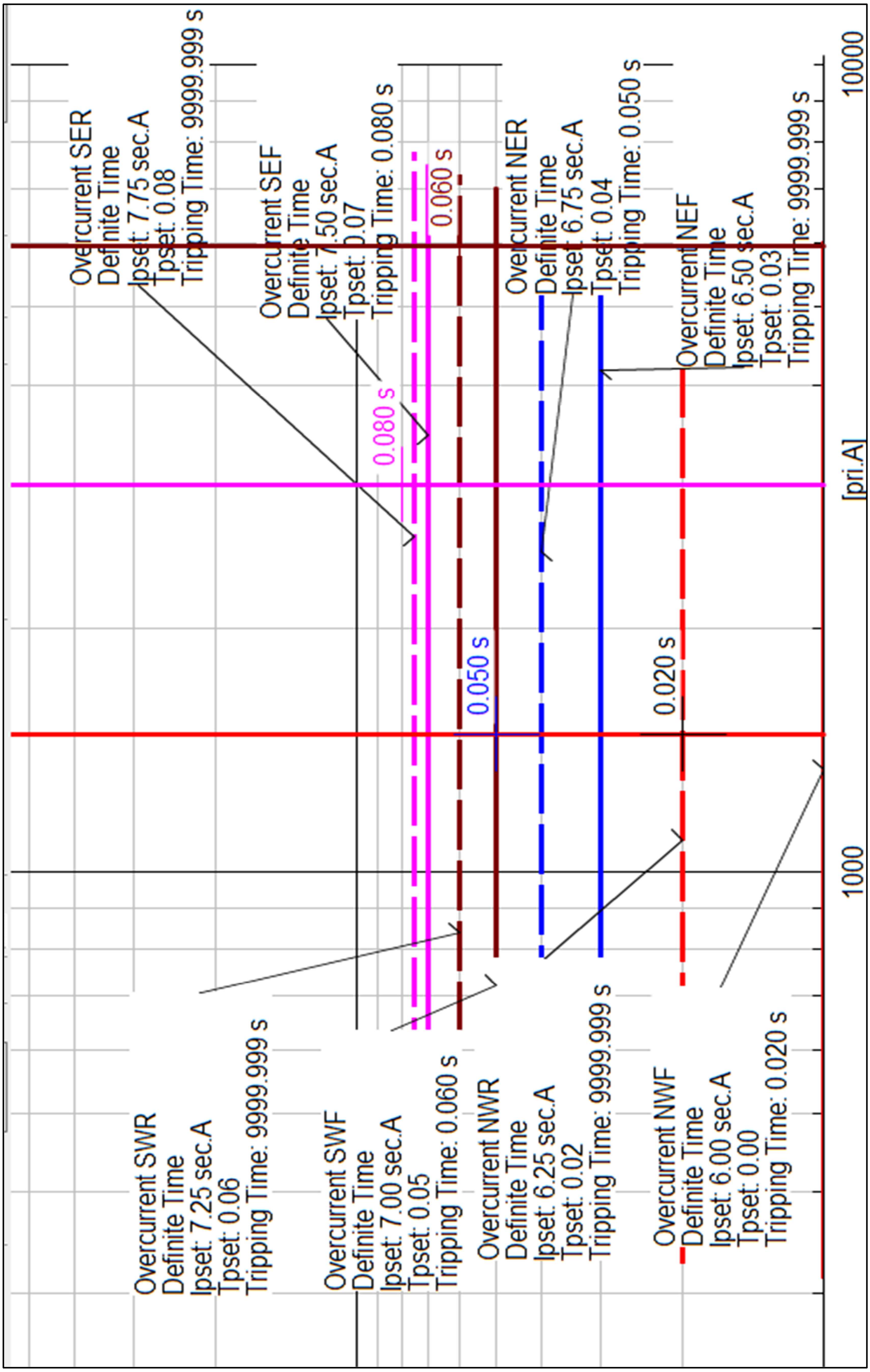


Figure 77: Magnified Relay Response to Network DT Directional Overcurrent Protection Example.

Figure 77 demonstrates the expected forward response for relays NWF (forward), SWF (forward), and NEF (forward), the correct response by the reverse looking element of SER. The complimentary relays set to sense faults in the opposite directions also respond correctly.

This affords confidence that the network model is adequate to evaluate the performance of Directional Agents' implementation within communications-aided unit protection schemes.

8.1.4.2.10 Summary Results of Applying Directional Overcurrent Protection to Passive Radial Distribution Networks

As reported in subsections 8.1.4.2.1 - 8.1.4.2.9 the test scenarios produced expected results, verifying the validity of network model in its expanded form to support integration of embedded generation.

This affords confidence that the network model is suitable for use to evaluate the performance of Directional Agents' implementation within communications-aided directional comparison unit protection schemes.

8.1.4.3 Results of Comparing Different Directional Protection Techniques

An intent expressed at the start of this work was try to evaluate the differences in performance that could be delivered by two different methods used to determine fault directionality associated with faults.

Section 7.1.4.3 introduces two techniques employed in protection relays to determine fault directionality based on:-

- Conventional directional overcurrent protection
- (Delta) Superimposed-component based techniques

Since the MiCOM P545 relay implements both types of algorithm, it was originally planned that the evaluation could be performed using these relays.

When, primarily because of operational restrictions due to Covid19, this became not possible, a mitigation plan was developed to re-scope the directional protection evaluation to fit within a simulation environment provided by DIgSILENT. Since the DIgSILENT library contains a simulation model for the MiCOM P545, it was hoped that this model could be used for evaluation purposes.

Consultation DIgSILENT's Technical Support [129], however, revealed that the standard model is not suitable for this intended purpose..

This superimposed component detection method is a fundamental feature of the MiCOM P545. Its use is not limited to a stand-alone fault location. Reference to the appropriate MiCOM P545 user manual [81] establishes that detection of superimposed current and voltage signals is an inherent part of the algorithms used for transmission line protection.

As well as being used for fault location, the superimposed (delta) components are used in a phase selection algorithm to enhance the distance protection algorithms. They are also used in fault direction detection processes used to implement (delta) Superimposed Directional Comparison protection schemes.

The superimposed directional comparison elements can be disabled in the MiCOM P54x and if this option is selected then the MiCOM P54x reverts to 'conventional' techniques to provide fault location and phase selection for the distance protection. If the superimposed elements are disabled, then the directional comparison schemes cannot be implemented.

Since the DIgSILENT model does not implement the feature, it is not possible to use the DIgSILENT simulation model to emulate superimposed directional comparison protection. Creating a credible superimposed directional comparison relay (be it a physical device or a simulation model) is far from a trivial exercise. It requires high speed, high accuracy, complex, frequency-tracked, digital signal processing. The author's previous industrial experience informs that typically it takes many 'man-years' of development effort to produce a robust model (e.g. GEC's LFDC, GEC Alstom's LFZR, ALSTOM (GE) P54x, etc.). Such commitment is beyond the scope of this study and so the exercise is curtailed.

8.1.4.3.1 Directional Protection Technique Evaluation Model

Lack of suitable models to mimic superimposed (delta) directional comparison algorithms means that the intended comparison of delta and conventional algorithms is not possible. Whilst simulating a superimposed (delta) algorithm is precluded, the DIgSILENT modelling environment does contain examples of directional overcurrent relays, and it was deemed appropriate to focus the investigation using a suitably adapted model of this type.

Another advantageous feature of the MiCOM P545 is the integrated teleprotection interface. Necessary to implement the line differential functionality, it can also be configured to provide the teleprotection interface necessary to implement 'carrier aided' schemes such as distance protection schemes, Aided DEF schemes, and directional comparison schemes. To model a directional comparison unit protection scheme, the teleprotection connection will also require modelling. Since the MiCOM P545 model provided by DIgSILENT has been deemed unsuitable, an alternative approach to satisfying the need for a suitable model is required. The model chosen will need to provide a suitable teleprotection interface in order to allow the directional comparison unit schemes to be modelled.

A simulation model of a Directional Agent is required. The model needs to provide directional (overcurrent) protection and be capable of integrating with a suitable teleprotection model to facilitate the creation of directional comparison unit protection scheme models.

Details of the design and implementation of the protection scheme simulation models used to evaluate directional comparison performance in this project is provided as Appendix I for reference (and for the potential benefit of anyone faced with the challenge of implementing a custom designed carrier-aided unit protection scheme).

8.1.4.4 Directional Comparison Protection Scheme Simulation Model Test Results

Appendix I details the process to create the models necessary to create a DIgSILENT environment to simulate the operation of a directional comparison unit protection scheme based on directional overcurrent principles.

Simulation models are developed for a Directional Agent and a teleprotection (communications interlink) relay.

The teleprotection relay facilitates the interconnection of two Directional Agents to form a directional comparison unit protection scheme. The unit scheme is based on permissive overreaching directional overcurrent elements. The directional overcurrent elements are implemented in Directional Agents. The design uses DIgSILENT standard library model components to implement directional overcurrent protection and appropriate scheme logic.

The model design described in Appendix I is reproduced in the following Figure 78 for reference.

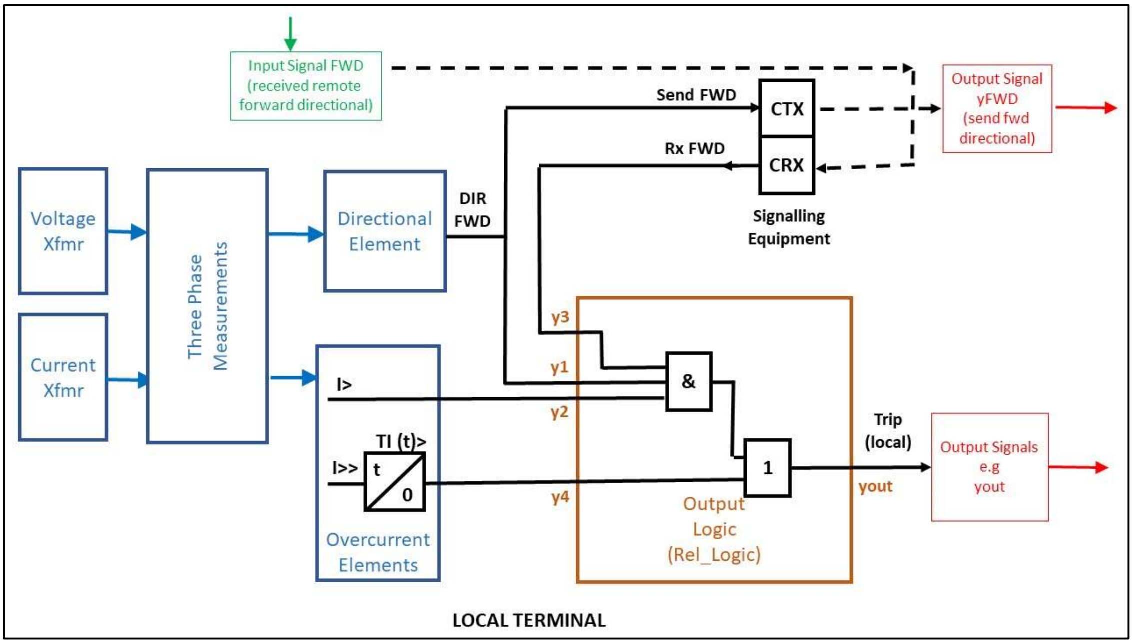


Figure 78: Functional Requirements for Directional Agent Simulation Model.

The signal definition for the Output Logic block I/O of the Directional Agent is recalled in the following Table 14.

Table 14: Directional Agent Output Logic Definitions

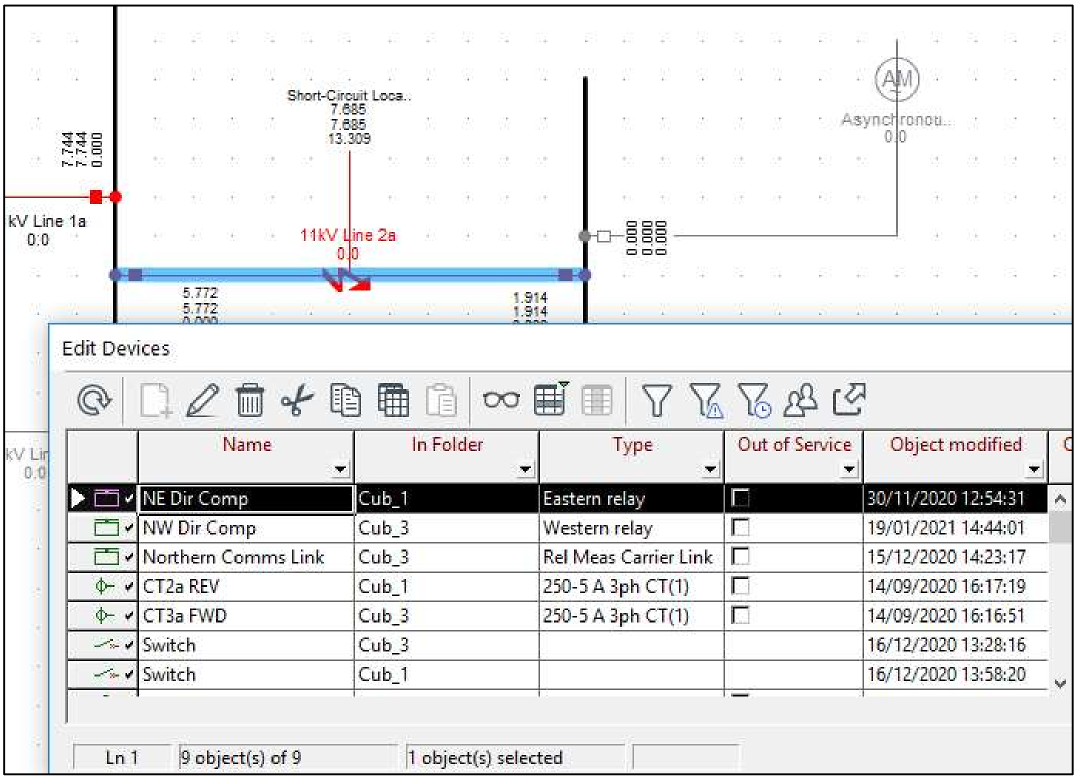
y1	=	local FORWARD direction detected
y2	=	local $I>$ operation
y3	=	(remote) FORWARD operation received
y4	=	local (back-up) non directional $I>>$ operation
y out	=	((y1 AND y2) AND y3) OR y4

Before the Directional Agent simulation model can be confidently used to evaluate directional comparison unit scheme performance for variations of network topology and configurations, it must be verified. This section describes the verification process and presents the results. Note that the section presents the results obtained at the conclusion of a lengthy iterative design/debug/develop process. Details of interim development steps are not presented.

The tool provided by DIgSILENT for debugging problems during model creation introduced in Appendix I is used to observe the outputs of the simulated directional comparison unit protection scheme under test in this exercise. The same tool is used for output reporting debug development, and in subsequent tests using the simulated directional comparison unit protection scheme.

The newly created Directional Agents are connected in pairs to form two directional comparison unit schemes, one protecting Line 2a, and the other protecting Line2b, on the test network.

Directional Agents 'NW Dir Comp' and 'NE Dir Comp' are connected together via the teleprotection relay 'Northern Comms Link' to form the Northern Directional Comparison unit scheme to protect Line2a as shown in the following Figure 79.

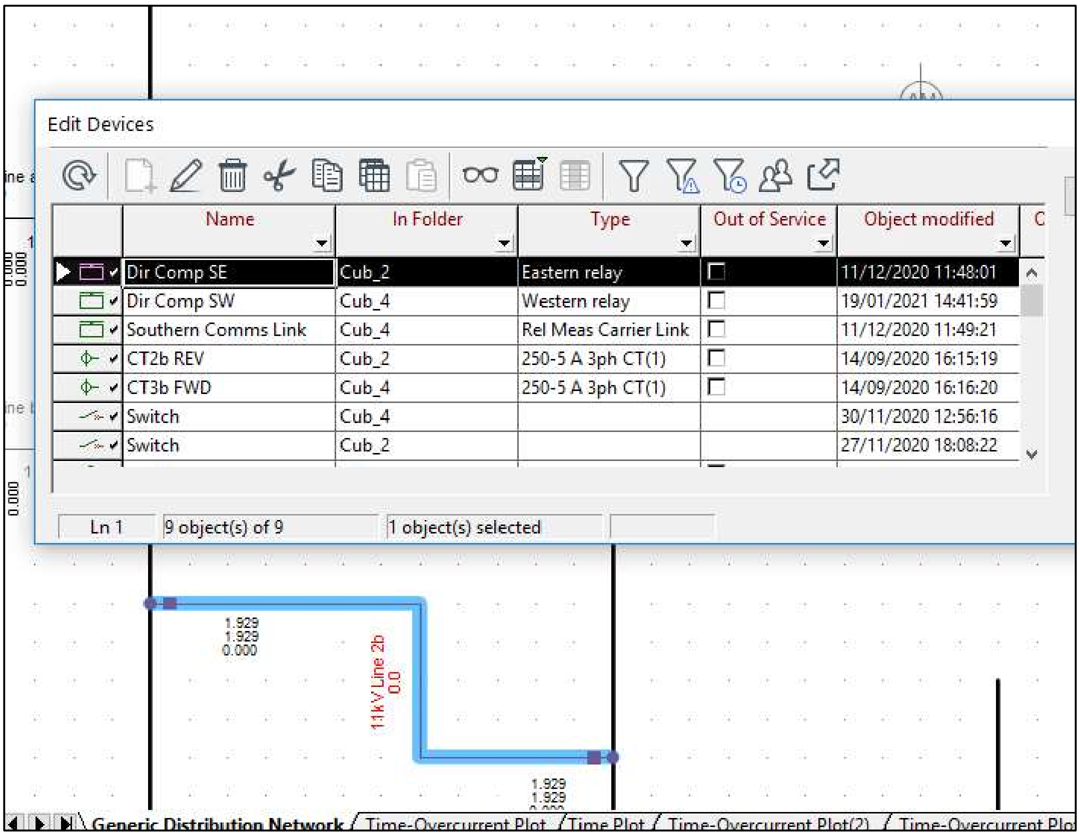


	Name	In Folder	Type	Out of Service	Object modified
✓	NE Dir Comp	Cub_1	Eastern relay	☐	30/11/2020 12:54:31
✓	NW Dir Comp	Cub_3	Western relay	☐	19/01/2021 14:44:01
✓	Northern Comms Link	Cub_3	Rel Meas Carrier Link	☐	15/12/2020 14:23:17
✓	CT2a REV	Cub_1	250-5 A 3ph CT(1)	☐	14/09/2020 16:17:19
✓	CT3a FWD	Cub_3	250-5 A 3ph CT(1)	☐	14/09/2020 16:16:51
✓	Switch	Cub_3			16/12/2020 13:28:16
✓	Switch	Cub_1			16/12/2020 13:58:20

Ln 1 | 9 object(s) of 9 | 1 object(s) selected

Figure 79: Allocation of Directional Agents to form Northern Directional Comparison Unit Protection Scheme for Line2a.

Directional Agents 'SW Dir Comp' and 'SE Dir Comp' are connected together via the teleprotection relay 'Southern Comms Link' to form the southern directional comparison unit scheme to protect Line2b as shown in the following Figure 80.



Name	In Folder	Type	Out of Service	Object modified	C
Dir Comp SE	Cub_2	Eastern relay	☐	11/12/2020 11:48:01	
Dir Comp SW	Cub_4	Western relay	☐	19/01/2021 14:41:59	
Southern Comms Link	Cub_4	Rel Meas Carrier Link	☐	11/12/2020 11:49:21	
CT2b REV	Cub_2	250-5 A 3ph CT(1)	☐	14/09/2020 16:15:19	
CT3b FWD	Cub_4	250-5 A 3ph CT(1)	☐	14/09/2020 16:16:20	
Switch	Cub_4			30/11/2020 12:56:16	
Switch	Cub_2			27/11/2020 18:08:22	

Figure 80: Allocation of Directional Agents to form Southern Directional Comparison Unit Protection Scheme for Line2b.

All Directional Agents are set for FORWARD operation, with the FORWARD sense indicating a direction of current flowing into the 11 kV ring from the relaying point.

A fault is applied mid-point on the northern Line2a as shown in the following Figure 81.

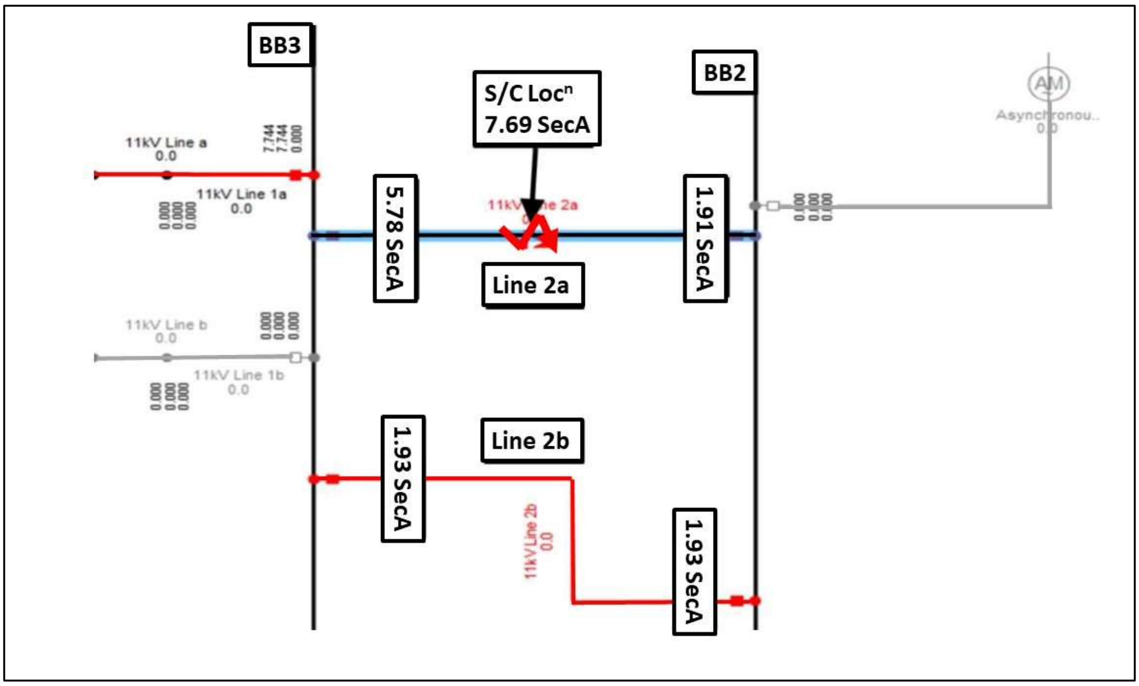
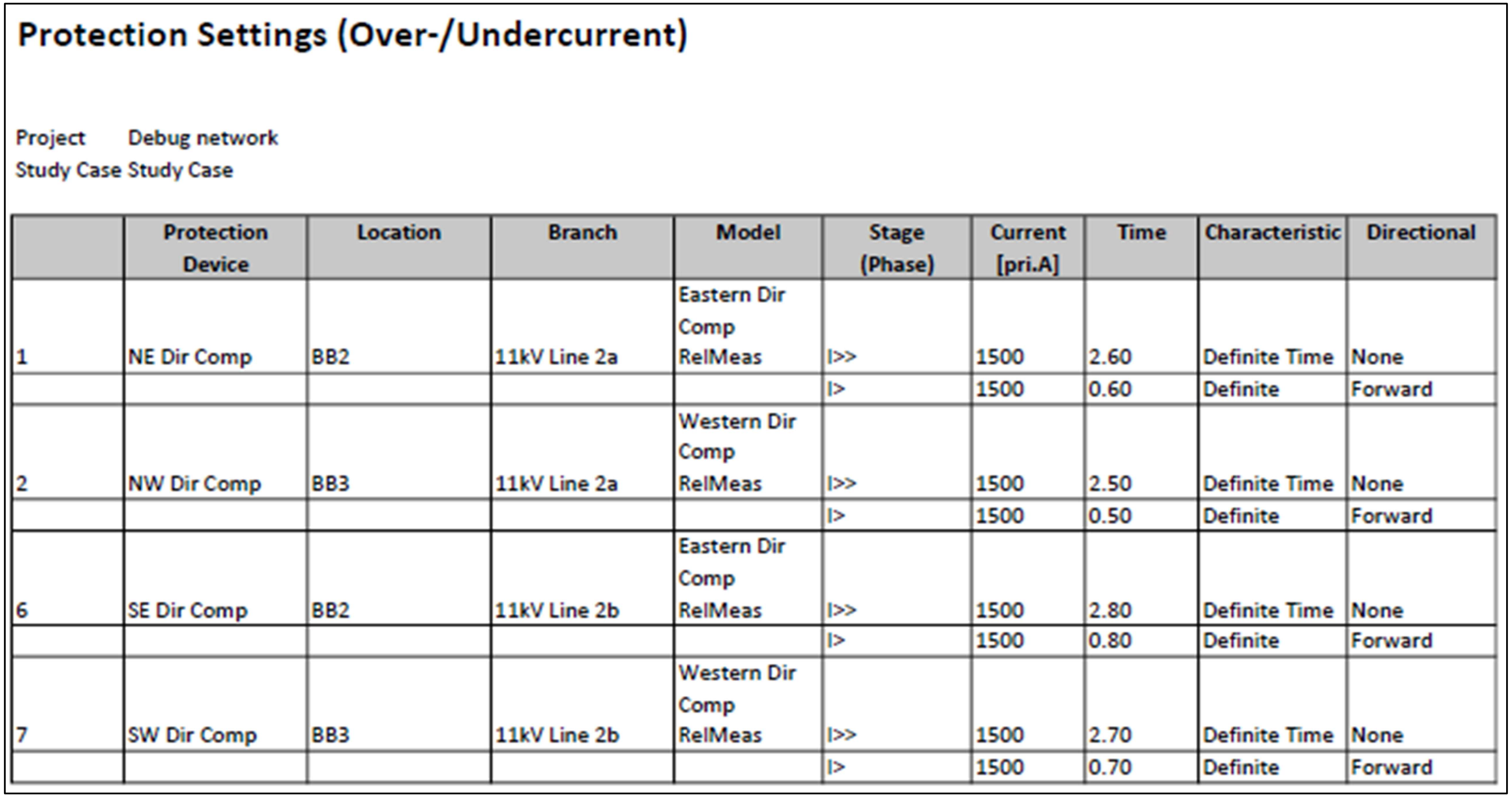


Figure 81: Fault Scenario to Verify Simulated Directional Comparison Unit Protection Scheme Model.

The following Figure 82 shows the settings (extracted directly from the simulator) applied to the overcurrent elements in the Directional Agents which form the directional comparison verification scheme.



Protection Settings (Over-/Undercurrent)

Project Debug network
Study Case Study Case

	Protection Device	Location	Branch	Model	Stage (Phase)	Current [pri.A]	Time	Characteristic	Directional
1	NE Dir Comp	BB2	11kV Line 2a	Eastern Dir Comp RelMeas	I>>	1500	2.60	Definite Time	None
					I>	1500	0.60	Definite	Forward
2	NW Dir Comp	BB3	11kV Line 2a	Western Dir Comp RelMeas	I>>	1500	2.50	Definite Time	None
					I>	1500	0.50	Definite	Forward
6	SE Dir Comp	BB2	11kV Line 2b	Eastern Dir Comp RelMeas	I>>	1500	2.80	Definite Time	None
					I>	1500	0.80	Definite	Forward
7	SW Dir Comp	BB3	11kV Line 2b	Western Dir Comp RelMeas	I>>	1500	2.70	Definite Time	None
					I>	1500	0.70	Definite	Forward

Figure 82: Directional Agent Overcurrent Settings Applied for Directional Comparison Unit Protection Scheme Model Verification Testing.

Notes:

1. $I>$ elements are generally intended to complement the directional elements and provide (near) instantaneous operation of local tripping if the permissive overreaching conditions are met. The directional elements supervise the local scheme logic and 'key the carrier' to send directional information to the remote terminal scheme logic.
2. $I>>$ elements are included to provide back-up. Typically they would be expected to operate if a communications disturbance prevented a unit protection decision being made.
3. For the illustrative purposes of this test, the overcurrent elements are not set very accurate nor sensitive. A value below the minimum fault current flowing at any corner is chosen and applied equally to all. The reason for applying this low value is to ensure that any failure to operate could be attributed to an incorrect directional decision, rather than a failure to pick-up.
4. Discrimination between overcurrent elements operation is useful for debugging and interpretation of results. For this reason all elements are set with different time delays. The (nominally instantaneous) $I>$ elements are set forward looking but with (non-instantaneous) operation delayed by 0.5, 0.6, 0.7, and 0.8 secs. $I>>$ elements are set non-directional with operate times of 2.5, 2.6, 2.7, and 2.8 secs.

The following Figure 83 shows the response of all the overcurrent elements when the fault described in Figure 81 is applied.

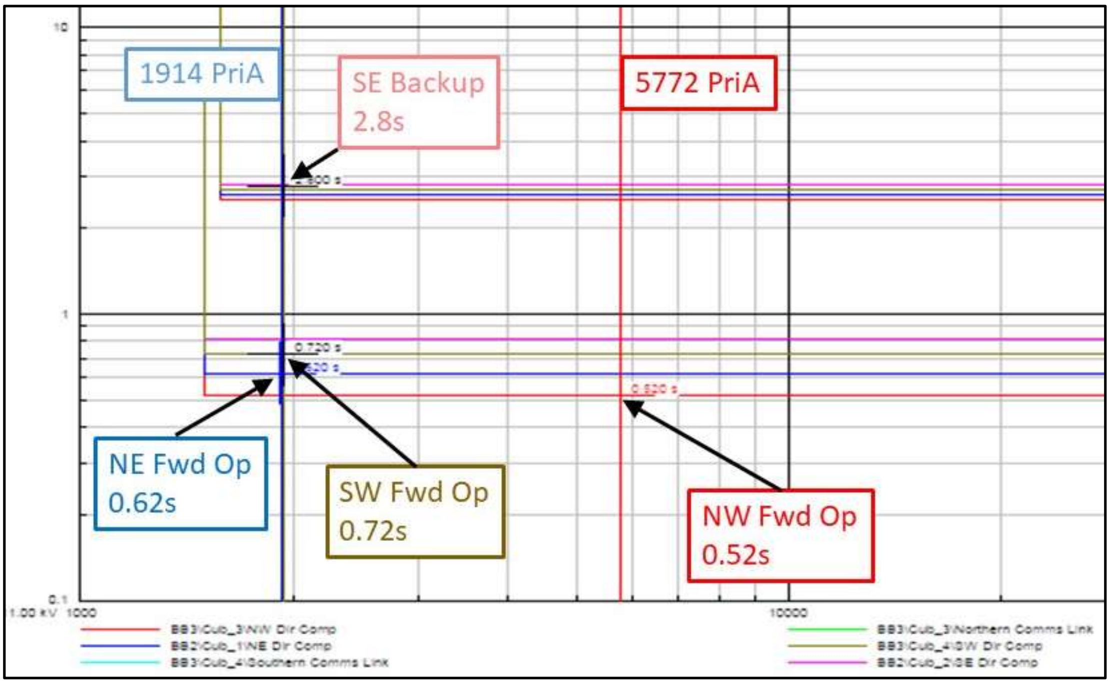


Figure 83: Operation Overcurrent Elements contained in the Northern and Southern Directional Comparison Schemes for a mid-point Fault on Line2a.

It can be seen from Figure 83 that the following elements operate:-

- NW Dir Comp $I>$,
- NE Dir Comp $I>$,
- SW Dir Comp $I>$, and
- SE Dir Comp $I>>$*.*

This is as expected and demonstrates correct response of the scheme to the fault as explained below.

The fault is internal to the Line2a which is protected by relays NW Dir Comp and Dir Comp NE. These operate 'instantaneously' in the forward sense. Combined together with a signalling channel they should provide discriminative unit protection. Relay Dir Comp SW sees current in the forward sense above setting. This is current is feeding the fault via Line2b and BB2. The Dir Comp SE relay operates with $I>>$ (as can be determined from the additional 2 seconds on the operate time). $I>>$ is set non-directional and sees the current in the reverse sense. Combined with a signalling channel, the lack of a forward signal from Dir Comp SE inhibits $I>$ on Dir Comp SW and so both relays trip back-up with a 2 second delayed operation.

Time-overcurrent plots such as that of Figure 83 are conveniently generated by the DIgSILENT software for overcurrent relays. In the case of the directional comparison schemes, it is the outputs from the Output Logic blocks of the Directional Agents of Figure 78, rather than the outputs of the overcurrent blocks that provide concise indication of Directional Agent tripping. The debug tool introduced in Appendix I provides a means of post-fault examination of the contents and output of the tripping logic.

The following Table 15 presents the logic responses generated by Directional Agents in response to a fault scenario similar to that presented in Figure 81 .

Table 15: Directional Comparison Unit Protection Scheme Model Performance Verification Test Summary.

Comms	Relay	Logic Signal (rounded)					Correct operation?	Verdict
		y1 (send FWD)	y2 (I>)	y3 (Rx FWD)	y4 (I>>)	yout (TRIP) (Logic AND of y's)		
In service	NW	0.02	0.52	0.02	2.5	0.52	Yes	☺ Correct
	NE	0.02	0.62	0.02	2.6	0.62	Yes	
	SW	0.02	0.72	no op Note 2	2.7	2.7	Yes Note 4	
	SE	no op Note 1	no op Note 1	0.02	2.8	2.8	Yes Note 4	
Out of service	NW	0.02	0.52	no op Note 3	2.5	2.5	Yes Note 4	☺ Correct
	NE	0.02	0.62	no op Note 3	2.6	2.6	Yes Note 4	
	SW	0.02	0.72	no op Note 3	2.7	2.7	Yes Note 4	
	SE	no op Note 1	no op Note 1	no op Note 3	2.8	2.8	Yes Note 4	

Numerical values represent the operating times of the logical elements (in seconds).

Notes:

1. No operation (no op) is indicative of a reverse fault at local end not detected by local forward looking I> element.

2. No operation (no op) is indicative of reverse fault at remote end not detected by remote forward looking I> element.

3. No operation (no op) is indicative of failed communications link.

4. Time delayed back-up operation due to tripping of non-directional I>> element.

The first four rows of results of Table 15 show the responses of each of the four Directional Agents when the teleprotection relays (Northern Comms Link, and Southern Comms Link) are both in service, and operational (i.e., both directional comparison schemes should be working correctly).

The latter four rows of results of Table 15 show the equivalent responses of each of the four Directional Agents but this time when the teleprotection relays (Northern Comms Link, and Southern Comms Link) are both out of service (i.e., both directional comparison schemes are failed and should be providing back-up protection only).

In all cases the outputs (yout) are correct.

From the results presented in Table 15, it is concluded that the simulation model of the directional comparison unit protection scheme, comprising a combination of simulations models of the Directional Agents and the teleprotection (communications interlink) relay is verified and considered suitable for performance evaluation.

8.1.4.5 Results of Relocating Voltage Polarising Source

So far, testing of the directional functionality of the Directional Agent models has been based on ‘conventional’ application and polarisation on the 11 kV system. That is with the current inputs connected to 11 kV phase CTs and the voltage polarisation input connected to the 11 kV VTs[8]. A key attraction of the proposal investigated in this work is to supply the voltage polarising input for such 11 kV Directional Agents from remote LV sources.

Considering again the protected network model of Figure 38, in this section of testing, the operation of the modelled directional comparison unit protection scheme is checked when the polarising voltage on the Eastern relays is re-assigned to a downstream voltage on the network connection to BB1. This represents a 400V line voltage (equivalent to 230 V phase voltage) connection.

---

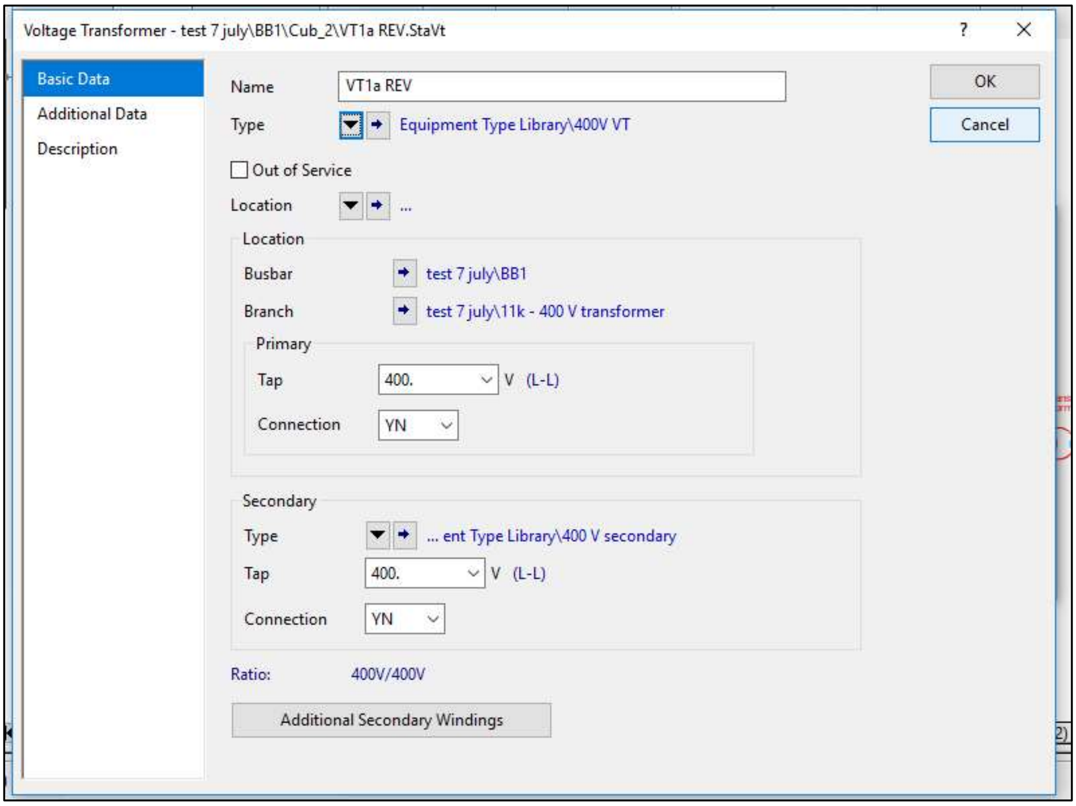
[8] Note the connection may be at the line or, more likely the busbar, but the connection will be 11 kV line-line voltage.

To facilitate LV polarisation of the Directional Agent simulation model, a suitable LV connection must be made. This requires the connection point on the network to be identified and accessed. Thereafter provision must be made for the relay to connect at this LV level and for the input conditioning and measurement management within the model to be correctly applied.

In the example, the voltage chosen as polarising input to the Eastern relays is the LV bus voltage at BB1. Nominally, this is at 400 V. The most common VT input voltage for a protection relay matches the standards for voltage measurement VTs at 100-120 V nominal. Normally an interposing transformation (typically realised as instrument/protection VTs) would be required to convert the line voltages to match the protection inputs. Some relays (e.g., MiCOM P14x), however, provide an option for direct 400 V nominal connection [76]. In the interests of offering a lowest cost solution, a direct 400 V connection, without the need for dedicated protection VTs could be attractive. This is the intended configuration for deploying the application in service.

For convenience of modelling, however, a (redundant) 400:400 V YN-YN instrument transformer model is used to provide the interface to the relay. In effect, this represents a 400 V rated 1:1 isolation transformer.

For reference, the following Figure 84 provides a screenshot of the simulated instrument VT details.



Voltage Transformer - test 7 july\BB1\Cub_2\VT1a REV.StaVt

Name: VT1a REV

Type: Equipment Type Library\400V VT

☐ Out of Service

Location: ...

Location

Busbar: test 7 july\BB1

Branch: test 7 july\11k - 400 V transformer

Primary

Tap: 400. V (L-L)

Connection: YN

Secondary

Type: ... ent Type Library\400 V secondary

Tap: 400. V (L-L)

Connection: YN

Ratio: 400V/400V

Figure 84: DIgSILENT Relay Model 400V Input VT Attributes.

The instrument VT model (designated ‘VT1a Rev’ in the network model) is attached to (400 V) BB1 in a reverse looking sense (i.e. looking ‘back/upstream’ towards the 11 kV BB2 via the 11 kV/400 V power transformer TR2).

Since the both windings of the instrument transformer are of the YN type, the magnitude and phase of each secondary winding is an equivalent of the voltage on the associated phase of the distribution busbar (and connected feeder) and the transformer should appear transparent.

As with the previous suite of tests, directional comparison unit protection scheme models are applied to protect Line2a and Line2b, and the DIgSILENT relay model debug tool is used to provide indication of the outputs of the four Directional Agents (NW, NE, SW, and SE) for analysis .

The following Figure 85 shows the test set-up. Similar to the test scenario represented in Figure 81, it presents a view of the generic distribution network being used to test the directional comparison protection proposal. In this case, however the two Eastern Directional Agents (NE Dir Comp, and Dir Comp SE) are polarised from a ‘reverse/upstream looking’ VT at the 400 V busbar BB1. A solid three-phase fault, F, is applied to the mid-point of Line 2a.

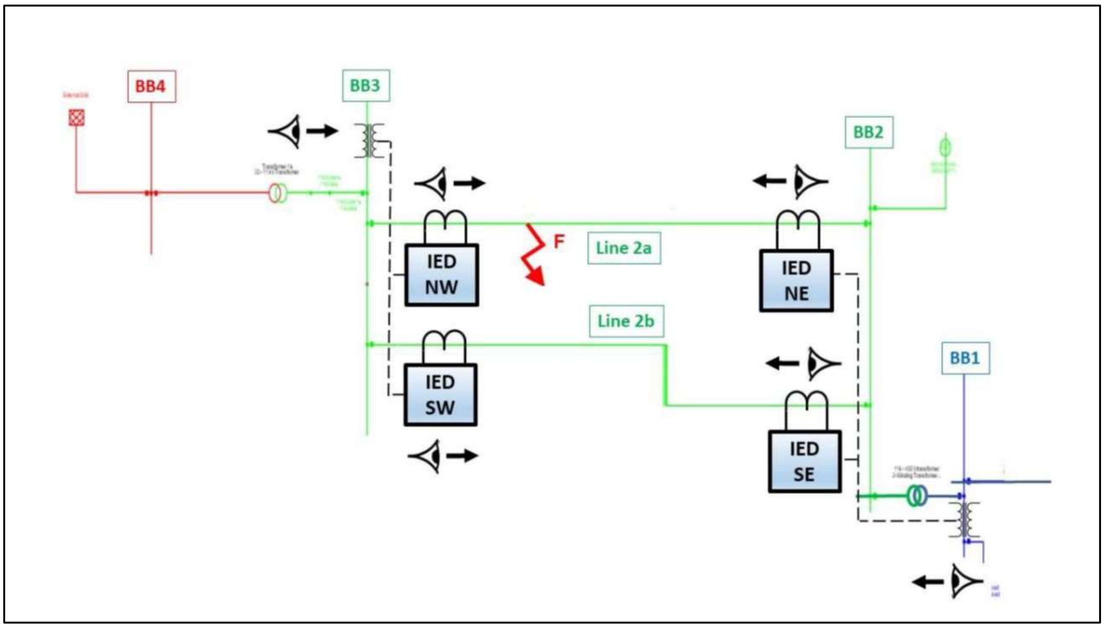


Figure 85: Example Faulted Generic Distribution Network with Selected LV Polarised Directional Agents.

Using the 'Protection Settings Output' function of the PowerFactory software, the settings applied to simulation models can be captured into an Excel spreadsheet. The following Table 16 is a summary of the settings applied to the four Directional Agent models (SE, SW, NE, NW) resident on the 11 kV 'ring' for the test.

Table 16: Directional Agent Settings Applied to for Directional Comparison Voltage Polarisation Checking Test.

Protection Device	Loc'n	Branch	Model	Stage (phase)	Current (Pri A)	Time Set (s)	Char	Direction
Dir Comp SE	BB2	11 kV Line 2b	Eastern Relay	*I>*	50	0.8	DT	Forward
				I>>	250	2.8	DT	None
Dir Comp SW	BB3	11 kV Line 2b	Western Relay	*I>*	50	0.7	DT	Forward
				I>>	250	2.7	DT	None
Dir Comp NE	BB2	11 kV Line 2a	Eastern Relay	*I>*	50	0.6	DT	Forward
				I>>	250	2.6	DT	None
Dir Comp NW	BB3	11 kV Line 2a	Western Relay	*I>*	50	0.5	DT	Forward
				I>>	250	2.5	DT	None

Note that, in practice, *I>* elements would be set instantaneous for fast selective tripping. Here they are set with staggered delays to differentiate operation of the elements and provide clarity for analysis. The back-up elements would not normally be expected to operate if the fault has been cleared by the instantaneous directional comparison scheme. (Delayed) operation of the elements is permitted for analysis purposes.

The following Figure 86 shows a 'time-overcurrent' plot of the overcurrent elements (*I>NW, I>NE, I>SW, I>SE, I>>NW, I>>NE, I>>SW, I>>SE*), which form the directional and back-up elements of the four Directional Agents resident on the 11 kV 'ring'.

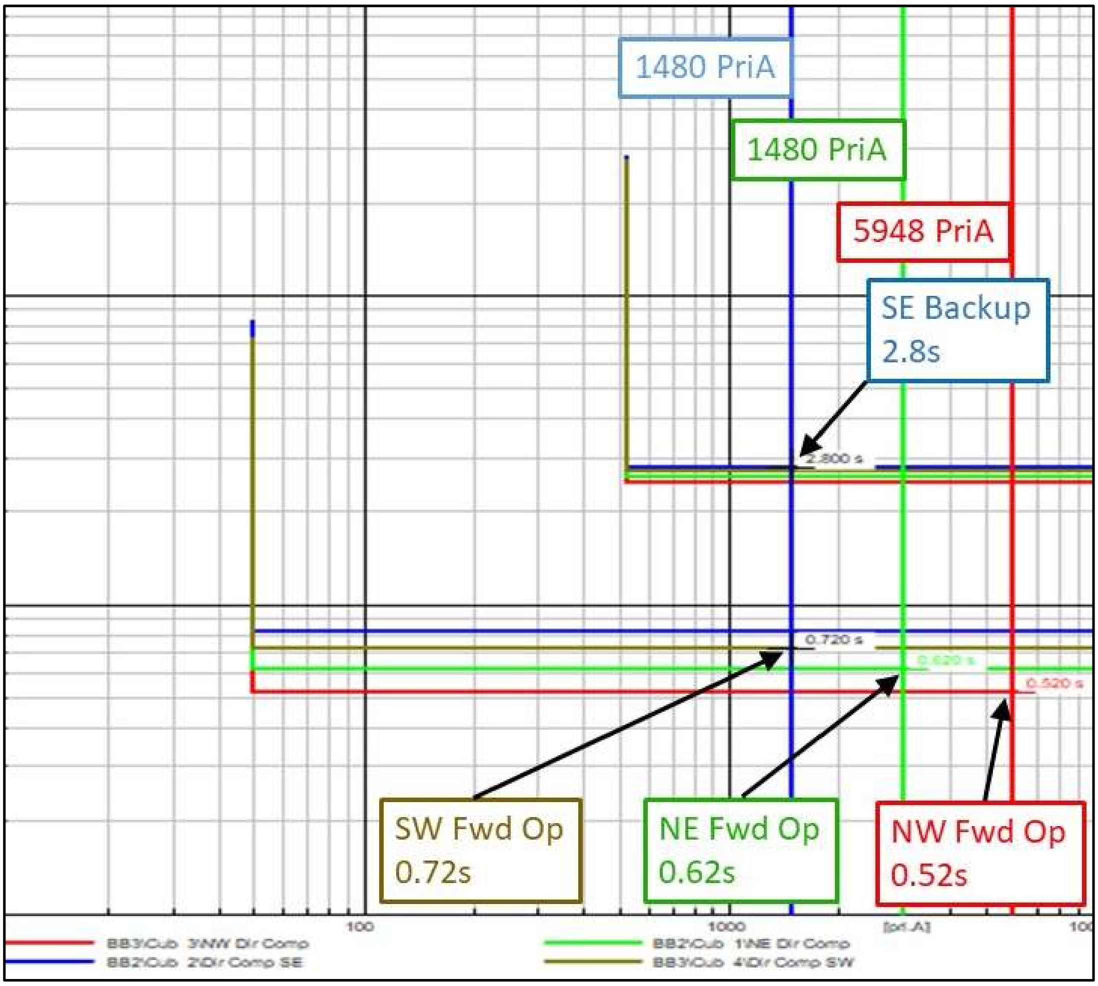


Figure 86: Time-Overcurrent Plot for Directional Agents Applied to 11 kV ring for Voltage Polarisation Checking Test.

Operating times displayed in Figure 86 are illustrative for the first overcurrent element of each Directional Agent to operate, not the operate time of the directional comparison output, yout. The state of the output of the directional comparison unit protection (yout) is determined by observation of the operation of the 'yout' values in the 'Flexible Data' fields in the Logic Block debug displays for each of the four Directional Agents (NW, NE, SW, SE).

The following Table 17 summarises the output response of the four Directional Agents for the fault scenario described by Figure 85 and Table 16. The overall scheme response (output) is also consolidated into the table.

Table 17: 11 kV Directional Agents Response Summary for 3ph, 0Ω Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, No Windfarm Connection at BB2

Fault Scenario	50% mid-line 2a 3-ph 0Ω No windfarm								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	0.02	2.5	0.52		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.62	0.02	2.6	0.62		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
	Note : y3 indicates no Rx FWD, so relay trips delayed back-up							PASS	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
	Note : Y1, y2 indicates no local FWD, so relay trips delayed back-up							PASS	
NW and NE trip Line2a in *I*> time (nominally instantaneous) as expected SW and SE restrain Line2b in *I*>> (back-up) time Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

To confirm correct response for a range of conditions, a variety of fault scenarios are applied. The detailed responses of the individual Directional Agents to the different fault scenarios are presented in Table 17, through Table 26.

Table 18: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at 10% Line2b, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	10% Line 2b 3-ph 0Ω Windfarm out of service.								Scheme Response
Expected Response	NW, SE, SW should see FWD, NE should see REV. Line 2b should trip, line 2a should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	nop	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	NW/NE see out of zone fault							PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	nop	nop	0.02	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	NW/NE see out of zone fault							PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		Result	0.02	0.72	0.02	2.7	0.72		
		Expected	0.02	0.72	0.02	2.7	0.72		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	0.02	0.82	0.02	2.8	0.82		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
Southern relays correctly detect internal fault. Northern relays correctly restrain as external fault. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 19: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at 90% Line2b, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	90% Line 2b 3-ph 0Ω Windfarm out of service								Scheme Response
Expected Response	NW, SE, SW should see FWD, NE should see REV. Line 2b should trip, line 2a should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	nop	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	NE sees out of zone fault							PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	nop	nop	0.02	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	NE sees out of zone fault							PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	0.02	2.7	0.72		
		ExpTT	0.02	0.72	0.02	2.7	0.72		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	0.02	0.82	0.02	2.8	0.82		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
Southern relays correctly detect internal fault. Northern relays correctly restrain as external fault. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 20: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at BB1, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	BB1 3-ph 0Ω								Scheme Response
Expected Response	NW, SW should see FWD. NE, SE should see REV. Only back-up tripping.								
	NW Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	nop	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip							PASS	
	NE Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	nop	nop	0.02	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip							PASS	
	SW Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip							PASS	
	SE Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip							PASS	
NW and NE trip Line2a in $I>$ time (nominally instantaneous) as expected SW and SE restrain Line2b in $I>>$ (back-up) time Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 21: 11 kV Directional Agents Response Summary for 3ph-N-E, 0 Ω Fault, applied at BB1, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	BB1 3-ph-N-E 0Ω								Scheme Response
Expected Response	NW, SW should see FWD. NE, SE should see REV. Only back-up tripping.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	nop	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip							PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	nop	nop	0.02	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip							PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip							PASS	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip							PASS	
NW and NE trip Line2a in *I*> time (nominally instantaneous) as expected SW and SE restrain Line2b in *I*>> (back-up) time Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 22: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at BB2, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	BB2 3-ph 0Ω								Scheme Response
Expected Response	NW, SW should see FWD. NE, SE should see REV. Only back-up tripping.								
	NW Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	nop	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	No Local FWD. Rx FWD. Back-up trip							PASS	
	NE Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	nop	0.62	0.02	2.6	2.6		
		ExpTT	nop	0.62	0.02	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	No Local FWD. Rx FWD. Back-up trip							PASS	
	SW Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD, Back-up trip.							PASS	
	SE Relay	Settings Ref	$I>$ 1pu FWD, $I>>$ 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	$I>$	Rx FWD	$I>>$	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip.							PASS	
NW and NE trip Line2a in $I>$ time (nominally instantaneous) as expected SW and SE restrain Line2b in $I>>$ (back-up) time Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 23: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at BB3, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays (Windfarm out of Service).

Fault Scenario	BB3 3-ph 0Ω No windfarm at BB2								Scheme Response
Expected Response	No current flow through zone. No tripping								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as ‘Expected’ below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	nop	nop	nop		
		ExpTT	nop	nop	nop	nop	nop		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as ‘Expected’ below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	nop	nop	nop		
		ExpTT	nop	nop	nop	nop	nop		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as ‘Expected’ below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	nop	nop	nop		
		ExpTT	nop	nop	nop	nop	nop		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SE Relay	Settings Ref	*I>* 1pu FWD, I>> 5pu None, times as ‘Expected’ below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	nop	nop	nop		
		ExpTT	nop	nop	nop	nop	nop		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
Upstream out of zone fault. No current flow in zone. No operation Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

Table 24: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at BB3, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays (Windfarm in Service).

Fault Scenario	BB3 3-ph 0Ω Windfarm connected at BB2								Scheme Response
Expected Response	No in zone fault. No tripping								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.5	2.5		
		ExpTT	nop	nop	0.02	2.5	2.5		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip.							PASS	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.62	nop	2.6	2.6		
		ExpTT	0.02	0.62	nop	2.6	2.6		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip.							PASS	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.7	2.7		
		ExpTT	nop	nop	0.02	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
	No local FWD start. Rx FWD. Back-up trip.							PASS	
	SE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.82	nop	2.8	2.8		
		ExpTT	0.02	0.82	nop	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
	Local FWD start. No Rx FWD. Back-up trip.							PASS	
Upstream out of zone fault. Downstream windfarm feeds some fault current through zone, but (both) Directional Comparison schemes restrain correctly. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation									✓ CORRECT

For the case of faults at BB3 as presented in Table 23 (no windfarm) and Table 24 (windfarm connected), the responses of the directional comparison unit schemes are the same (restrain). The responses of the individual Directional Agents are different between the two cases, however. This is because, for the no windfarm case, there is no current flow from west to east and so none of the elements start. When the windfarm is connected, current flows from east to west to feed the fault as can be determined from Figure 87. The overcurrent elements pick up, but all currents flow in the same sense through the zone. The fault is hence detected as external and so in this case, as well as for the no-windfarm case, the directional comparison unit schemes correctly restrain.

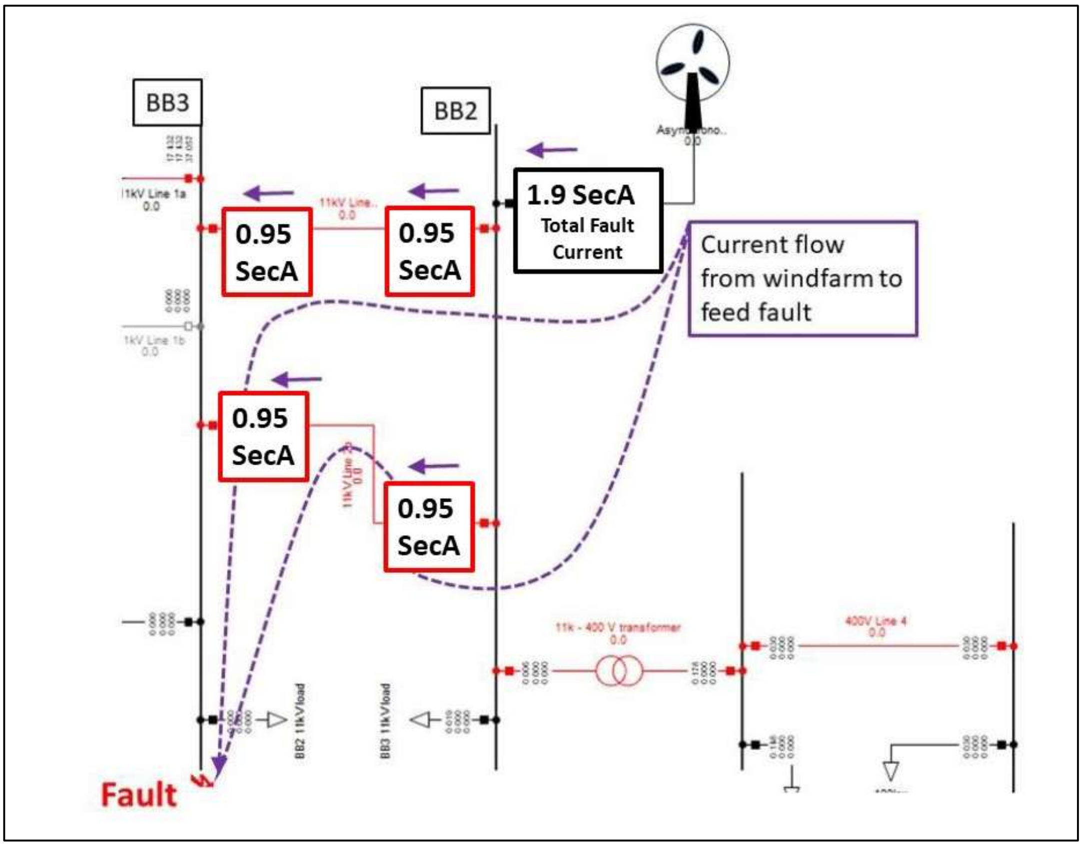


Figure 87: Fault Current Summary for 3ph, 0 Ω Fault, applied at BB3, with windfarm connected.

Table 25: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at 10 % Line2b, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

Fault Scenario	10% Line 2b 3-ph 0Ω Windfarm in service.								Scheme Response
Expected Response	NW, NE should recognise out of zone fault, SW, SE should see internal fault. Line 2b should trip, line 2a should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	nop	nop		
		ExpTT	*	*	*	*	*		
		Logic match?	✓	✓	✓	✓	✓		
	• Since NW doesn't see FWD fault.							PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.62	nop	nop	nop		
		ExpTT	*	*	*	*	*		
		Logic match?	✓	✓	✓	✓	✓		
	• Since NE doesn't receive POR							PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	0.02	2.7	0.72		
		ExpTT	0.02	0.72	0.02	2.7	0.72		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I*>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	0.02	0.82	0.02	2.8	0.82		
		Logic match?	✓	✓	✓	✓	✓		
	SW/SE see internal fault							PASS	
Southern relays correctly detect internal fault. Northern relays correctly restrain as external fault. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✓ CORRECT

For the case of faults at 10% Line2b as presented in Table 18 (no windfarm) and

Table 25 (windfarm connected), the responses of the directional comparison unit schemes are the same (restrain). The responses of the individual Directional Agents may be different between the two cases, however. This is because current may flow either way through the Northern line to feed the fault in Line 2b according to the relative strengths of the sources. In the case when the windfarm is connected (refer Figure 88), current flows from east to west in the Northern line to feed the fault and hence the elements on the Northern line pick up. Since the current is flowing through the zone to feed an external fault, the directional comparison unit scheme on the Northern line correctly restrains.

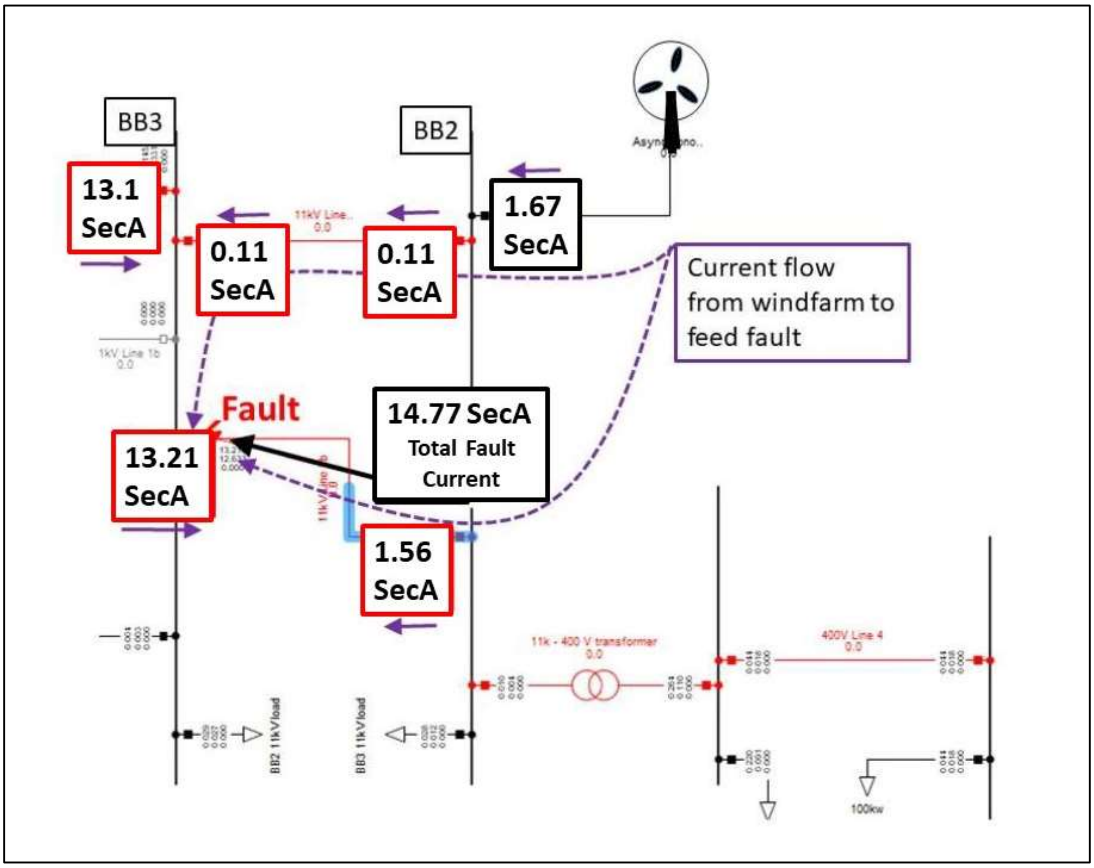


Figure 88: Fault Current Summary for 3ph, 0 Ω Fault, applied at 10% Line2b, with windfarm connected.

Table 26: 11 kV Directional Agents Response Summary for 3ph, 0 Ω Fault, applied at 90% Line2b, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, (Windfarm out of Service).

<table>
<tr><td>Fault Scenario</td><td colspan="8">90% Line 2b 3-ph 0Ω Windfarm in service</td><td rowspan="34">Scheme Response</td></tr>
<tr><td rowspan="33">Expected Response</td><td colspan="8">NW, SE, SW should see FWD, NE should see REV. Line 2b should trip, line 2a should not.</td></tr>
<tr><td rowspan="7">NW Relay</td><td>Settings Ref</td><td colspan="5">I> 1pu FWD, I>> 5pu None, times as 'Expected' below</td><td rowspan="7">Terminal Verdict</td></tr>
<tr><td colspan="6">Fault Response</td></tr>
<tr><td>Logic Signal</td><td>y1</td><td>y2</td><td>y3</td><td>y4</td><td>yout</td></tr>
<tr><td>Indicates</td><td>Send FWD</td><td>I></td><td>Rx FWD</td><td>I>></td><td>TRIP</td></tr>
<tr><td>RecTT</td><td>0.02</td><td>0.52</td><td>nop</td><td>2.5</td><td>2.5</td></tr>
<tr><td>ExpTT</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td></tr>
<tr><td>Logic match?</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td colspan="7">• Since NE sees out of zone fault</td><td>PASS</td></tr>
<tr><td rowspan="7">NE Relay</td><td>Settings Ref</td><td colspan="5">I> 1pu FWD, I>> 5pu None, times as 'Expected' below</td><td rowspan="7">Terminal Verdict</td></tr>
<tr><td colspan="6">Fault Response</td></tr>
<tr><td>Logic Signal</td><td>y1</td><td>y2</td><td>y3</td><td>y4</td><td>yout</td></tr>
<tr><td>Indicates</td><td>Send FWD</td><td>I></td><td>Rx FWD</td><td>I>></td><td>TRIP</td></tr>
<tr><td>RecTT</td><td>nop</td><td>nop</td><td>0.02</td><td>2.6</td><td>2.6</td></tr>
<tr><td>ExpTT</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td></tr>
<tr><td>Logic match?</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td colspan="7">• Since NE sees out of zone fault</td><td>PASS</td></tr>
<tr><td rowspan="7">SW Relay</td><td>Settings Ref</td><td colspan="5">I> 1pu FWD, I>> 5pu None, times as 'Expected' below</td><td rowspan="7">Terminal Verdict</td></tr>
<tr><td colspan="6">Fault Response</td></tr>
<tr><td>Logic Signal</td><td>y1</td><td>y2</td><td>y3</td><td>y4</td><td>yout</td></tr>
<tr><td>Indicates</td><td>Send FWD</td><td>I></td><td>Rx FWD</td><td>I>></td><td>TRIP</td></tr>
<tr><td>RecTT</td><td>0.02</td><td>0.72</td><td>0.02</td><td>2.7</td><td>0.72</td></tr>
<tr><td>ExpTT</td><td>0.02</td><td>0.72</td><td>0.02</td><td>2.7</td><td>0.72</td></tr>
<tr><td>Logic match?</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td colspan="7">SW/SE see internal fault</td><td>PASS</td></tr>
<tr><td rowspan="7">SE Relay</td><td>Settings Ref</td><td colspan="5">I> 1pu FWD, I>> 5pu None, times as 'Expected' below</td><td rowspan="7">Terminal Verdict</td></tr>
<tr><td colspan="6">Fault Response</td></tr>
<tr><td>Logic Signal</td><td>y1</td><td>y2</td><td>y3</td><td>y4</td><td>yout</td></tr>
<tr><td>Indicates</td><td>Send FWD</td><td>I></td><td>Rx FWD</td><td>I>></td><td>TRIP</td></tr>
<tr><td>RecTT</td><td>0.02</td><td>0.82</td><td>0.02</td><td>2.8</td><td>0.82</td></tr>
<tr><td>ExpTT</td><td>0.02</td><td>0.82</td><td>0.02</td><td>2.8</td><td>0.82</td></tr>
<tr><td>Logic match?</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td colspan="7">SW/SE see internal fault</td><td>PASS</td></tr>
<tr><td colspan="9">Southern relays correctly detect internal fault. Northern relays correctly restrain as external fault.
Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation</td><td>✓
CORRECT</td></tr>
</table>

For the case of faults at 90% Line2b as presented in Table 19 (no windfarm) and Table 26 (windfarm connected), the responses of the directional comparison unit schemes are the same (restrain). The responses of the individual Directional Agents may be different between the two cases, however. This is because current may flow either way through the Northern line to feed the fault in Line 2b according to the relative strengths of the sources. In the case when the windfarm is connected (refer Figure 89), current flows from west to east in the Northern line to feed the fault and hence the elements on the Northern line pick up. Since the current is flowing through the zone to feed an external fault, the directional comparison unit scheme correctly restrains.

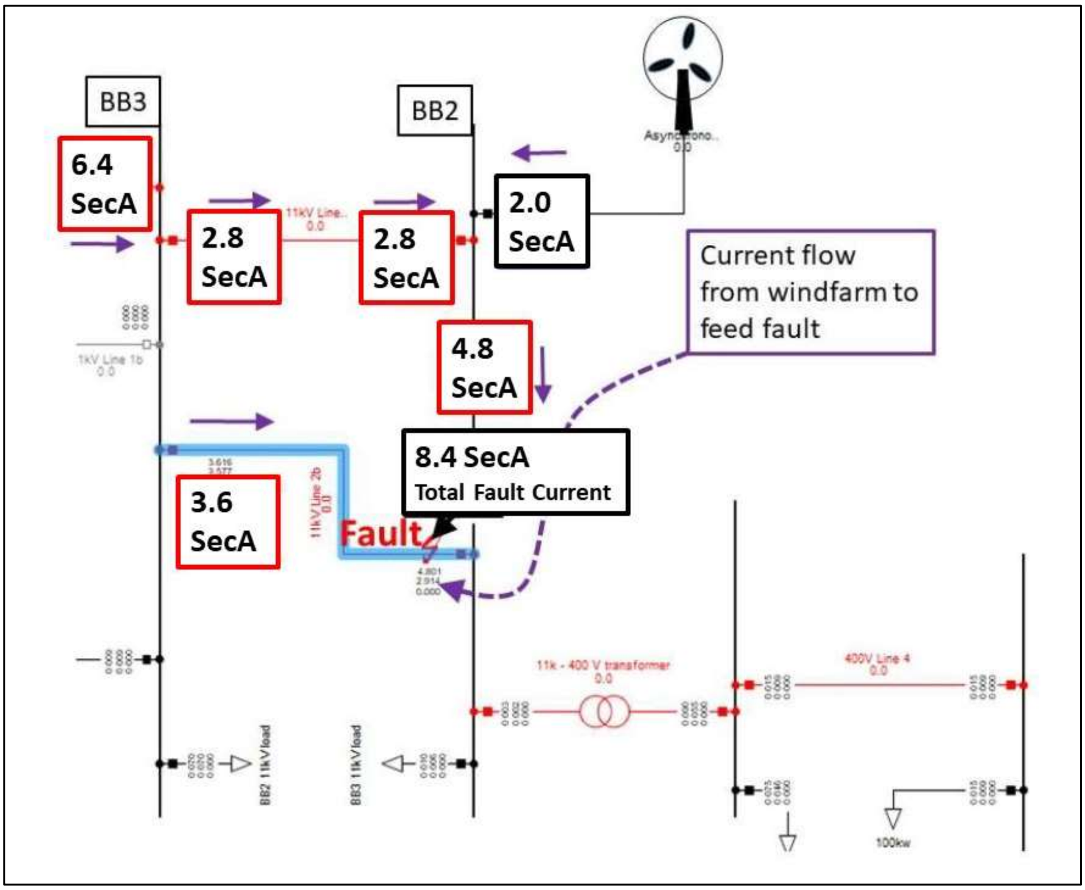


Figure 89: Fault Current Summary for 3ph, 0Ω Fault, applied at 10% Line2b, with windfarm connected.

For convenience the summary responses of the corresponding directional comparison unit schemes are presented in the following Table 27.

Table 27: Directional Comparison Scheme Fault Response Summary for LV Polarised Eastern Relays.

Fault Classification	Fault Details	Results Table	Dir Comp Scheme Response	Verdict
Internal Northern (Line2a) Windfarm at BB2 OOS	3ph, 0 Ω, 50% Line2a	Table 17	Northern Line Trip Southern Line Restrain	Correct operation as expected
Internal Southern (Line2b) Windfarm at BB2 OOS	3ph, 0 Ω, 10% Line2b	Table 18	Northern Line Restrain Southern Line Trip	Correct operation as expected
Internal Southern (Line2b) Windfarm at BB2 OOS	3ph, 0 Ω, 90% Line2b	Table 19	Northern Line Restrain Southern Line Trip	Correct operation as expected
External Windfarm at BB2 OOS	3-ph-N, 0 Ω, BB1	Table 20	Directional Comparison restrains both lines	Correct operation as expected
External Windfarm at BB2 OOS	3-ph-N-E, 0 Ω, BB1	Table 21	Directional Comparison restrains both lines	Correct operation as expected
External Windfarm at BB2 OOS	3-ph 0 Ω, BB2	Table 22	Directional Comparison restrains both lines	Correct operation as expected
External Windfarm at BB2 OOS	3-ph 0 Ω, BB3	Table 23	Directional Comparison restrains both lines	No operation as expected Note 2
External Windfarm at BB2 in service	3-ph 0 Ω, BB3	Table 24	Directional Comparison restrains both lines	Correct operation as expected
Internal Southern (Line2b) Windfarm at BB2 OOS	3ph, 0 Ω, 10% Line2b	Table 25	Northern Line Restrain Southern Line Trip	Correct operation as expected
Internal Southern (Line2b) Windfarm at BB2 OOS	3ph, 0 Ω, 90% Line2b	Table 26	Northern Line Restrain Southern Line Trip	Correct operation as expected

Notes:

1. OOS – Out of Service (windfarm not connected)
2. Correct operation indicates operation (i.e. tripping – either instantaneous directional comparison or delayed back-up according to fault type). No operation indicates no current flowing, no element pick-up and hence no tripping.

8.1.5 Protection Testing with Varying Fault Impedances

To test the impact of increasing fault impedance on the performance of the protection, a suite of tests is similar to those of section 8.1.4.5 were performed. The difference however is that, rather than the faults being of the three-phase solid (0 Ω) type, the (resistive) impedance in the fault path was increased. In all cases, as the fault resistance increases, so the protection becomes less reliable. The limits of stability are established with this suite of tests.

For each of the network topologies and fault positions tested, the limiting value of resistance at which the protection scheme gave incorrect results is noted, and the effect is reflected in each of the tables of results. For reference, the settings applied for this suite of tests are as per Figure 82.

8.1.5.1 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 4 Ω. The scheme performance at this value is shown in the following Table 28.

Table 28: 11 kV Directional Agents Response Summary for 3ph, 4 Ω Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

Fault Scenario	50% mid-line 2a 3-ph 4 Ω No Windfarm								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✗	✓	✗		
								FAIL	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
The failure is due to insufficient current flowing at NE to operate I>> back-up elements. Directional performance is correct. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

8.1.5.2 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 10% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 1 Ω. The scheme performance at this value is shown in the following

Table 29.

Table 29: 11 kV Directional Agents Response Summary for 3ph, 1 Ω Fault, applied at 10% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

Fault Scenario	10% mid-line 2a 3-ph 1 Ω No Windfarm								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✗	✓	✗		
								FAIL	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	nop	nop	nop		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✗	✗		
								FAIL	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	nop	nop	0.02	nop	nop		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✗	✗		
								FAIL	
The failure is due primarily to insufficient current flowing at NE and SE to operate I>> back-up elements. Directional performance is correct. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

8.1.5.3 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 90% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 1.3 Ω. The scheme performance at this value is shown in the following Table 30.

Table 30: 11 kV Directional Agents Response Summary for 3ph, 1.3 Ω Fault, applied at 90% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm disconnected at BB2.

Fault Scenario	90% mid-line 2a 3-ph 1.3 Ω No Windfarm								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	0.02	2.5	0.52		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.62	0.02	2.6	0.62		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	0.02	2.7	0.72		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✖	✓	✖		
								FAIL	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✖	✖	✓	✓	✖		
								FAIL	
The failure is due to incorrect decision making by relays SE and SW. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✖ INCORRECT

8.1.5.4 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 3 Ω. The scheme performance at this value is shown in the following Table 31.

Table 31: 11 kV Directional Agents Response Summary for 3ph, 3 Ω Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

Fault Scenario	50% mid-line 2a 3-ph 3 Ω Windfarm connected								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.52	nop	2.5	0.52		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✗	✓	✓		
								FAIL	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	mop	nop	0.02	2.6	2.6		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.72	nop	2.7	2.7		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.8	2.8		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
The failure is due to NE making incorrect directional decision. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

8.1.5.5 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 10% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 1 Ω. The scheme performance at this value is shown in the following

Table 32.

Table 32: 11 kV Directional Agents Response Summary for 3ph, 1 Ω Fault, applied at 10% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

Fault Scenario	10% mid-line 2a 3-ph 1 Ω Windfarm connected								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.52	nop	2.5	2.5		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	2.6	2.6		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.72	nop	nop	nop		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✓	✗	✗		
								FAIL	
	SE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	*I>*	Rx FWD	*I>>*	TRIP		
		RecTT	nop	nop	0.02	nop	nop		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✓	✓	✓	✗	✗		
								FAIL	
The failure is due directionality elements operating incorrectly Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

8.1.5.6 11 kV Directional Agents Response Summary for 3ph, Resistive Fault, applied at 90% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

For this scenario, the limiting value of fault resistance at which the protection started to display incorrect operation is approximately 0.3 Ω. The scheme performance at this value is shown in the following

Table 33.

Table 33: 11 kV Directional Agents Response Summary for 3ph, 0.3 Ω Fault, applied at 90% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

Fault Scenario	90% mid-line 2a 3-ph 0.3 Ω Windfarm connected								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.52	0.02	2.5	0.52		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.62	0.02	2.6	0.62		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SW Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.72	0.02	2.7	0.72		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✗	✓	✗		
								FAIL	
	SE Relay	Settings Ref	*I*> 1pu FWD, *I*>> 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I*>>	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
The failure is due to incorrect decision making by relays SE and SW. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

8.1.5.7 11 kV Directional Agents Response Summary for 3ph, Resistive Faults, applied to Line2b.

To assess the impact of resistive faults on the parallel Line 2b, similar fault scenarios to those described in sections 8.1.5.1 – 8.1.5.6 were repeated but with the fault applied to line 2b. In all cases for high resistive three-phase faults on Line 2b, the directional elements worked correctly for fault resistance impedances up to 10 Ω.

8.1.6 Protection Performance with for Single-Phase-to-Earth Faults

To assess the impact of single-phase-to-earth faults on the scheme, a series of faults similar to those detailed in 8.1.5 were repeated but with single phase-to-earth faults applied.

In all cases the operation of the protection scheme gives cause for concern.

For reference purposes, the following

Table 34 records one arbitrarily chosen example test with a 0 Ω A-E fault applied at 50% of the line 2a (windfarm connected).

Table 34: 11 kV Directional Agents Response Summary for Ph-E 0 Ω Fault, applied at 50% Line2a, with 11 kV Polarised Western Relays and 400 V Polarised Eastern Relays, Windfarm connected at BB2.

Fault Scenario	50% mid-line 2a Ph-E 0 Ω Windfarm connected								Scheme Response
Expected Response	NW, NE, SW should see FWD, SE should see REV. Line 2a should trip instantaneous, line 2b should not.								
	NW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.52	0.02	2.5	0.52		
		ExpTT	0.02	0.52	0.02	2.5	0.52		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	NE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.62	0.02	2.6	0.62		
		ExpTT	0.02	0.62	0.02	2.6	0.62		
		Logic match?	✓	✓	✓	✓	✓		
								PASS	
	SW Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.72	0.02	2.7	0.72		
		ExpTT	0.02	0.72	nop	2.7	2.7		
		Logic match?	✓	✓	✗	✓	✗		
								FAIL	
	SE Relay	Settings Ref	*I>* 1pu FWD, *I>>* 5pu None, times as 'Expected' below					Terminal Verdict	
		Fault Response							
		Logic Signal	y1	y2	y3	y4	yout		
		Indicates	Send FWD	I>	Rx FWD	*I>>*	TRIP		
		RecTT	0.02	0.82	0.02	2.8	0.82		
		ExpTT	nop	nop	0.02	2.8	2.8		
		Logic match?	✗	✗	✓	✓	✗		
								FAIL	
The failure is due to incorrect decision making by relay SE. Note : RecTT – recorded trip time, ExpTT – expected trip time, nop - no operation.									✗ INCORRECT

With faults applied, all directional elements operated under all conditions even those where operation may appear to be an incorrect response. This throws some doubt over the credibility of the proposal, but is not entirely unexpected as the relative phases of the voltages and currents are expected to vary according to fault parameters. Further investigation is required in this respect. Initially, it is considered that the performance of the DIgSILENT directional comparison relay models created during this project are likely to be contributors to the problem. The limited facilities provided to debug relay model performance however make this a difficult proposition and it is considered that a better approach would be to repeat the test scenarios and investigate using proven, commercially available directional protection devices. Accordingly, the issue is commended, with priority, into the category of proposed future work.

8.1.7 Distribution Network Protection Testing Results Summary

Through section 8.1 results have been presented to verify the network model introduced at Figure 21. Using time-graded overcurrent protection, a network model configured as a passive radial network as illustrated in Figure 24 has been benchmarked. Directional Agent and Teleprotection (Communications Interlink) relay simulation models have been introduced as per Figure 38 and their suitability to be deployed to provide directional comparison unit protection schemes has been tested. The principle of polarising directional protection from remote low-voltage connection points on the network has been demonstrated.

Accordingly, the configurable network model introduced at Figure 21 is considered robust and proven for the evaluation of directional comparison unit protection schemes deployed as per Figure 38.

The simulation models of Directional Agents and Teleprotection (Communications Interlink) relays (as presented in Appendix I) necessary to construct directional comparison unit protection scheme simulation models for evaluation have been extensively exercised. Whilst the results of applying solid (0 Ω) three-phase faults are encouraging, some concerns are raised by the response of the models as fault resistances increase (although these may be alleviated by the inclusion of more sensitive elements such as SEF in practical realisation). More concerning, however, is the performance of the models under single-phase-to-earth fault conditions and further work is strongly urged to eliminate any possibilities of errors being attributable to the simulation models in advance of renewed efforts to establish performance limits.

Combined, the results lend support to the proposal that directional comparison techniques employing Directional Agents deriving information from LV polarising signals and HV current measurements may provide suitable protection for evolving electrical distribution networks. The results do, however, expose that further development and evaluation work is required.

The network model is considered a suitable platform to provide future evaluation opportunities with which to explore practical performance issues and determine operational performance limits – ideally with proven, commercially available, manufactured and approved hardware devices. The simulation models are considered to require further development and proving before they could be used to evaluate of the concepts with confidence

8.2 Distributed Low-Voltage Measurements Evaluation

Section 8.2 associates with evaluating LV polarisation issues.

The objective of this work package is to assess the feasibility of providing a compact, cost effective AC voltage measuring device that can be used to provide a polarising signal suitable for use by a Directional Agent IED. The polarising signal should wirelessly deliver numerical representation of LV mains voltage (230 V) input.

Identified research activities are literature review followed by candidate selection, and subsequent proof-of-concept testing.

Because of cost and space considerations, voltage transformers (VTs) are often unavailable for use by distribution protection. This can be an obstacle to enjoying the benefits that applying directional protection can bring. Providing voltage polarisation by means of a small cost-effective transducer is attractive.

The concept of a 'Voltage Cube' has emerged (Figure 18). The idea is to have something that physically resembles the mains plug-in power cubes that typically deliver DC at 5 V, 9 V, 12 V, 15 V, 19 V, etc., but instead of providing a DC supply, rather, the device should provide a numeric representation of the mains voltage from which it is supplied. The numerical measurements would be transmitted (ideally wirelessly) from the device using Ethernet communications. From this idea the following avenues open for exploration.

- What component parts would be required to implement a Voltage Cube to give a wireless measurement of the mains voltage?
- Could a prototype Voltage Cube be implemented and used to
    - Investigate the suitability of using this wireless voltage?
    - Assess its suitability for providing the necessary voltage input for directional comparison protection
        - Accuracy of signal
        - Availability of signal
        - Speed, response time, latency, consistency, jitter, etc., of communications
        - Possible compensation of communication variance (GOOSE ping-pong, directional blinding angles, etc.)
    - Combine the wireless voltage with conventional current signals to provide directional comparison distribution protection.

8.2.1 Voltage Cube Literature Review

The Voltage Cube concept is intended to wirelessly present a Directional Agent with a non-conventional voltage polarising signal to provide a reference for directionality.

Section 2.2 of this work considers the impact of ICT on protection, and explains that the introduction of microprocessors and ICT into protection and other electrical substation devices brings new opportunities and approaches. The term ‘Digital Substation’ has been widely adopted within the industry to mean a type of electrical substation where (the majority of) hardwiring of devices is eliminated by the deployment of IEDs (and other such ‘intelligent’ devices) which rely on communications to operate [130], [131], [132]. Seamless interconnectivity relies on clearly defined interfaces and protocols such as IEC 61850 (introduced in section 2.3), but the effectiveness of the approach has seen the principles extend to other items of plant such as switchgear and transformers.

Companion to IEC 61850 are the IEC 61869 standards [133]. Available for purchase from the IEC (webstore.iec.ch), IEC 61869 comprises a set of standards to define the requirements for instrument transformers such as the CTS and VTs used by protection devices. The set of standards extends to include (in part 9) the additional requirements for digital output for instrument transformers. For a purchase-free introduction to the IEC 61869 standards Grasset, however, provides a useful summary [134].

Since the IEC 61869 standard precisely details the specification and presentation of numerical measurement values from substation IEDs, and since the Voltage Cube fits precisely within this categorisation, no further literature review in this respect is considered necessary.. However, online ‘literature’ may provide a bountiful source of inspiration for those interested in developing a concept model, exploring fit and form. Some of these are explored in the following sections.

8.2.2 Voltage Cube Candidate Proposals

The search facilities of a well-known internet marketplace can quickly provide inspiration for many things. Such a search was the starting point for an investigation into the feasibility of producing a low-cost voltage transducer capable of providing a digitised polarising signal for a directional protection device.

The term 'wireless mains voltage' may not ring true to a power systems engineer, but to a search engine it can prompt a return of a raft of valuable possibilities. The results from such a search offered a number of interesting potential candidates from which to explore concept model/ prototype creation. Amongst the more credible potential candidates, a search of 'mains voltage interface', and/or, 'wireless (Ethernet) interface' and similar terms exposed the following list of devices.

- Wireless Hubs
- Raspberry Pi
- Wireless Voltmeter
- Wireless Oscilloscope
- Broadband Extender Flex

These possibilities are discussed in terms of the potential functionality that they could provide to a concept Voltage Cube, as well offering indicative estimates of costs to implement. Note that the costing are estimates based on typical internet selling prices taken around the time of writing.

8.2.2.1 Voltage Cube Feasibility based around Wireless Hub and Raspberry Pi

One option considered is to combine the functionalities of a wireless hub (for communications interface) with a voltage adaptor (for mains voltage interface) and a Raspberry Pi (for signal acquisition and communications management)

A wireless interface realised in the form of a wireless hub could be sourced for around £15.

The hub supports four LAN ports with protocols to Wi-Fi 802-11 [135] and as such could support the physical wireless interface connectivity required by the Voltage Cube. It features a voltage adaptor to provide a low-voltage DC supply, and could consequently provide the mains voltage connectivity from which to capture mains voltage measurements.

It does not, however, contain signal processing provision of the type that would be required to package the measurements into a structure suitable for interface to IEC 61869 compliant IEDs. To implement the processing functionality required, consideration is given to combining a wireless hub with a Raspberry Pi.

A Raspberry Pi has been described as "a low cost, credit-card sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse. It is a capable little device that enables people of all ages to explore computing, and to learn how to program in languages like Scratch and Python" [136]. It provides an easy-access low-cost route into developing micro-controller applications. As López, et al, demonstrate [137], it lends itself to applications where process control and internet technologies meet and hence could be eminently suitable for use as the controlling engine for a Voltage Cube. At around £30 for an entry-level kit, if used in conjunction with the wireless hub package, it should contain the necessary components and adaptation capability to allow a functional prototype to be created. Whilst such a creation could provide the necessary interfaces, connectivity, and capability, it would need substantial development to afford the required functionality.

Using simple component parts, therefore, whilst it may be possible to have a prototype Voltage Cube based on a wireless hub, a voltage adaptor, and a Raspberry Pi for around £50 in component costs, due to requirement to implement the functionality in a programmable controller, it is suggested that more convenient options might be afforded by an approach based either on a wireless voltmeter or on a wireless oscilloscope where some of the necessary mains-signal acquisition functionality may already have been developed.

8.2.2.2 Voltage Cube Feasibility based on Wireless Voltmeter

Wireless voltmeters are available for around £20. Such a device would provide a multi-function DC meter based on 2.4G wireless data transmission technology.

The meter can measure miscellaneous parameters such as voltage, current, power, charge and discharge capacity, watt-hour, time, and temperature.

It has over-current protection, under-voltage protection, and limited protection and other protection functions.

The instrument can automatically identify the direction of the current, and the battery capacity can be monitored in real time.

The instrument uses TFT LCD display, display information is comprehensive, user-friendly and better interaction.

The wireless voltmeter is cheap and the basic elements for a Voltage Cube implementation are featured, but it only supports DC measurement, and the sample rate is very slow. It is not, therefore, considered suitable.

8.2.2.3 Voltage Cube Feasibility based on Voltage Oscilloscope

The Hantek IDSO 1070A is a wireless oscilloscope that delivers it’s functionality, in part, by offloading its user interface to be supported on a remote laptop/tablet/smart ‘phone.

The device is illustrated in the following Figure 90 and is available for less than £150[9].

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[9] Price check on Ebay £137.44 @ 10 May 2021

Figure 90: Hantek Wireless Oscilloscope.

As illustrated, the ‘scope doesn’t feature a traditional display, instead, it relies on transmitting display data at high speed to a laptop or equivalent where software implements a graphical user display. The price includes the ‘scope, the display software, mains and battery power supply provision, and a pair of test probes.

With appropriate probes (x10 supplied), it is possible to use it to measure domestic mains input voltage. With 70 MHz bandwidth, 125 MSa/s (2.5 MSa/cycle @ 50 Hz) and 8-bit vertical resolution, the accuracy seems appropriate for accurate measurement of electrical distribution system analogue quantities. With integral wireless communications, it should be able to present the measurements in a useful format. It should be noted that although the wireless communications provide the capability for transferring digitised versions of (for example) mains voltage quantities, they are understood to achieve this by means of transferring simple csv formatted frames, rather than conforming to the desired standard IEC 61850-9.

Although it is DC battery powered, the 'scope is supplied with a mains charger that connects to a single-phase 230 V supply.

Power supply and serial communications can be made via USB connections, but with a charged battery and connection via WiFi, it can be used completely isolated. This makes it ideal for working in high voltage applications.

8.2.2.4 Voltage Cube Feasibility based on Broadband Extender Flex

The following Figure 91 shows an image of a BT Broadband Extender Flex.

Figure 91: BT Broadband Extender Flex

The device (in the case of the example shown, a specific device marketed by BT in the UK), uses the mains electricity in a (domestic) property to extend broadband network connectivity throughout the property from the incoming hub.

The principle is based on Power Line Carrier (PLC) which uses power conductors as a medium to support (higher than mains-frequency) modulated electrical communications systems. Traditionally used by protection engineers to implement, for example phase-comparison protection schemes [138], the concepts have been adapted and adopted for use in the domestic environment (for example, Ricci, et al., [139]).

At less than £75[10] for a pair of matched devices, the Broadband Extender Flex are not only attractively priced, but they also provide much of the required functionality of the desired Voltage Cube. The Broadband Extender Flex has a mains voltage interface. It has a (wired) Ethernet interface, and provides a degree of connectivity between the two. These features clearly make it a potentially attractive starting point for a prototype/concept model. The device construction is also attractive for the intended application, comparing most favourably compared with a conventional VT.

The following Figure 92 shows a deconstructed BT Broadband Extender Flex device.

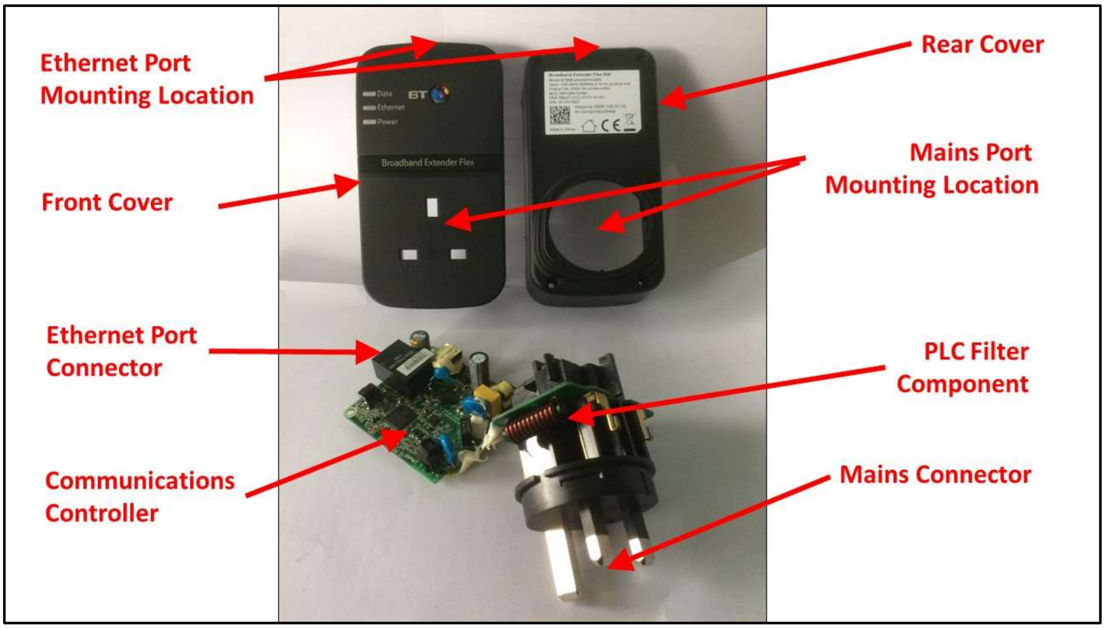

Figure 92: Deconstructed BT Broadband Extender Flex

In the figure, key components are visible and have been identified for reference.

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[10] BT list price £74.99 @ 10 May 2021

Whilst the device has a mains voltage connection and interface, a communications controller, an Ethernet interface, appealing construction, and an attractive price, it has no voltage measurement capability and no wireless interface requiring that some functional enhancing would be necessary to adapt it for prototyping purposes.

It may be argued, however that being blessed with a hardwired Ethernet interface, it may be less susceptible to cyber-attack than a wireless equivalent. Issues of cyber-security are beyond the intended scope of this work, but the topic will be briefly revisited in the later chapter on suggestions for future work.

It is also worth noting that in the field of substation automation, it is common to equip IEDs with alternative, or duplicate, media with which to connect to communications ports. Thus it is possible to envisage a commercial solution featuring a choice of wireless, wired, or fibre-optic Ethernet communications interfaces.

8.2.3 Voltage Cube Proof-of-Concept Model Selection

From the options assessed, the wireless voltage oscilloscope option is chosen as the one with which to pursue initial investigations. The main reason for choice is that it is the closest match to the required functionality – sufficiently close to allow rudimentary field testing, at least, to be performed. Should the studies move forward to offer the possibilities for site trials, then the choice may be revisited to purpose a solution more fully aligned to the functional requirements of communicating in accordance with IEC 61850-9, thus affording industry conformance.

8.2.4 Voltage Cube Proof-of-Concept Testing

With the Hantek IDSO1070A ‘scope seemingly possessing most of the features necessary to deliver Voltage Cube functionality[11], it seems an ideal starting point for from which to create a prototype model.

A Hantek IDSO1070A ‘scope was purchased to evaluate its performance for use as a simple single-phase WiFi voltage acquisition unit.

The Hantek IDSO1070A is a two-channel digital oscilloscope.

It does not have an integrated user interface/display (UI). Instead, it supports a remote UI on a laptop or mobile device. Communication with the UI is either via USB or WiFi serial connection.

Although it is battery powered, it also has an ac mains charger. So by connecting one input channel to the mains connection it could monitor a mains voltage signal and communicate the voltage quantity wirelessly.

The input channel rating is 35 V pk (max). So with a (supplied) 10x probe, it is possible to measure a 250 V rms (350 V pk) phase-neutral voltage.

Setting up the device as a basic oscilloscope communicating with the associated UI software on a laptop and connecting one of the input probes to a mains input gave an immediate demonstration of the devices’ ability to provide the necessary prototype functionality. The following Figure 93 shows the UI software running on a standard laptop and acquiring a mains voltage input signal connected to one of the ‘scopes’ input channels. The sampled values are being communicated wirelessly between the ‘scope and the laptop.

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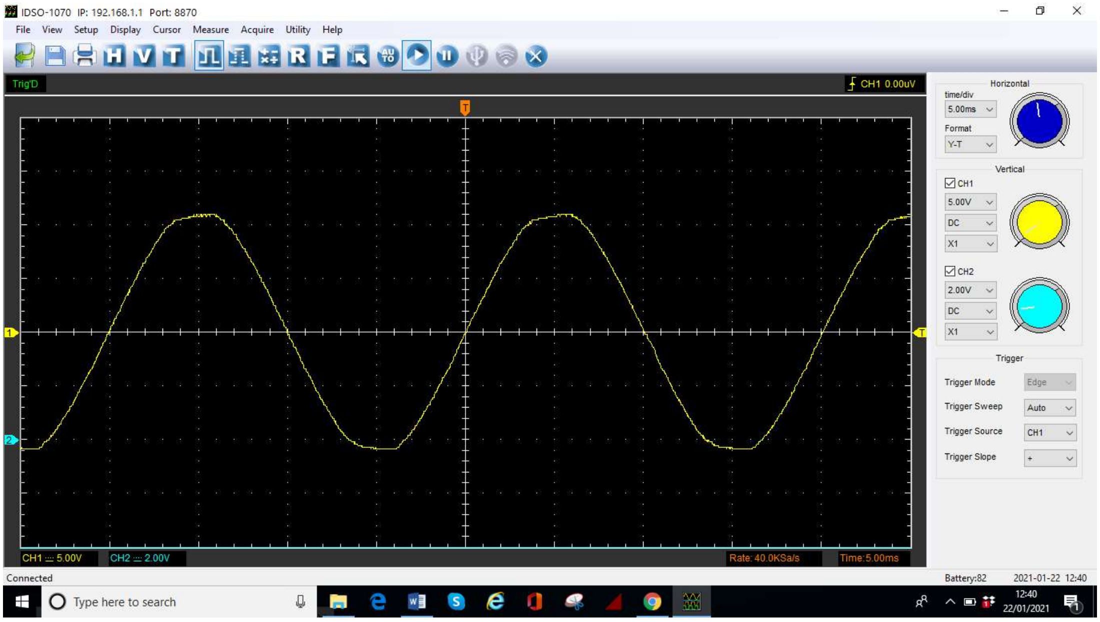
[11] The most notable deficiency is that the communications of sampled voltage values is not conformant with IEC61850-9.



CH1 0.00uV

time/div 5.00ms
Format Y-T

☑ CH1 5.00V DC X1
☑ CH2 2.00V DC X1

Trigger Mode Edge
Trigger Sweep Auto
Trigger Source CH1
Trigger Slope +

CH1 ⎓ 5.00V
CH2 ⎓ 2.00V
Rate: 40.0KSa/s
Time: 5.00ms

Battery:82 2021-01-22 12:40
12:40 22/01/2021

Figure 93: Mains Waveform Display on (remote) Hantek 'Scope UI.

The 'scope was set to measure the signal and connected via WiFi to a laptop (Lenovo T460 standard UoM issue) running the display software.

As an exercise to gauge WiFi performance, the 'scope was positioned indoors (in a domestic house adjacent a BT 'Homehub') and the laptop taken on an excursion around the house and surrounding areas. An example test set-up is shown in Figure 94.

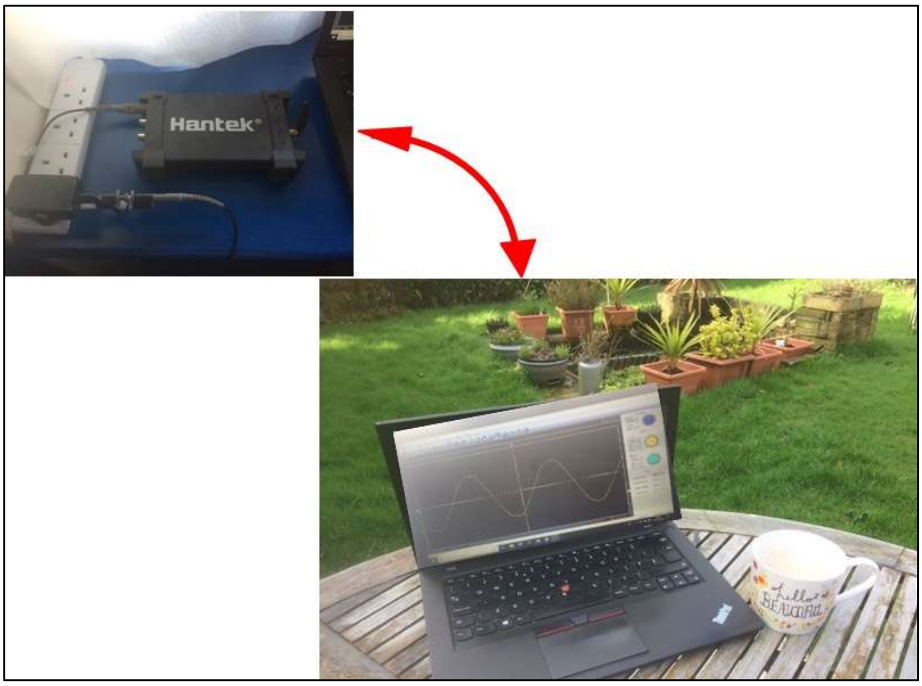


Figure 94: Voltage Cube Prototype Proof-of-Concept Testing .

Whilst the performance (operating distance) of the WiFi connection was not as good as that of the domestic BT hub/router servicing the same premises, coverage of around 10m was reliable.

Signal boosting and path optimisation techniques boast connectivity distances of several hundred metres that should prove adequate for the intended application.

The investigation demonstrates that around £150 can acquire enough technology to provide the functionality sought from a wireless Voltage Cube by adopting and adapting the design of a wireless digital oscilloscope.

The result of the study, therefore, is that producing a voltage acquisition unit suitable for use with a Directional Agent as conceptually illustrated in Figure 95 is feasible. An 'off the shelf' oscilloscope is capable of providing most of the required functionality for around £150. Adaptation of the design to provide conformity to IEC 61869 and improve wireless coverage would inevitably increase costs, and as a somewhat 'niche' design, the product is unlikely to benefit from the cost-pricing breaks that high volume commodities such as oscilloscopes might enjoy. Nonetheless, experience suggests that a suitable product could be brought to market for under £1000, delivering value and fit.

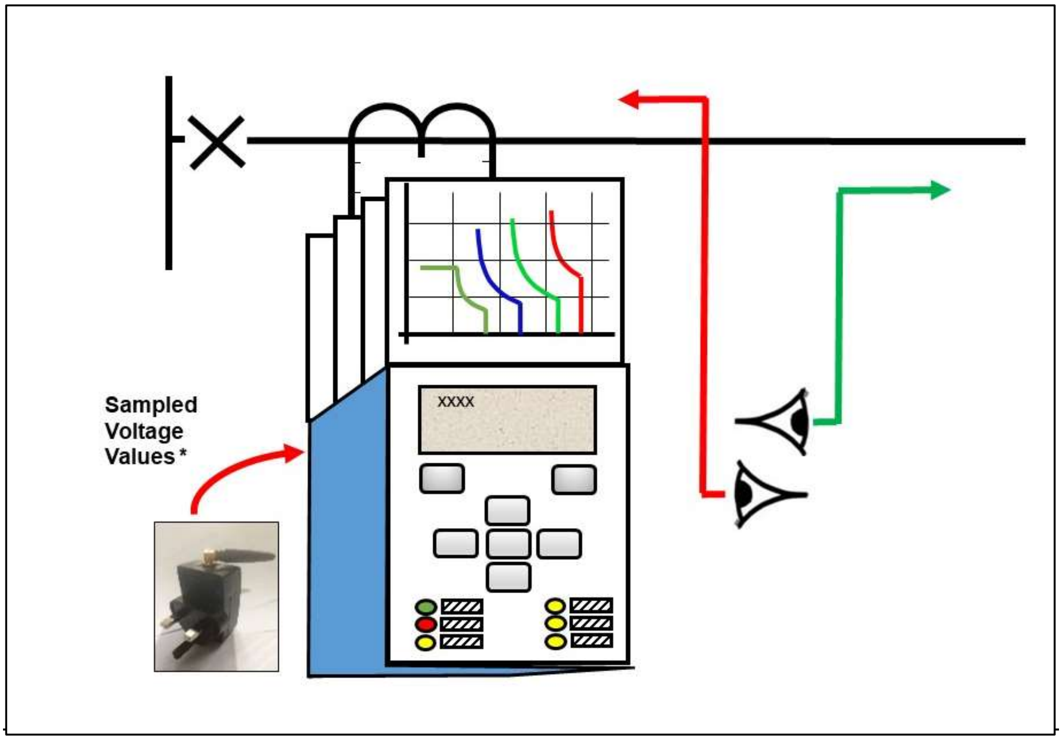


Figure 95: Directional Agent Concept.

8.3 Wireless Connectivity Results

The intent of this section had been to present the results of conjunctive testing to demonstrate the interconnectivity of directional comparison unit scheme elements using wireless communications.

Unfortunately, due primarily to working restrictions imposed to try to curb the Covid19 pandemic, the anticipated work could not be undertaken.

Testing of wireless communication was limited to the rudimentary ‘proof-of-concept’ testing associated with evaluating low-cost voltage acquisition as presented in 8.2.4.

Chapter 9 Conclusions

Motivated by a desire to contribute to developing a more sustainable future by improving accessibility to greener sources of energy, this work aspires to equip electrical distribution networks with improved protection solutions. Promising "Wide-Area Protection of Distribution Networks using Directional Agents derived from LV Polarising Voltage Signals and HV Current Measurements", the work introduces a proposal to evolve proven electrical distribution protection techniques to work better in applications with embedded generation. Combined with a novel approach to the measurement of power system signals, wirelessly-connected so-called 'Directional Agents' are proposed to provide protection for smart grids.

At the inception of the studies, it was anticipated that the research would assess directional protection principles for suitability to protect emerging smart electrical distribution grids, which are distinguished by increasing penetration levels of embedded generation from renewable resources. It was considered that the work would also assess the feasibility of a novel approach to power system signal measurements, and that it would appraise the suitability of wireless Ethernet connectivity technology to provide the necessary interconnectivity to deliver the protection offering. Thereafter the work could extend to preparing prototype devices to enable the effectiveness of the proposal to be assessed by conjunctive testing.

The work was disrupted, however, by the global Covid-19 pandemic. This resulted in a need to amend project plans and re-appraise expected outcomes. Revised objectives were agreed to reflect that the work would need to be undertaken in what was, essentially, a domestic environment. Activities intended to assess directional protection principles were revised to shift the emphasis to appraisal by network simulation studies. Prototyping and conjunctive testing activities were suppressed in favour of additional simulation testing and extended literature studies.

To deliver network simulation capabilities, the DIgSILENT PowerFactory power system analysis software application was chosen. Using this, a model of a generic electrical distribution network was created, from which the protection concept could be evaluated. The model developed presents a configurable 11 kV distribution network, similar to those found in the UK, providing interconnection between a 33 kV grid supply and various loads including low-voltage (400 V) consumer loads. Amongst other features, the 11 kV configurable network allows feeder connections to be connected in parallel. In combination with the inclusion of dispatchable generation, this makes the model capable of stimulating reverse power flows.

When studies are to be performed using simulation models, it is essential that the credibility of the models is assured before they are used as evaluation tools. Since the network models used in this study were bespoke designed for the project, it was important to establish credibility for them. To deliver this, significant investment was made in proving the model before deploying it to evaluate new approaches. Verification of the model was achieved through an iterative design process. To validate the model, overcurrent benchmark testing was employed.

Non-directional overcurrent protection is commonly used on conventional passive radial distribution networks. The theory and practice of inverse definite minimum time (IDMT) overcurrent grading is robust, and well understood by protection engineers. Accordingly, IDMT overcurrent grading was selected as a reference to benchmark test the network model. The network model developed in the study can replicate a conventional passive radial distribution network. Using this configuration of the model a protection grading exercise based on non-directional IDMT overcurrent was adopted to validate the network model. With correlation between there theoretically predicted overcurrent performance for the network model, and the results of simulated protection tests performed on the model demonstrated, it is concluded that the distribution network model developed for this work accurately represents a dynamic network, typical of those in the UK that are evolving towards smart network operations. Further, in doing so, it provides a valid test vehicle with which to evaluate new distribution network protection ideas.

With a validated model, the studies could progress to evaluate the performance of directional overcurrent protection on the 11 kV network. Within the simulation environment, directional overcurrent models were integrated within communicating Directional Agents to implement directional comparison protection schemes. Initially voltage polarising for the Directional Agents was derived conventionally from adjacent voltage transformers on the 11 kV network. Within the simulation environment, the communications of command information (directional qualifiers) between connected Directional Agents has been implemented with purpose-designed simulated teleprotection devices. In practical applications, this could be realised using the GOOSE messaging services hosted by communications conformant with internationally respected standards such as IEC 61850-8-1.

Performance of the proposal has been tested for differing network topologies, for various supply scenarios, and for an assortment of fault types. For the various configurations, faults were simulated at different locations across the network and the response of the directional comparison protection schemes was observed.

Whilst the results of applying solid (0 Ω) three-phase faults are encouraging, some concerns are raised by the response of the models as fault resistances increase. More concerning, however, is the performance of the models under single-phase-to-earth fault conditions.

It is clear that under high-resistance fault conditions, and under all single-phase-to-earth fault conditions, the operation of the directional comparison scheme is not as intended. In most cases the incorrect operation of the scheme output can be attributed to the incorrect operation of individual directional elements implemented in the direction comparison relay models - models created specifically for this exercise. Due to the rudimentary tools provided by the DIgSILENT environment for debugging relay model design, it is difficult to draw meaningful conclusions as to the exact source of the problem. The problem could be attributable to a fundamental flaw in the approach, a problem with the network simulation model, a problem with the custom-designed relay simulation models, or a combination of all. Whilst the latter case is a likely scenario, immediate suspicions fall on the operation of the custom-designed directional comparison models since these are a relatively unproven part of the research modelling. Independent of this issue, development of the models to adapt them for single-phase polarisation has been identified as an activity worthy of further merit. The results of the single-phase-to-earth testing in particular add emphasis to a recommendation to further investigate the prospects of providing reliable directionalisation for faults including single-phase-to-earth faults from a single-phase polarising signal. Covid19 limitations prevented testing being performed on validated (commercially available) models. As Covid19 restrictions are limited, and hardware-in-the-loop testing becomes a more practical possibility again, the approach could provide valuable insight to guide potential future development.

The network model is considered a suitable platform to provide future evaluation opportunities with which to explore practical performance issues and determine operational performance limits – ideally with proven, commercially available, manufactured and approved hardware devices. The simulation models are considered to require further development and proving before they could be used to confidently continue the evaluation of the concept.

Combined, the results lend support to the proposal that directional comparison techniques employing Directional Agents deriving information from LV polarising signals and HV current measurements may provide suitable protection for evolving electrical distribution networks. The results do, however, expose that further development and evaluation work is required concerning the validity of the polarising method and its use to determine directionality based on single-phase stimulation.

Concerning physical aspects of remotely locating the polarising signal, feasibility studies – primarily in the form of published literature review but also supplemented by rudimentary field testing - demonstrate that it is possible to design, and deploy, small 'plug-and-play' wirelessly connected voltage acquisition units (Voltage Cubes). These devices, containing low-voltage transducers, would be capable of remotely acquiring system measurements and communicating these measurements in accordance with respected international standards such as IEC 61850-9-2. From this it is concluded that a proposed approach to replace conventional protection voltage transformers used to polarise overcurrent protection by small, cost-effective, 'plug-and-play' Voltage Cubes is feasible.

Concerning wireless communications, primarily guided by literature review, it can be concluded that, subject to appropriate precautions against, for example, cyber security, being observed, wireless communications could be used to provide the potentially wide-area system-level connectivity required by Directional Agents and LV voltage acquisition devices (Voltage Cubes) forming the directional comparison protection schemes intended by the work.

Consolidating the conclusions, the key takeaways from this research work are, therefore, considered to be that:-

- Directional comparison schemes can provide effective protection for distribution networks featuring embedded generation.
- Voltage polarised overcurrent techniques can provide robust indications of directions of power flows across distribution networks.
- Directional polarising references can feasibly be derived from LV locations on the consumer network, and used to provide directionality to (HV) overcurrent protection techniques to implement Directional Agents.
- Directional Agents can be connected using IEC 61850-8-1 GOOSE messaging to implement directional comparison schemes.
- A Voltage Cube concept proposal offers the prospect of a small, low-cost, mains connected device capable of delivering a low-voltage polarising reference to Directional Agents, obviating the need for need for large expensive protection voltage transformers to be added.
- The Voltage Cube concept offers the prospect of delivering the voltage polarisation signal to Directional Agents via Ethernet communications.
- Availability and advantages of wireless communications may be employed, with appropriate precautions against issues such as cyber security, to provide (at least in part) the interconnectivity required to implement directional comparison schemes based on Directional Agents and Voltage Cubes.

Reflecting on the outcomes of the research, the author considers that the concept behind the proposal is sound. The simulation tests have demonstrated that the protection performance is robust and appropriate. The proposed technologies are considered sufficiently mature and commercially attractive to warrant further investigations.

The outcomes from the research provide a basis from which ideas outlined in the proposal could be developed further. These include scope for refining aspects of the proposal, determining operational limits, and exploring practical performance issues. For practical performance investigations, ideally, this would be pursued in conjunction with an industrial/commercial partner with product development capabilities.

Chapter 10 Suggestions for Future Work

As expressed in the Conclusions, the outcomes from the research provide a basis from which ideas outlined in the proposal could be developed further. These include scope for refining aspects of the proposal – particularly aspects associated with polarising the directional elements from single-phase sources, assessing operational limits, and exploring practical performance issues. For practical performance investigations, ideally, this would be pursued in conjunction with an industrial/commercial partner with product development and test capabilities.

There is scope for refining aspects of the proposal within the simulation environment. Extensions identified as worthy of consideration relate (i) to the presentation of the polarising quantity used to determine directionality and (ii) the method of determination of the directionality.

Concerning the polarising quantity, consider that when feeder protection can avail itself of both current transformer (CT), and voltage transformer (VT) inputs, improvements over the protection afforded by overcurrent protection can be enjoyed by both distance protection and directional protection. Whilst both of these bring improvements over protection based solely on current signals, they are both burdened by costs of providing voltage inputs. A notable difference between the two, however, is that directional protection can be implemented with a single VT whereas distance protection requires a VT pole per phase. If only a single voltage input is required it brings potentially significant cost and size benefits. In this study, the simulation models of Directional Agents all employed three-phase polarisation. To maximise the potential benefits of a Voltage Cube approach to polarisation, a goal would be to implement the scheme with a single-phase voltage connection at each terminal. Whilst the performance of such a configuration could be predicted from that of the three-phase solution that has been evaluated, developing new simulation models to mimic this arrangement could provide reassurances ahead of possible product development. Further, noting that the simulation studies conducted have employed a 'direct' connection between the measurement point (VT) and the relay input. If the Voltage Cube concept was to be realised (or indeed any other non-conventional instrument transformer-based solution according to IEC 61869) then the voltage signal would be presented as an IEC 61850-9-2 SAV/SMV data stream. The implications of this presentation of measurement data presents scope for future research.

Concerning the determination of directionality of power flows, within the original project scope had been an intention to compare the difference in performance between two approaches to the determination of directional decision making. A widely used method, and indeed the one that dominated in the Covid19-impacted work is based on conventional voltage polarised directional overcurrent protection. The other method uses the theory of superposition to detect transient components of voltage and current and to use these to determine directionality. The technique has been used for transmission applications such as that provided by GE's MiCOM P545 and has the advantage of providing fast results. A disadvantage is that it has traditionally be expensive due to a requirement for high-speed sampling and intensive processing to manipulate the transient components. Accordingly, it has not really found favour for distribution protection applications. It could be interesting to evaluate the suitability. Whilst this might be possible in a simulation environment, it may require sophisticated models to be developed – and perhaps more importantly, validated – before simulation studies could be undertaken. Alternatively, evaluation could be performed in line with the pre-Covid19 intentions by evaluating the attributes of commercially available devices such as the P545.

The Voltage Cube concept is interesting. Its use has been considered within this work as an acquisition unit to supplement protection schemes, but it could be interesting to consider other potential applications where distributed voltage (or similar) measurements might be required, and this might provide fruitful avenues for additional research. Further, whilst the use of a Voltage Cube approach has the potential to bring benefits such as cost savings to directional comparison schemes, it does expose the protection to risks. In particular, if the feeder hosting the Voltage Cube was, itself, subject to a short-circuit fault, then the voltage polarising signal, so vital to the directional decision making process, would be lost. Provision of redundancy could mitigate this risk by deploying multiple Voltage Cubes across different LV feeders. This may present challenges around arbitration of received signal information, etc., and so this could also form a useful stream of further research.

Returning to the basic protection scheme concept introduced by this work, theoretical and simulation studies provide encouragement that it has merit, has potential for practical application, and is worthy of further study. Some degree of conjunctive testing to demonstrate overall performance with physical hardware devices is likely to be needed before commercial interest might be fully stimulated by the idea, and this is a logical next step. Ideally, the conjunctive testing would be undertaken using devices designed and manufactured to industrial standards. For this reason, this aspect of potential future work is most likely to yield success if it is undertaken in conjunction with an interested, and suitably-equipped, industrial partner. As well as answering the perhaps obvious question of "Does the idea work in practice?", physical models would facilitate a more detailed evaluation, and possibly afford stronger endorsement than a literature review, when it comes to assessing the suitability of wireless communications for the intended application. Such a study is likely to be of interest to those working in the broad domain of substation protection, control, and automation, especially those interested to exploit the attractions of wireless connectivity. This could involve examining the impact of various issues associated with wireless communications, such as propagation delays, interference, jitter etc. In the context of communications within and without the substation boundaries topics such as time synchronisation and cyber security have the potential to open more research windows.

Whether it be in an academic environment, or an industrial context, the research exposes many avenues for further investigation. It is the author's view that the ideas that have been researched in this work have the potential to bring pragmatic improvements to the protection of distribution networks. An industrial partnership could bring them quickly to commercial realisation.

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Appendix I: Creation of DIgSILENT Directional Comparison Scheme Simulation Model

This Appendix presents details of the creation of a DIgSILENT Directional Comparison Scheme Simulation Model.

Whilst creation of a specific type of protection scheme model is described, the principles should be generally applicable to the creation of any DIgSILENT relay simulation model. This Appendix is prepared to aid anyone who might be faced with a similar challenge.

This Appendix concentrates on the practical details of developing the model. Specific functionality of the models are presented for explanatory example purposes only. No responsibility nor liability is accepted for the correctness or otherwise of any models arising from the use of the work. It is provided for guidance only.

Introduction

A simulation model is required to enable evaluation of directional comparison protection in a DIgSILENT PowerFactory network simulation model.

A scheme comprising directional comparison relays communicating together to exchange teleprotection command signals is required.

The desired protection functionality is similar to that which might be realised by the directional comparison feature offered by MiCOM P545 relays, suitably configured, and coupled via appropriate carrier-aided telecommunications equipment. Whilst the DIgSILENT PowerFactory software supports simulation models which simulate the functionality of MiCOM P545, the model is based on generic DIgSILENT models which do not faithfully represent the details of the MiCOM implementation. Additionally, suitable teleprotection models were not available ‘off the shelf’.

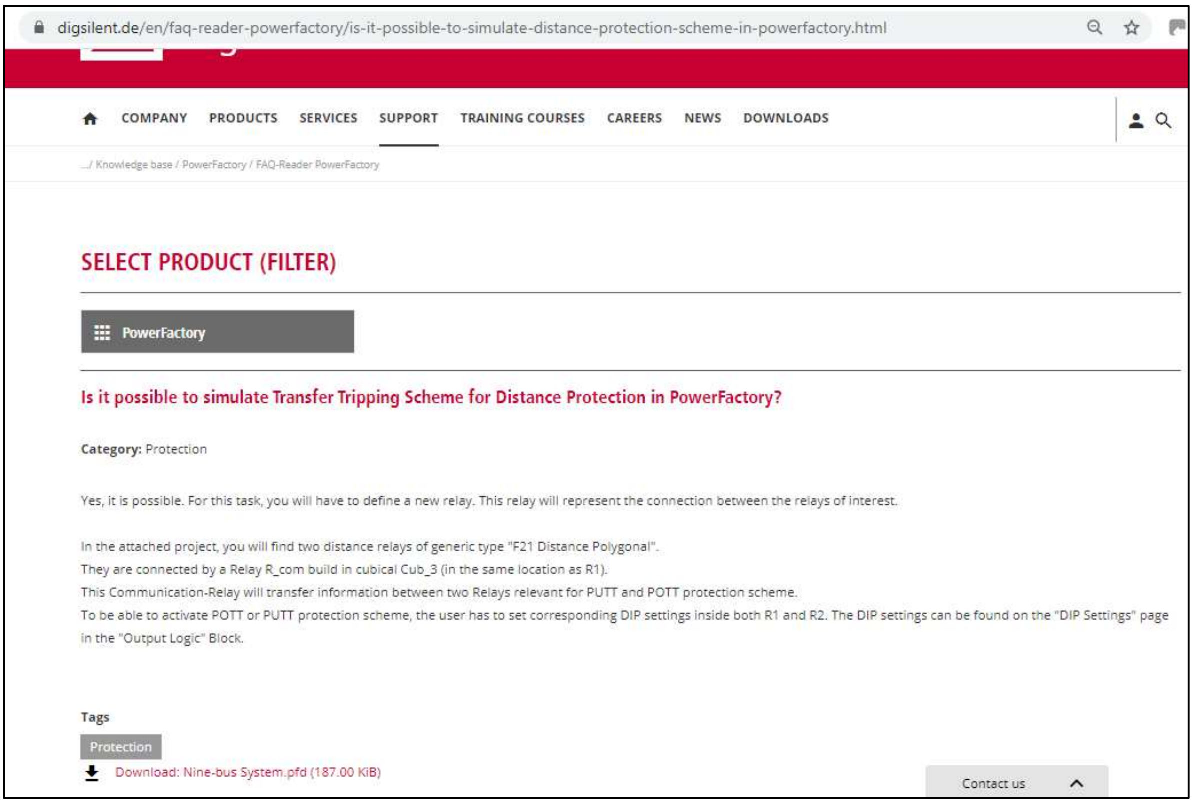
There was, therefore, a requirement for appropriate models of directional comparison relays (with teleprotection interface), as well as a model of a teleprotection (carrier-aided intertripping) relay, suitably interconnected to from the scheme.

Since the DIgSILENT relay library includes the MiCOM P545 relay it was assumed that this would suffice. However it became apparent that the desired features were not supported by the model. After some deliberations with the DIgSILENT technical support team, it was concluded that an 'of-the-shelf' model to suit the project requirements was not forthcoming and something unique would need to be created.

In conjunction with DIgSILENT technical support, a potential starting point was identified in a tutorial exercise on the DIgSILENT website identified by the following hyperlink:-

https://www.digsilent.de/en/faq-reader-powerfactory/is-it-possible-to-simulate-distance-protection-scheme-in-powerfactory.html. (November 2020).

The following associated screenshot (Appendix Figure 1) is taken from the link.



Is it possible to simulate Transfer Tripping Scheme for Distance Protection in PowerFactory?

Category: Protection

Yes, it is possible. For this task, you will have to define a new relay. This relay will represent the connection between the relays of interest.

In the attached project, you will find two distance relays of generic type "F21 Distance Polygonal".
They are connected by a Relay R_com build in cubical Cub_3 (in the same location as R1).
This Communication-Relay will transfer information between two Relays relevant for PUTT and POTT protection scheme.
To be able to activate POTT or PUTT protection scheme, the user has to set corresponding DIP settings inside both R1 and R2. The DIP settings can be found on the "DIP Settings" page in the "Output Logic" Block.

Download: Nine-bus System.pfd (187.00 KiB)

Appendix Figure 1: DIgSILENT Transfer Tripping Scheme Reference Screenshot.

The example is referred to as the Nine-bus example. It uses the term 'Interlink' for the teleprotection communications linkage between relays in a scheme. It may be noted that terminology such as communications, interlink, teleprotection, communications-assisted (protection), carrier-aided (protection), and combinations/permutations of similar terms are often used interchangeably to describe the protection signalling communications interface connecting two (or more) relays in a scheme for the purpose of exchanging teleprotection commands (intertripping, permissive tripping, blocking, etc.) signals.

Although a scheme based around an Interlink model, offered seemingly a promising start, it became apparent that the task to create a working directional comparison unit protection scheme model would be a more difficult than anticipated task as there was little, if any user, support documentation.

Background to the Scheme Design

To implement directional comparison unit protection, it is necessary to integrate directional protection elements into a communications-assisted (carrier-aided) unit protection scheme.

In such a scheme the response of directional elements at different terminals in the protected zone are combined. The combination of directional decisions forms the basis of tripping at each terminal. directional comparison does not need to be restricted to two-terminal schemes – the principles are similarly applicable to multi-terminal schemes – but for simplicity and convenience the study considers two-terminal protection schemes applied to each of the lines 2a and 2b in the generic network model presented in Figure 21 of the main body of this report (reproduced below)

Figure 22

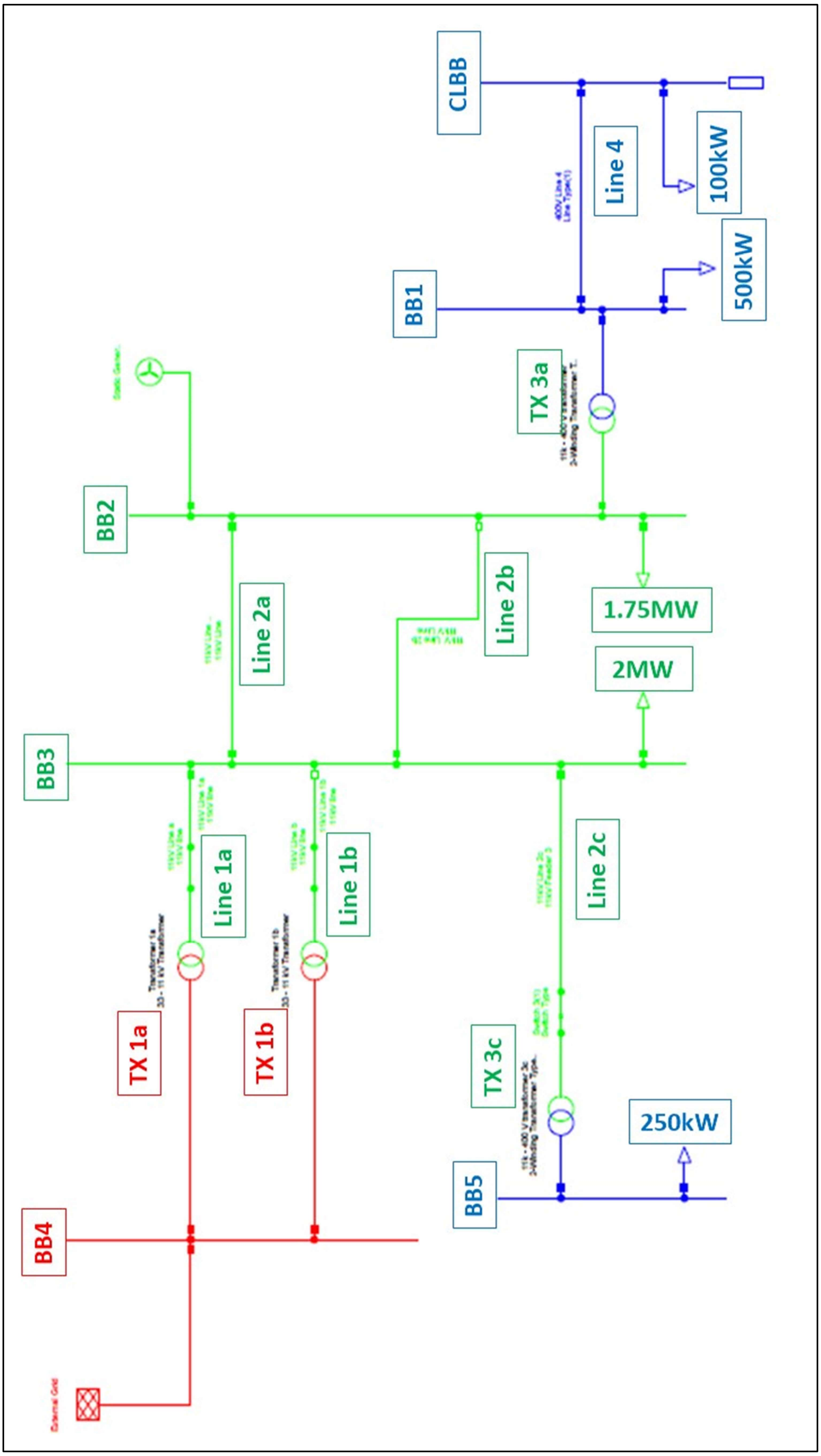
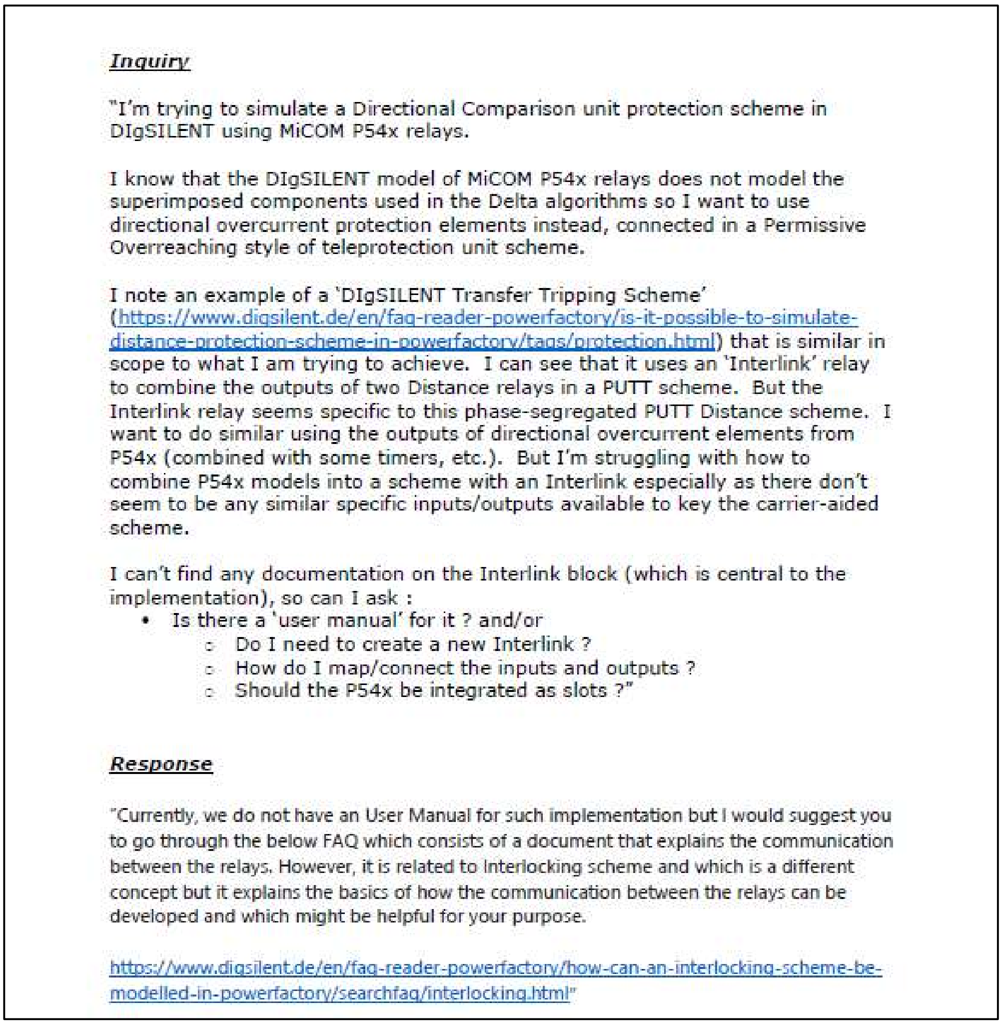

CLBB
BB1
BB2
BB3
BB4
BB5
Line 4
100kW
500kW
TX 3a
Line 2a
Line 2b
1.75MW
2MW
Line 1a
Line 1b
Line 2c
TX 1a
TX 1b
TX 3c
250kW
Transformer 1a
33 - 11 kV Transformer
Transformer 1b
33 - 11 kV Transformer
11k - 400 V transformer 3c
2-Winding Transformer Type

Figure 21. Generic UK Distribution Network modelled in PowerFactory. (from main body of report).

DIgSILENT PowerFactory provides many protection simulation models. A library of generic protection models (e.g. distance, overcurrent, etc.) is provided and a suite of adaptations of these models mimic a comprehensive collection of many manufacturer specific (e.g. SEL, ABB, Areva, etc.) protection devices (e.g. MiCOM P545). Unfortunately, in the context of this project, the simulation modelling of communications-assisted (carrier-aided) teleprotection schemes is less well supported. Interrogation of DIgSILENT's published materials and user support service effectively concluded that a suitable directional comparison scheme model was not available. If one was required, it would need to be designed, implemented and tested by the user. For augmentation, the following Appendix Figure 2 provides an abridged summary of inquiry and response in this matter.



Inquiry

"I'm trying to simulate a Directional Comparison unit protection scheme in DIgSILENT using MiCOM P54x relays.

I know that the DIgSILENT model of MiCOM P54x relays does not model the superimposed components used in the Delta algorithms so I want to use directional overcurrent protection elements instead, connected in a Permissive Overreaching style of teleprotection unit scheme.

I note an example of a 'DIgSILENT Transfer Tripping Scheme' (https://www.digsilent.de/en/faq-reader-powerfactory/is-it-possible-to-simulate-distance-protection-scheme-in-powerfactory/tags/protection.html) that is similar in scope to what I am trying to achieve. I can see that it uses an 'Interlink' relay to combine the outputs of two Distance relays in a PUTT scheme. But the Interlink relay seems specific to this phase-segregated PUTT Distance scheme. I want to do similar using the outputs of directional overcurrent elements from P54x (combined with some timers, etc.). But I'm struggling with how to combine P54x models into a scheme with an Interlink especially as there don't seem to be any similar specific inputs/outputs available to key the carrier-aided scheme.

I can't find any documentation on the Interlink block (which is central to the implementation), so can I ask :

- Is there a 'user manual' for it ? and/or
    - Do I need to create a new Interlink ?
    - How do I map/connect the inputs and outputs ?
    - Should the P54x be integrated as slots ?"

Response

"Currently, we do not have an User Manual for such implementation but I would suggest you to go through the below FAQ which consists of a document that explains the communication between the relays. However, it is related to Interlocking scheme and which is a different concept but it explains the basics of how the communication between the relays can be developed and which might be helpful for your purpose.

https://www.digsilent.de/en/faq-reader-powerfactory/how-can-an-interlocking-scheme-be-modelled-in-powerfactory/searchfaq/interlocking.html"

Appendix Figure 2: Abridged Summary of DIgSILENT Teleprotection Scheme Support.

Note. This figure is constructed from email exchange (S Potts / DIgSILENT) October 2020.

It can be noted that construction of the directional comparison scheme model is not an absolute necessity to verify correct directional operation of individual elements. By observing the output of simulated directional overcurrent protection devices, the directional response of individual relays on the 11 kV lines is quite apparent. It is arguable, therefore, that developing a simulated directional comparison scheme is something of an un-necessary commitment since scheme performance could be predicted using the outputs of the individual protection elements. The responses could then be concentrated into, for example, a database for analysis, and that could be adequate for performance evaluation.

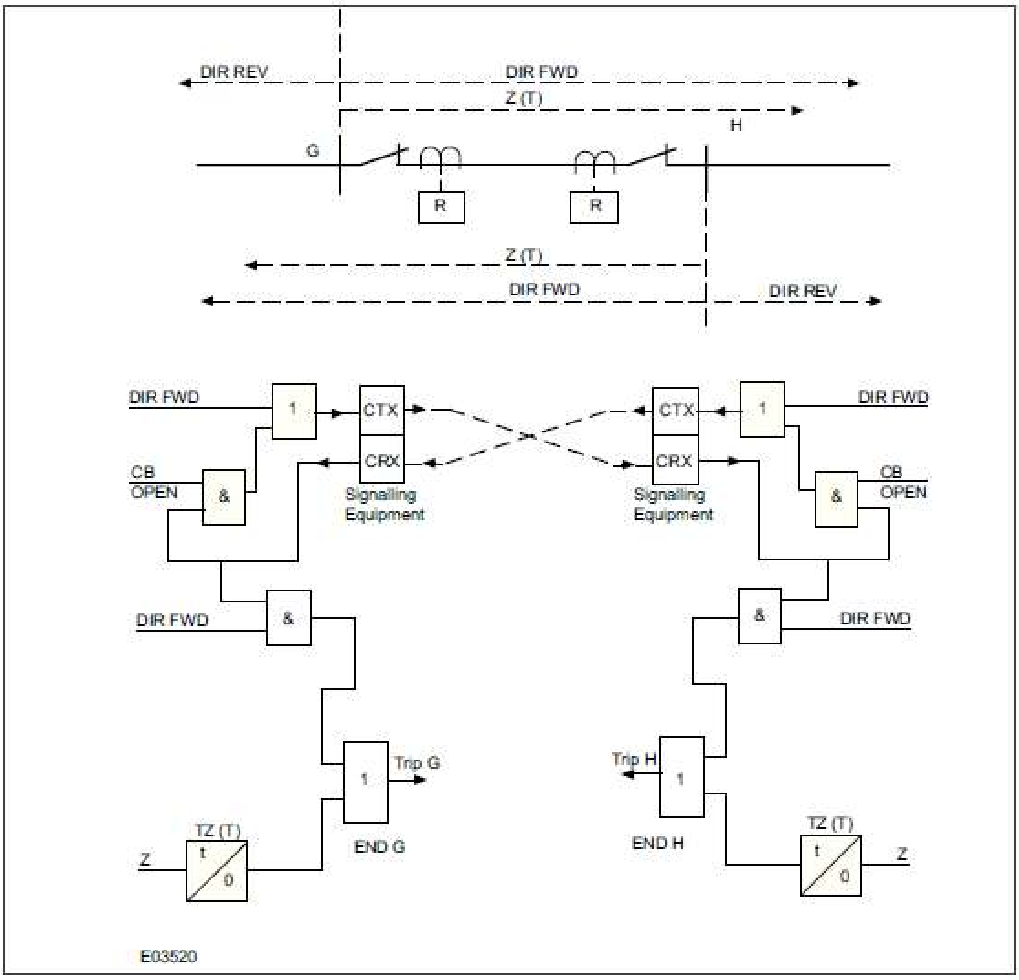
Nonetheless, creation of a directional comparison protection scheme model should provide a more convenient vehicle with which to demonstrate network protection performance, and a useful addition to the project library.

Modelling a Directional Comparison Protection Scheme Simulation in DIgSILENT PowerFactory

The DIgSILENT website 'DIgSILENT Transfer Tripping Scheme' example Appendix Figure 1 is identified as being similar in scope to what is needed for this project. The website example scheme uses a specific 'Interlink' relay to combine the outputs of two generic 'F21' distance relays in a PUTT scheme.

The intended directional comparison scheme is based on using directional overcurrent protection relays with an input/output structure similar to that used by the F21 distance relays to interface to the Interlink relay in the example - the principles used in the PUTT example are recycled to implement a directional comparison protection scheme.

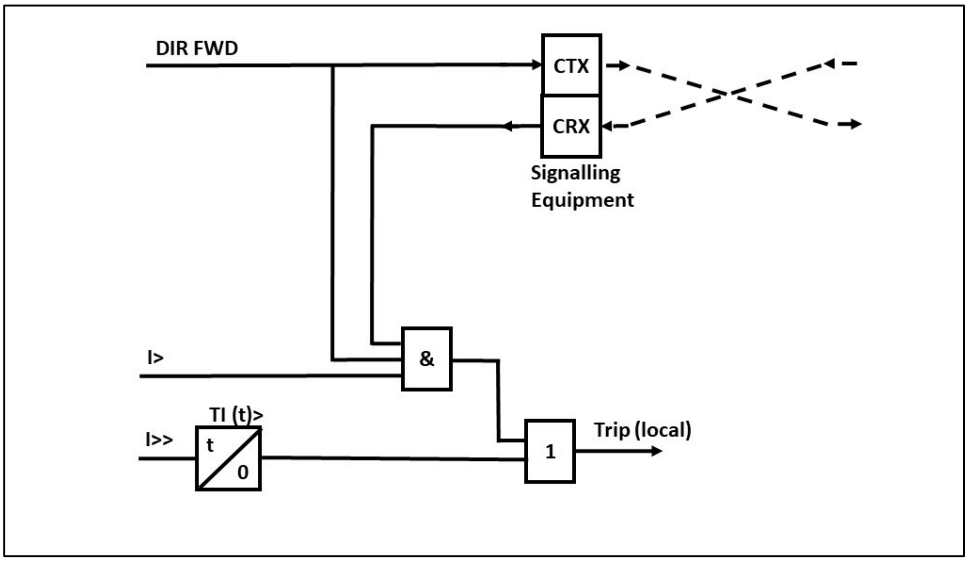
The intended directional comparison scheme is based on the principle of a Permissive Overreaching scheme [140] and reproduced below as Appendix Figure 3 for convenience.



Appendix Figure 3: Permissive Overreaching Delta Directional Comparison Scheme.

The scheme of Appendix Figure 3 is typically used for three-pole tripping. A single composite forward directional signal is used in conjunction with individual phase-measuring elements and an OR logic. Traditionally, phase-segregated protection was not provided in directional comparison schemes due to limitations on communications bandwidth capabilities but, with improved services, phase segregated implementations are feasible.

The scheme of Appendix Figure 3 can be simplified to remove the single-end fed remote echo logic and modified to one based on directional overcurrent protection as shown in the following Appendix Figure 4.



Appendix Figure 4: Permissive Overreaching Overcurrent-Based Directional Comparison Terminal.

Note that only the local terminal logic is shown. Remote terminal logic is a mirror image.

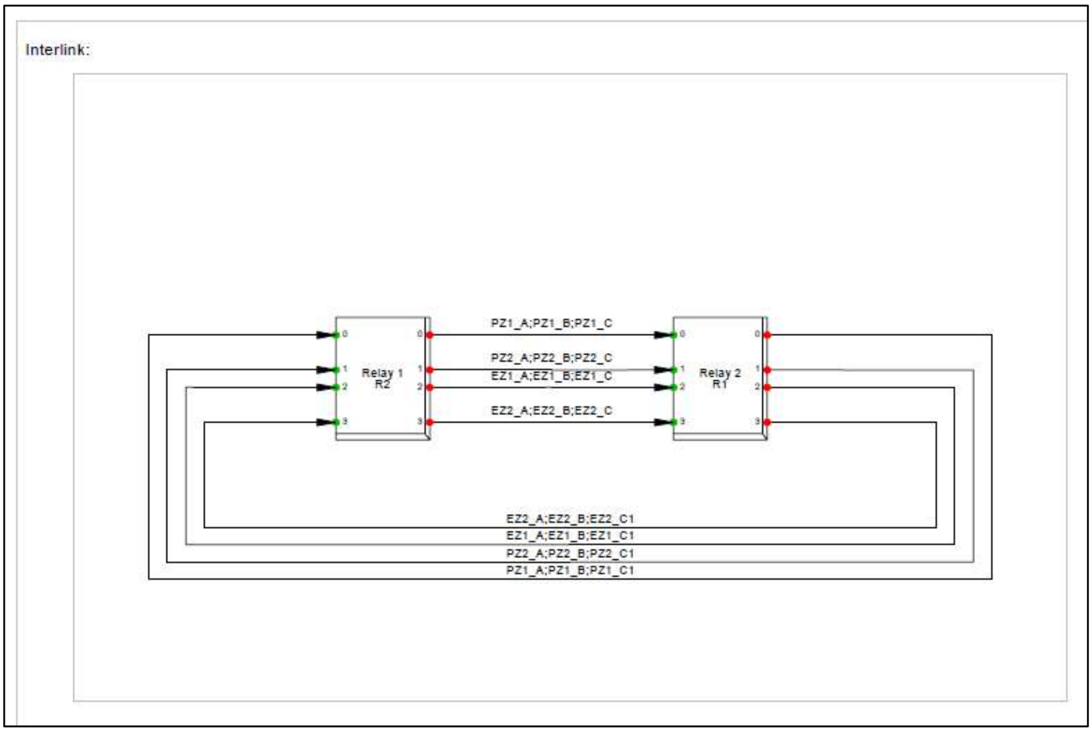
Also, as stated, the implementation may take the form of a phase-segregated protection and tripping scheme, or more commonly as a composite three-phase tripping scheme.

In the directional overcurrent scheme two overcurrent elements are used at each terminal.

A stage 1 overcurrent element (I>) is included. Intended to provide low-set instantaneous forward operation, it should operate similarly to the directional element and is, therefore, somewhat redundant. It is, however included as a debugging/evaluation aid that may be used to control the extent of the overreaching employed by the scheme.

Stage 2 overcurrent element (I>>) is included to provide time-delayed high-set back-up protection. It particularly assures fault clearance in a pre-defined time in the event of ‘communications failure’ and also can be useful for debugging unexpected operations.

Implementing the scheme requires teleprotection signalling equipment to convey command signals between the terminal devices. In the DIgSILENT example model this is achieved by using an ‘Interlink’ element which is dedicated to conveying 4 (three-phase) command signals (designated *PZ1(A;B;C), PZ2(A;B;C), EZ1(A;B;C),* and *EZ2(A;B;C)*) between two terminal relay blocks (designated R1 and R2) as depicted in the following figure (Appendix Figure 5) taken from the DIgSILENT R-COM example.



Appendix Figure 5: Interlink Block Connectivity.

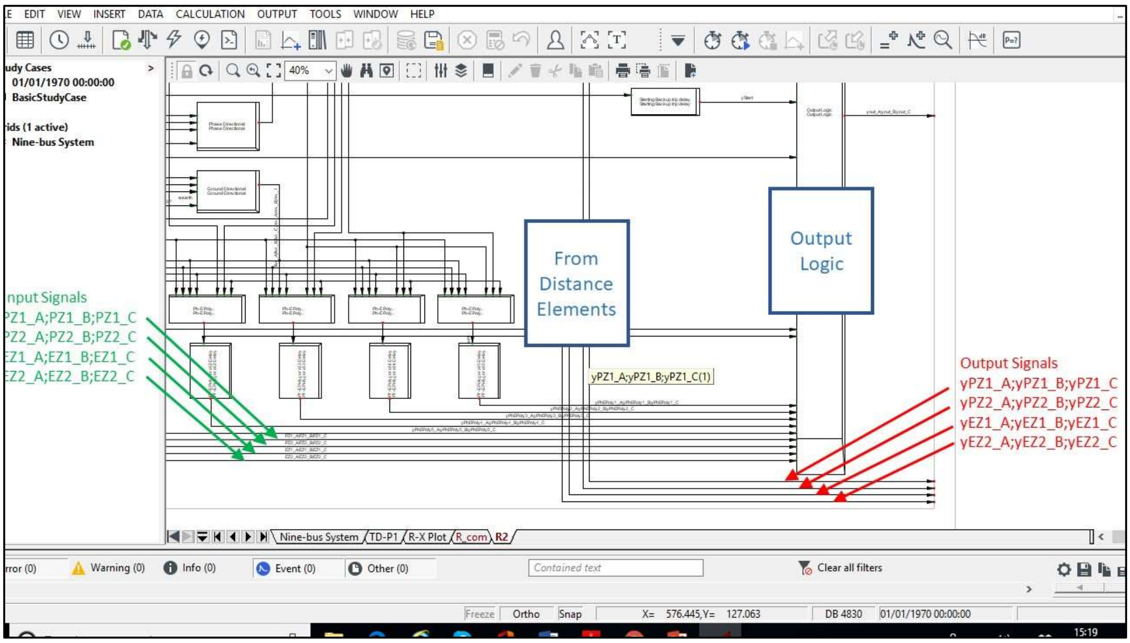
In the example, the four groups of three signals are used to convey phase-segregated PUTT command signals (A, B, C) for Phase (P) and Earth/Ground (E) elements associate with distance protection zones 1 (Z1) and 2 (Z2).

The Interlink block directly connects binary input signals (yPZ1_A, etc.) to binary outputs (PZ1_A, etc.) to mimic the communication interconnection required between the two relays.

The outputs from the Interlink block feed into the inputs (PZ1_A, etc.) of the connected Relay block and input directly to the internal logic block of the relay element. Their functionality is defined by this internal logic.

The inputs to the Interlink block connect to the outputs (*yPZ1_A*, etc.) of the relay block and emanate from distance protection elements.

The connectivity within the generic F21 distance relay is as demonstrated in the following annotated DIgSILENT screenshot (Appendix Figure 6).



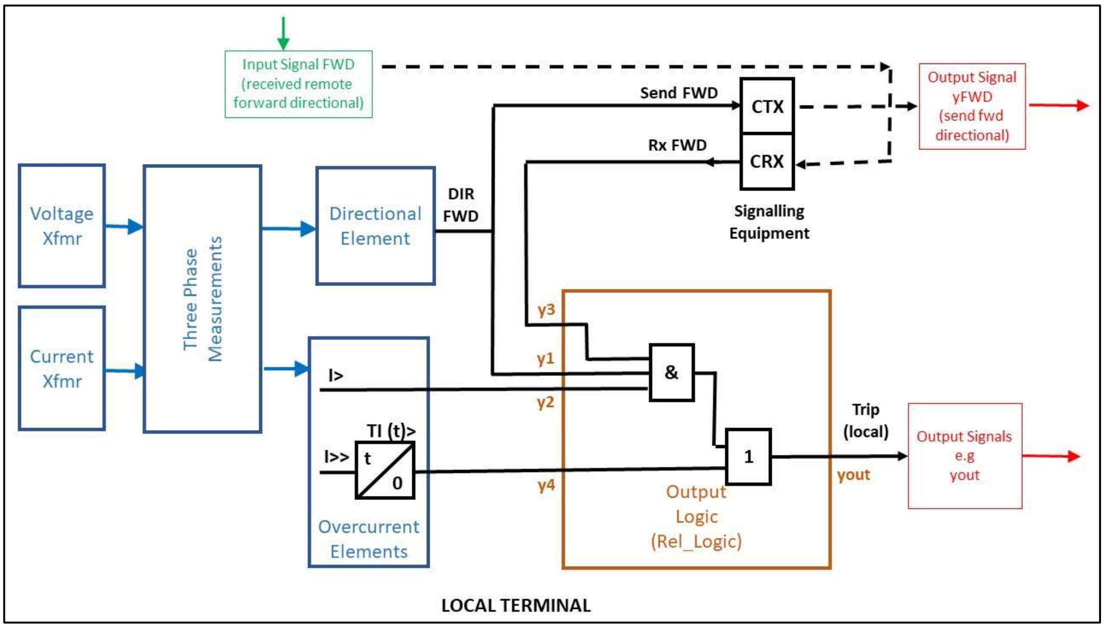
Appendix Figure 6: Permissive Command Signal Connectivity within DIgSILENT Generic F21 Distance Relay Example.

In effect, the Interlink block provides 12 transfer command signals (with pre-allocated nomenclatures) that could be available to similar applications.

Respecting the nomenclature allocation allows the Interlink block to be re-deployed to provide similar functionality in similar applications (such as directional comparison) without having to create a new element.

Thus, by defining a Directional Agent block element using a signal allocation similar to the format (*P/E Z 1/2 _ A;B;C*) and combining it with a dedicated Teleprotection (Communications Interlink) block similar to the Interlink example it should be possible to implement the desired directional comparison scheme within a DIgSILENT environment.

Based on this, a proposal for the Directional Agent block element aligned with the DIgSILENT relay model structure is, therefore, outlined in the following Appendix Figure 7.



Appendix Figure 7: Functional Requirements for Directional Agent Block Element.

Directional Agent DIgSILENT Model Creation

To provide two-terminal unit protection, two Directional Agents relay are needed and they require a Teleprotection (Communications Interlink) model to connect them together via a communications link (carrier aided) in a Permissive Overreaching arrangement.

The process for creating a relay model in the DIgSILENT PowerFactory is supported by the descriptions presented in the DIgSILENT documentation "Create Relay Models", and associated "Technical Reference" manuals, available at the DIgSILENT website:- https://www.digsilent.de/en/powerfactory-download.html?folder=files%2Fdownloads%2Fprivate%2F10_PowerFactory%2F00_PowerFactory_2020%2F70_Technical+References#navigation7105 (October 2020).

To model a relay in DIgSILENT requires the relay to be created according to defined block type interface declarations and defined functional elements.

Appendix Figure 7 presents the elements required to construct the Directional Agent DIgSILENT simulation model. Although the (nine-bus) example Interlink relay block on which it is based makes provision for a number of phase-segregated command signal transfer, for simplicity, a design using a single signal for a three-pole tripping configuration of Directional Agent is presented here.

In line with these requirements for the directional comparison scheme, for the Directional Agent in the Appendix Figure 7:-

- *PZ1_A*, etc. (of the nine bus example), are replaced by the directional FWD input received from the remote relay
- *yPZ1_A*, etc. (of the nine bus example), are replaced by the directional *yFWD* output transmitted to the remote relay.
- yout is the ultimate tripping output. It is three-phase tripping.
- The Voltage Transformer block simulates the behaviour of a voltage transformer. In DIgSILENT language "The VT type class name is *TypVT* and the VT class name is *StaVt*."
  - For the VT block no inputs are needed. This is because a VT element located in the grid will eventually be referenced to the relay in this slot, and the VT element will have its own type. Accordingly, this field is left empty.
  - The output signals are
    - *U2r_A;U2i_A,U2r_B;U2i_B,U2r_C;U2i_C*

- The Current Transformer block simulates the behaviour of a current transformer. In DIgSILENT language "The CT type class name is *TypCT* and the CT class name is *StaCt*."
  - For the CT block no inputs are needed. This is because a CT element located in the grid will eventually be referenced to the relay in this slot, and the CT element will have its own type. Accordingly, this field is left empty.
  - The output signals are
    - *I2r_A;I2i_A,I2r_B;I2i_B,I2r_C;I2i_C*

- The Measurement blocks calculate the fundamental quantities used by the protection. They are described by the type class *TypMeasure* and the element class *RelMeasure*. Two blocks are provided – one for voltages, one for currents.
  - The inputs to the Measurement blocks are

    - *wIr_A;wIi_A,wIr_B;wIi_B,wIr_C;wIi_C, wUr_A;wUi_A,wUr_B;wUi_B,wUr_C;wUi_C*

  - The outputs from the Measurement blocks are
    - *I_A;I_B;I_C,U_A;U_B;U_C, I2r_A;I2i_A,I2r_B;I2i_B,I2r_C;I2i_C, 3xIo*
    - *U2r_A;U2i_A,U2r_B;U2i_B,U2r_C;U2i_C*

- The Directional block simulates the directional characteristic typical of most overcurrent relays. Typically it uses current signal(s) polarised by voltage signal(s) displaced by a maximum torque angle (MTA). It is described by the type class *TypDir* and the element class *RelDir*.
  - The inputs to the Directional block are
      - *wUpol_A;wUpol_B;wUpol_C, wUpolr_A;wUpoli_A,wUpolr_B;wUpoli_B, wUpolr_C;wUpoli_C, wIop_A;wIop_B;wIop_C,wIopr_A;wIopi_A, wIopr_B;wIopi_B,wIopr_C;wIopi_C*
  - The outputs from the Directional block are
    - *yout,fwd_A;fwd_B;fwd_C,rev_A;rev_B;rev_C*

- The Instantaneous Overcurrent block implements a directional/non-directional overcurrent/undercurrent definite time element. It is described by the type class *TypIoc* and the element class *RelIoc*.
  - The inputs to the *I*> Overcurrent block are
    - *Iabs_A;Iabs_B;Iabs_C,wfwd_A;wfwd_B;wfwd_C, wrev_A;wrev_B;wrev_C*
  - The outputs from the *I*> Overcurrent block are
    - *yout,y_A;y_B;y_C*

  - The Time Overcurrent block implements a directional/non-directional overcurrent/undercurrent time dependent element. It is described by the type class *TypToc* and the element class *RelToc*.
  - The inputs to the *I*> Overcurrent block are
    - *Iabs_A;Iabs_B;Iabs_C,wfwd_A;wfwd_B;wfwd_C,wrev_A;wrev_B;wrev_C*
  - The outputs from the *I*>> Overcurrent block are
    - *yout,y_A;y_B;y_C*

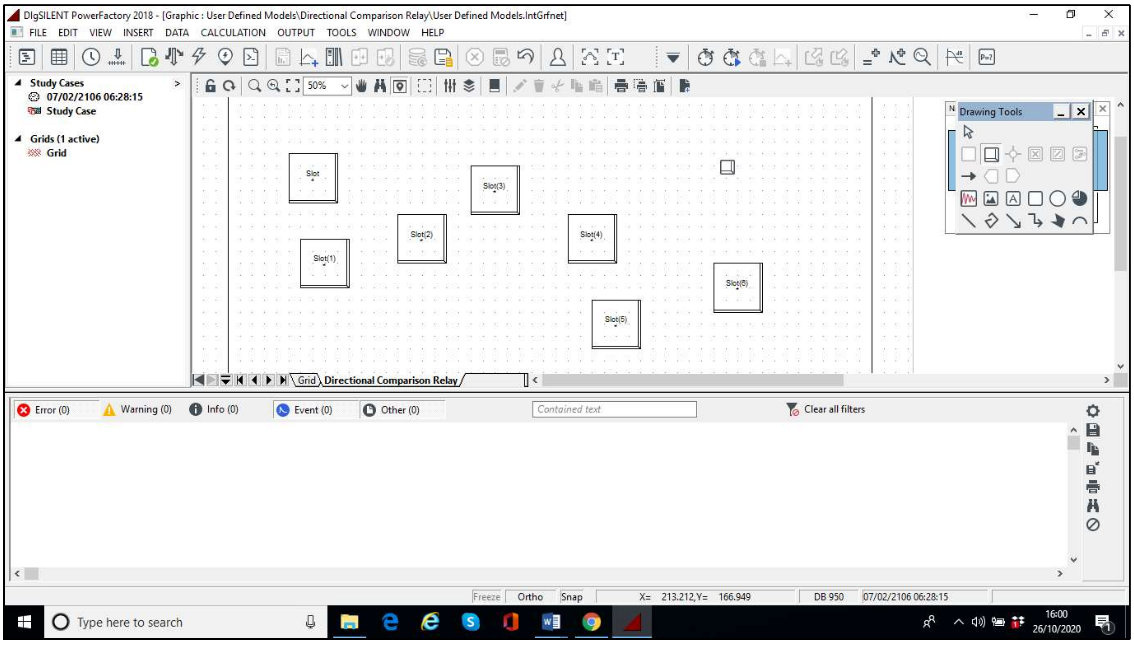
- The Logic block described by the type class *TypLogdip* and the element class *RelLogdip* converts a specified number of outputs into a single output quantity and assigns a switching device and switching command to the relay with which the logic block is associated.
  - The inputs to the Logic block are
    - *y1,y2,y3,y4*
  - The outputs from the Logic block are
    - *POR* (indication) , and *yout* (tripping)

Note that in the above descriptors, only inputs and outputs pertinent to this particular application are listed. Full listings are presented in the relevant DIgSILENT Technical References.

The following sequence of screenshots (Appendix Figure 8 through Appendix Figure 17) detail the process of defining and integrating the blocks to create the model (note that the precise contents of the descriptive windows have may need to be modified as the model develops.

The process starts by creating a new project in DIgSILENT (named '*Directional Comparison Relay Creation*' in this example) and then adding a new sheet (named '*Directional Comparison Relay*' in this example) which needs to be of the type '*Block/Frame Diagram'*.

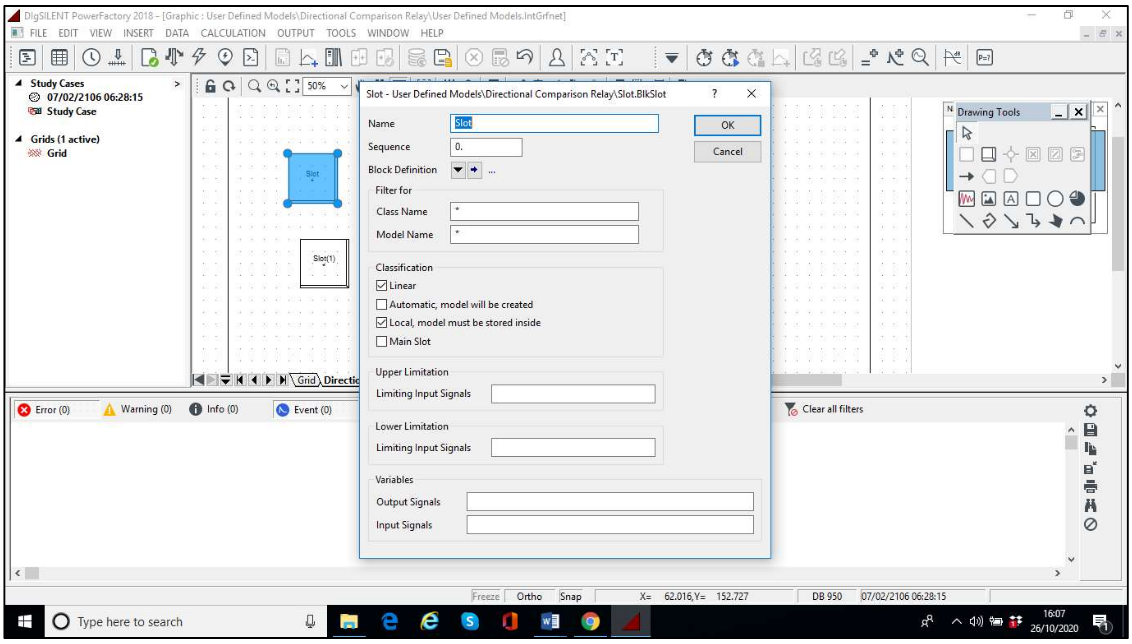
In this example the directional comparison relay features seven blocks (CT, VT, Measurement, Directional, 2x Overcurrent, and Logic) so seven slots need to be added to the diagram to house the blocks. The slots are added using the □ icon as shown in the following Appendix Figure 8.



Appendix Figure 8: DIgSILENT Relay Creation - Slot Placement within Block Frame Creation Process.

Classnames and input/output signals then need to be specified for each of the slots.

'Right clicking' on the slot graphic presents a toolbox to facilitate the specification for the slot as shown in the following Appendix Figure 9.



Slot - User Defined Models\Directional Comparison Relay\Slot.BlkSlot

Name: Slot

Sequence: 0.

Block Definition

Filter for
Class Name: *
Model Name: *

Classification
☑ Linear
☐ Automatic, model will be created
☑ Local, model must be stored inside
☐ Main Slot

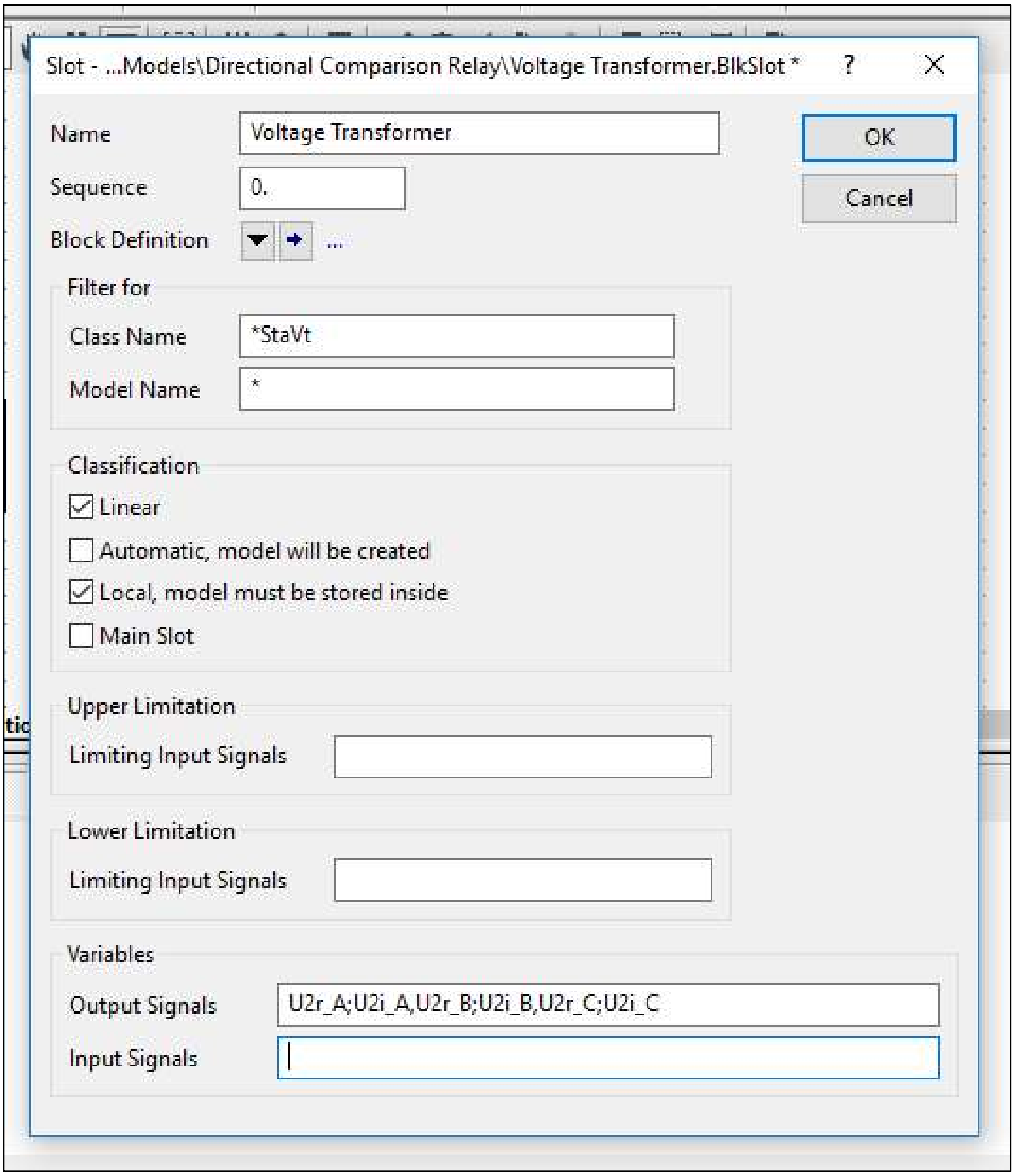
Upper Limitation
Limiting Input Signals:

Lower Limitation
Limiting Input Signals:

Variables
Output Signals:
Input Signals:

Appendix Figure 9: DIgSILENT Relay Creation - Slot Specification Window Example.

The specification details for each of the seven slots is presented in the following sequence of seven screenshots (Appendix Figure 10 through Appendix Figure 16).



Slot - ...Models\Directional Comparison Relay\Voltage Transformer.BlkSlot *

Name: Voltage Transformer

Sequence: 0.

Block Definition

Filter for

Class Name: *StaVt

Model Name: *

Classification

☑ Linear

☐ Automatic, model will be created

☑ Local, model must be stored inside

☐ Main Slot

Upper Limitation

Limiting Input Signals:

Lower Limitation

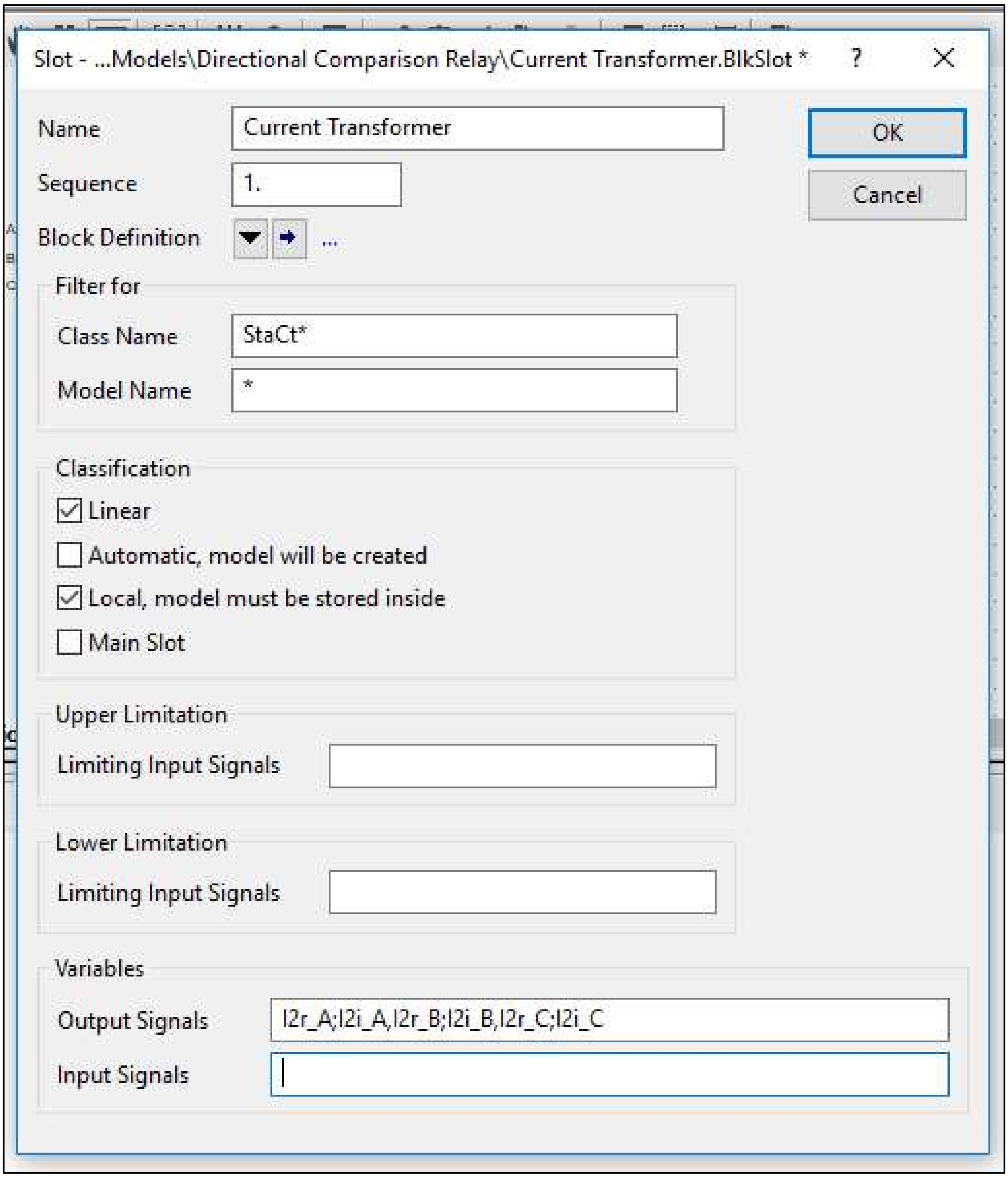
Limiting Input Signals:

Variables

Output Signals: U2r_A;U2i_A,U2r_B;U2i_B,U2r_C;U2i_C

Input Signals:

Appendix Figure 10: DIgSILENT Relay Creation – VT Slot Specification.



Slot - ...Models\Directional Comparison Relay\Current Transformer.BlkSlot *

Name: Current Transformer

Sequence: 1.

Block Definition

Class Name: StaCt*

Model Name: *

☑ Linear

☐ Automatic, model will be created

☑ Local, model must be stored inside

☐ Main Slot

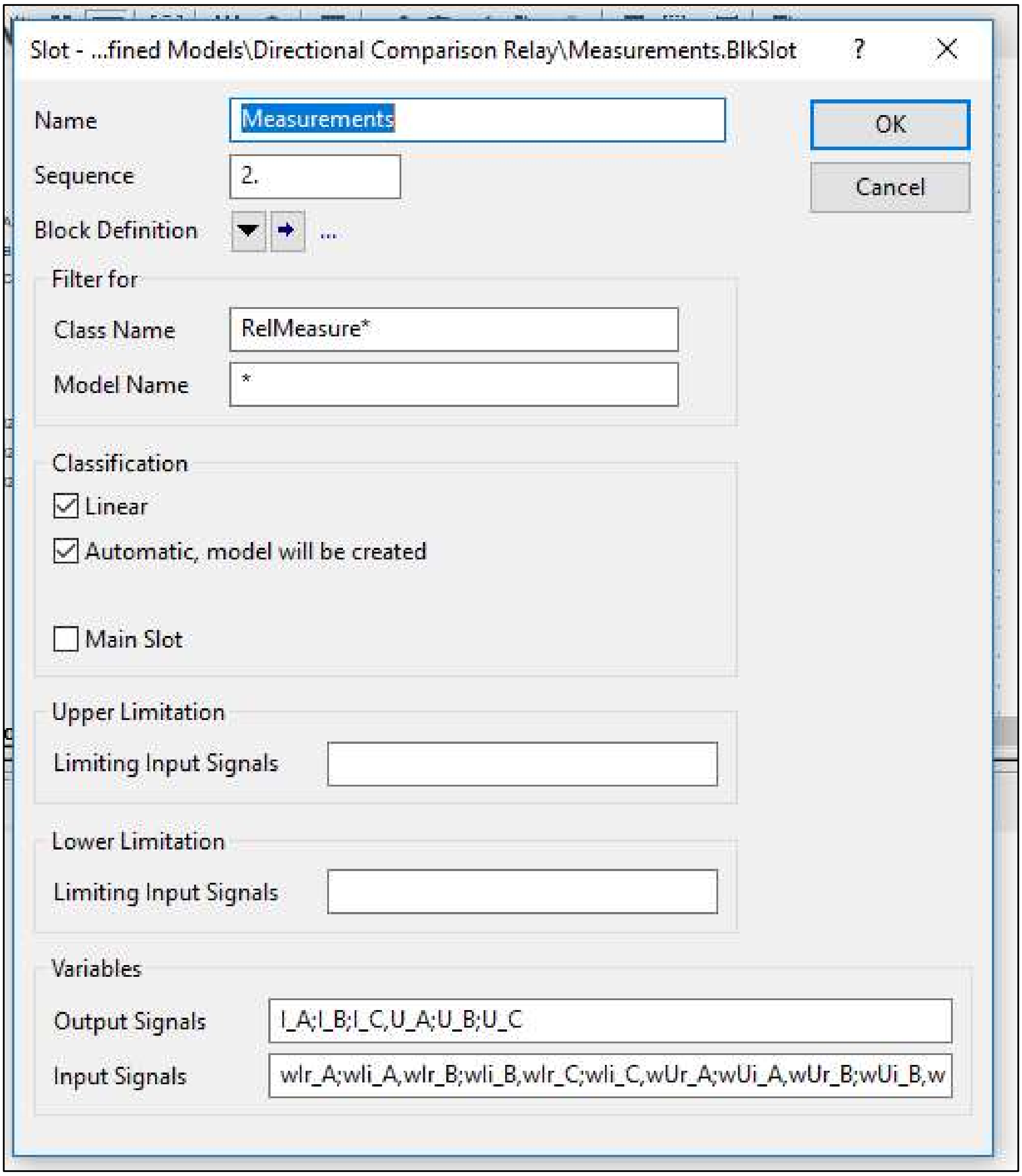
Limiting Input Signals:

Limiting Input Signals:

Output Signals: I2r_A;I2i_A,I2r_B;I2i_B,I2r_C;I2i_C

Input Signals:

Appendix Figure 11: DIgSILENT Relay Creation – CT Slot Specification.


Slot - ...fined Models\Directional Comparison Relay\Measurements.BlkSlot

Name: Measurements

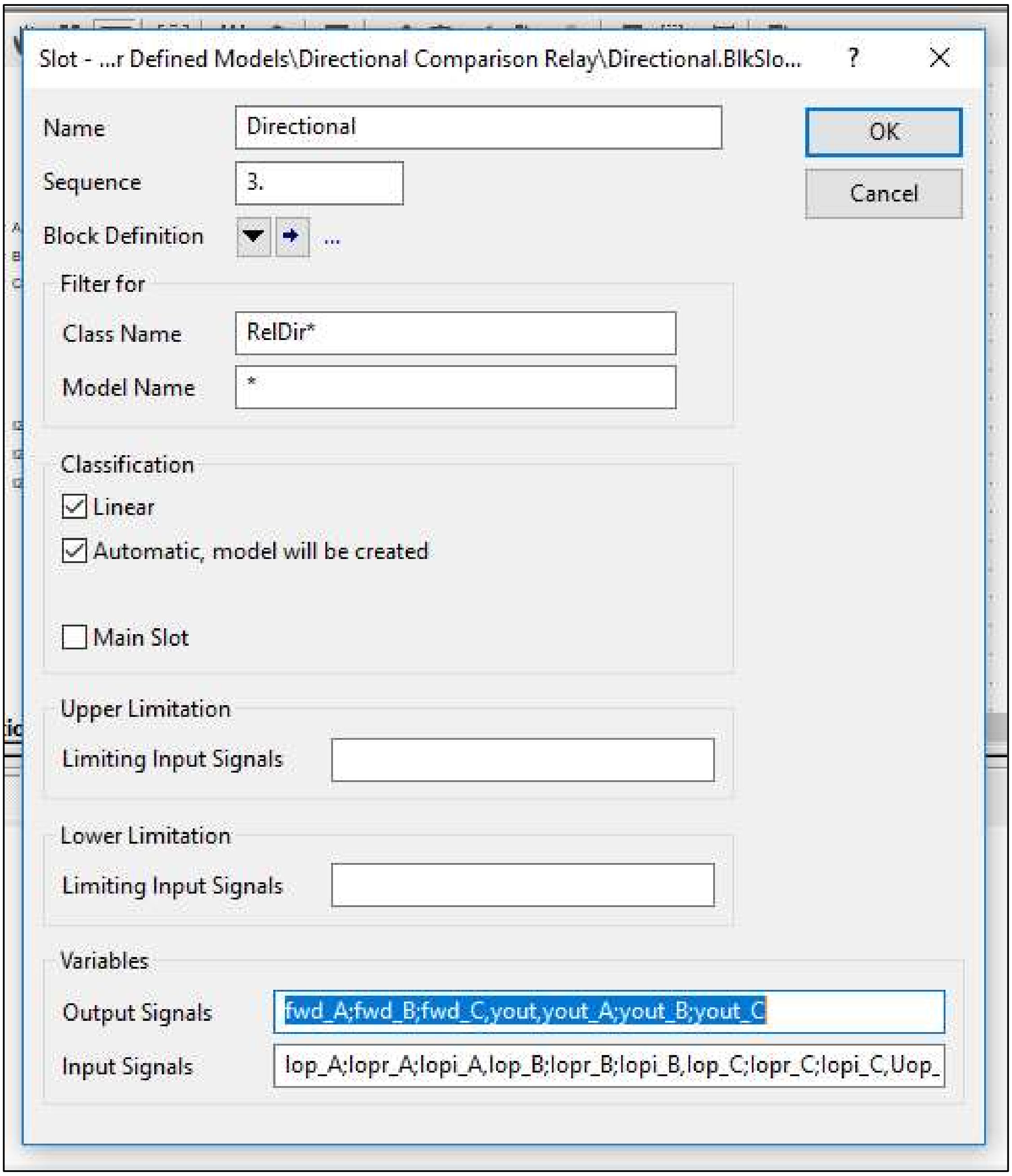
Sequence: 2.

Filter for
Class Name: RelMeasure*
Model Name: *

Classification
☑ Linear
☑ Automatic, model will be created
☐ Main Slot

Variables
Output Signals: I_A;I_B;I_C,U_A;U_B;U_C
Input Signals: wIr_A;wIi_A,wIr_B;wIi_B,wIr_C;wIi_C,wUr_A;wUi_A,wUr_B;wUi_B,w

Appendix Figure 12: DIgSILENT Relay Creation – Measurements Slot Specification.



Slot - ...r Defined Models\Directional Comparison Relay\Directional.BlkSlo...

Name: Directional

Sequence: 3.

Block Definition

Class Name: RelDir*

Model Name: *

☑ Linear

☑ Automatic, model will be created

☐ Main Slot

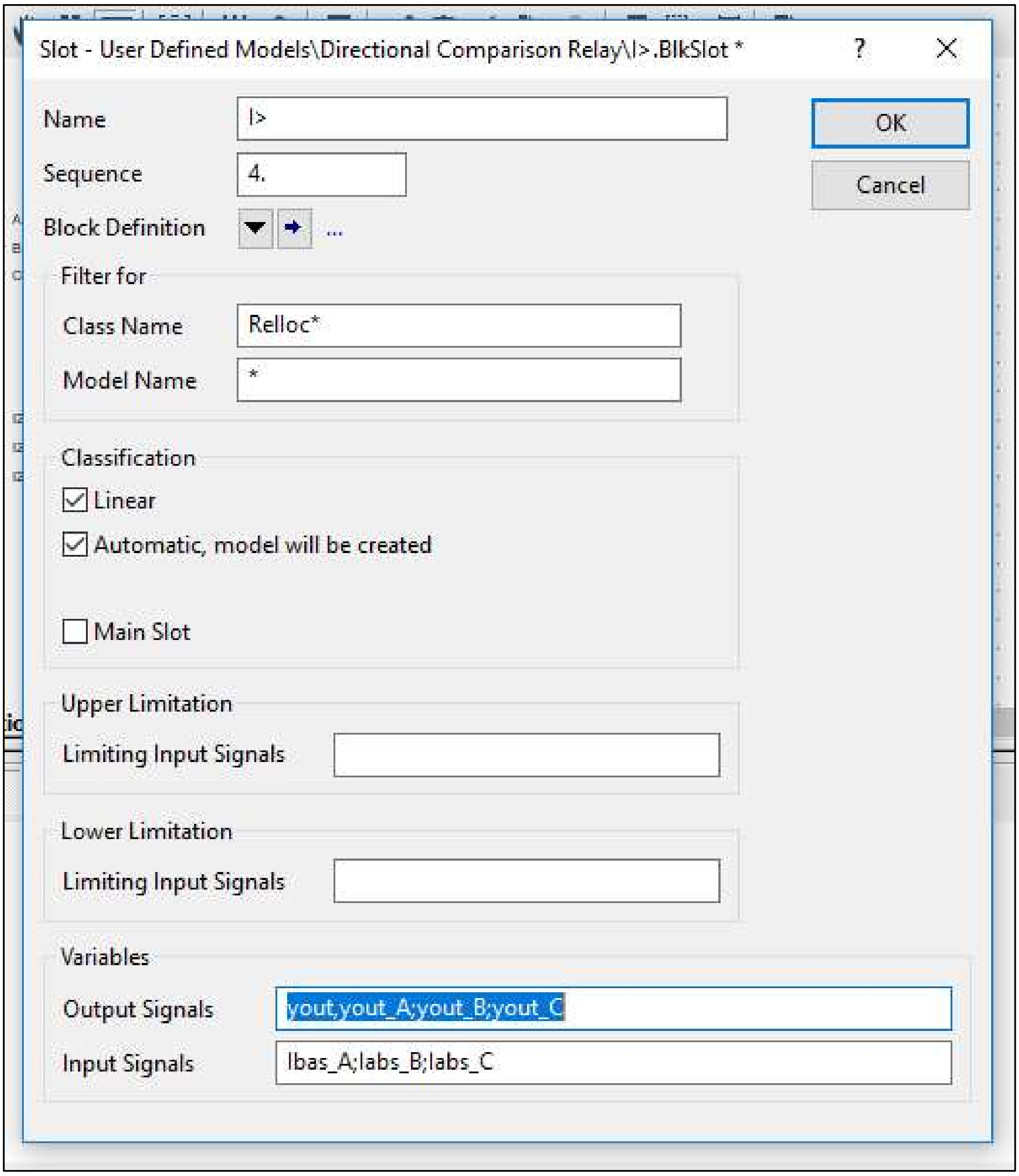
Limiting Input Signals:

Limiting Input Signals:

Output Signals: fwd_A;fwd_B;fwd_C,yout,yout_A;yout_B;yout_C

Input Signals: Iop_A;Iopr_A;Iopi_A,Iop_B;Iopr_B;Iopi_B,Iop_C;Iopr_C;Iopi_C,Uop_

Appendix Figure 13: DIgSILENT Relay Creation – Directional Slot Specification.



Slot - User Defined Models\Directional Comparison Relay\I>.BlkSlot *

Name: I>

Sequence: 4.

Block Definition

Filter for

Class Name: Relloc*

Model Name: *

Classification

☑ Linear

☑ Automatic, model will be created

☐ Main Slot

Upper Limitation

Limiting Input Signals:

Lower Limitation

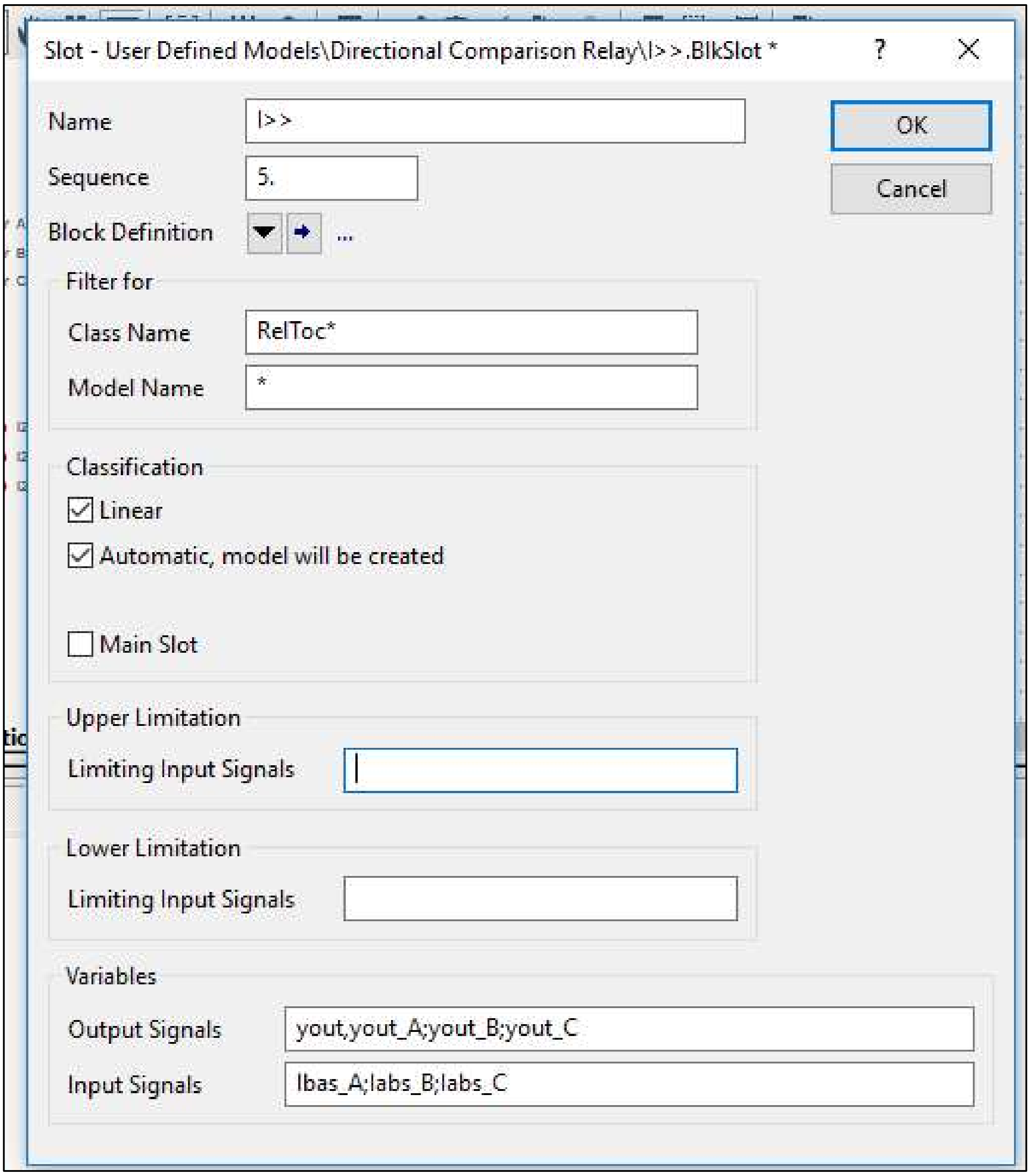
Limiting Input Signals:

Variables

Output Signals: yout,yout_A;yout_B;yout_C

Input Signals: Ibas_A;Iabs_B;Iabs_C

Appendix Figure 14: DIgSILENT Relay Creation – Instantaneous Overcurrent Slot Specification.



Slot - User Defined Models\Directional Comparison Relay\I>>.BlkSlot *

Name: I>>

Sequence: 5.

Block Definition

Filter for

Class Name: RelToc*

Model Name: *

Classification

☑ Linear

☑ Automatic, model will be created

☐ Main Slot

Upper Limitation

Limiting Input Signals:

Lower Limitation

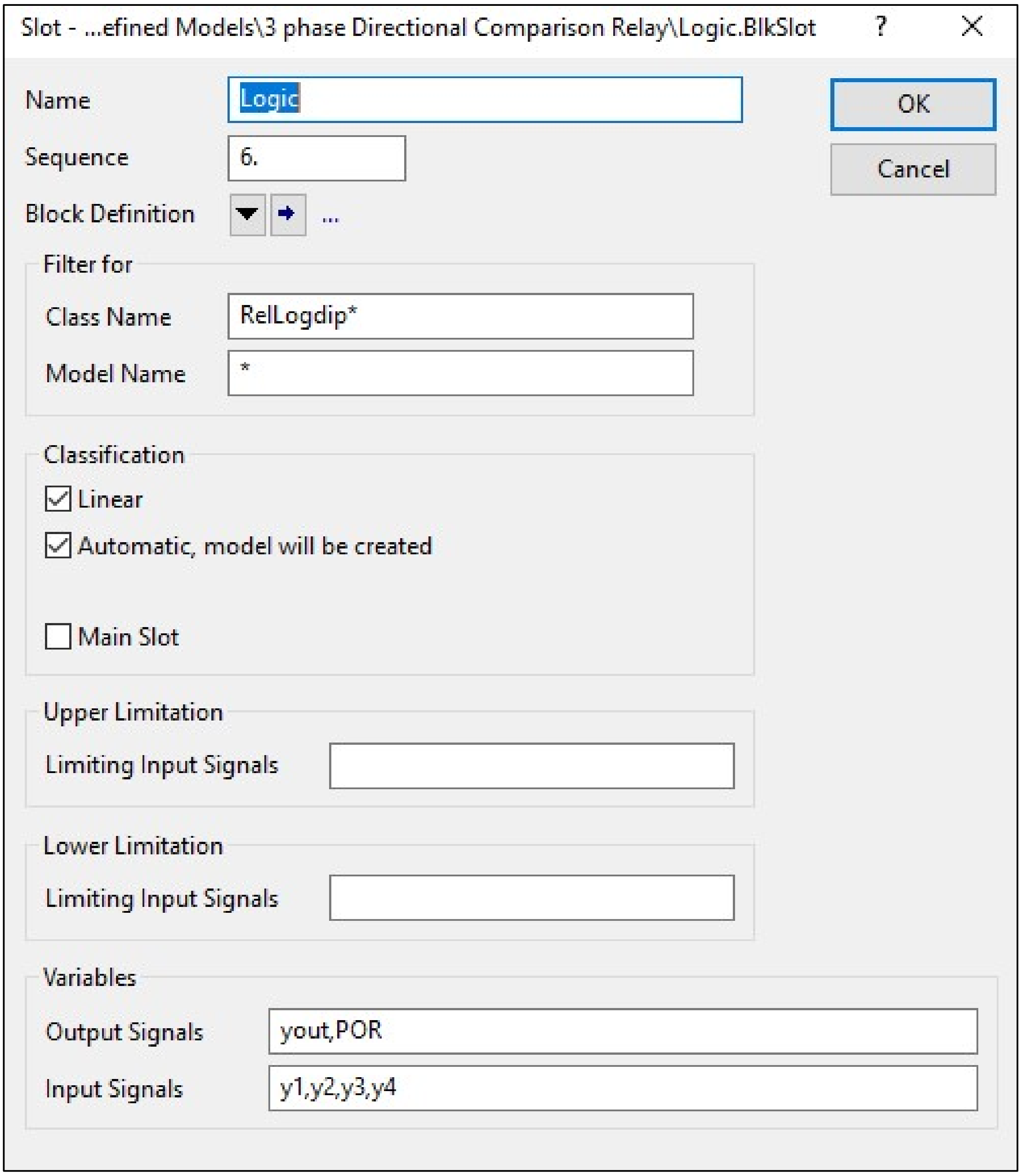
Limiting Input Signals:

Variables

Output Signals: yout,yout_A;yout_B;yout_C

Input Signals: Ibas_A;Iabs_B;Iabs_C

Appendix Figure 15: DIgSILENT Relay Creation – Time-Delayed Overcurrent Slot Specification.



Slot - ...efined Models\3 phase Directional Comparison Relay\Logic.BlkSlot

Name: Logic

Sequence: 6.

Block Definition

Filter for

Class Name: RelLogdip*

Model Name: *

Classification

☑ Linear

☑ Automatic, model will be created

☐ Main Slot

Upper Limitation

Limiting Input Signals:

Lower Limitation

Limiting Input Signals:

Variables

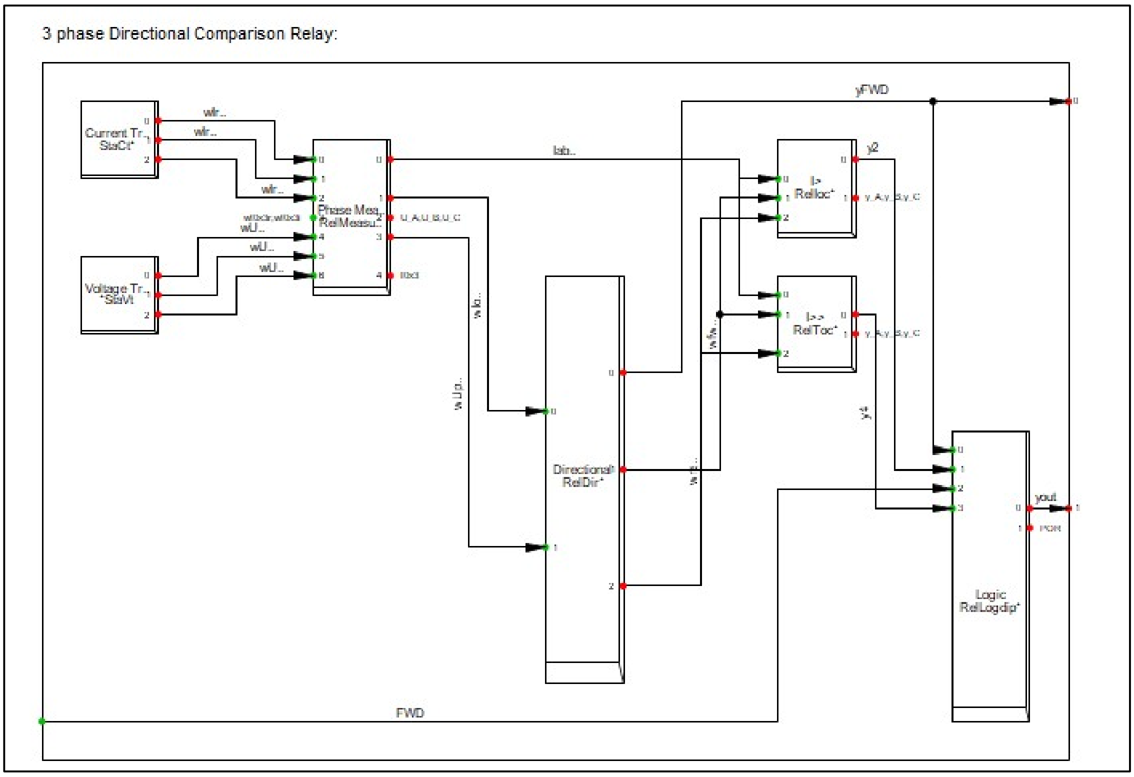
Output Signals: yout,POR

Input Signals: y1,y2,y3,y4

Appendix Figure 16: DIgSILENT Relay Creation – Relay Logic Slot Specification.

Note that for all but the VT and CT blocks, the self-explanatory '*Automatic, model will be created*' box is checked.

The slots are then linked using the → icon to form the following relay diagram (Appendix Figure 17).

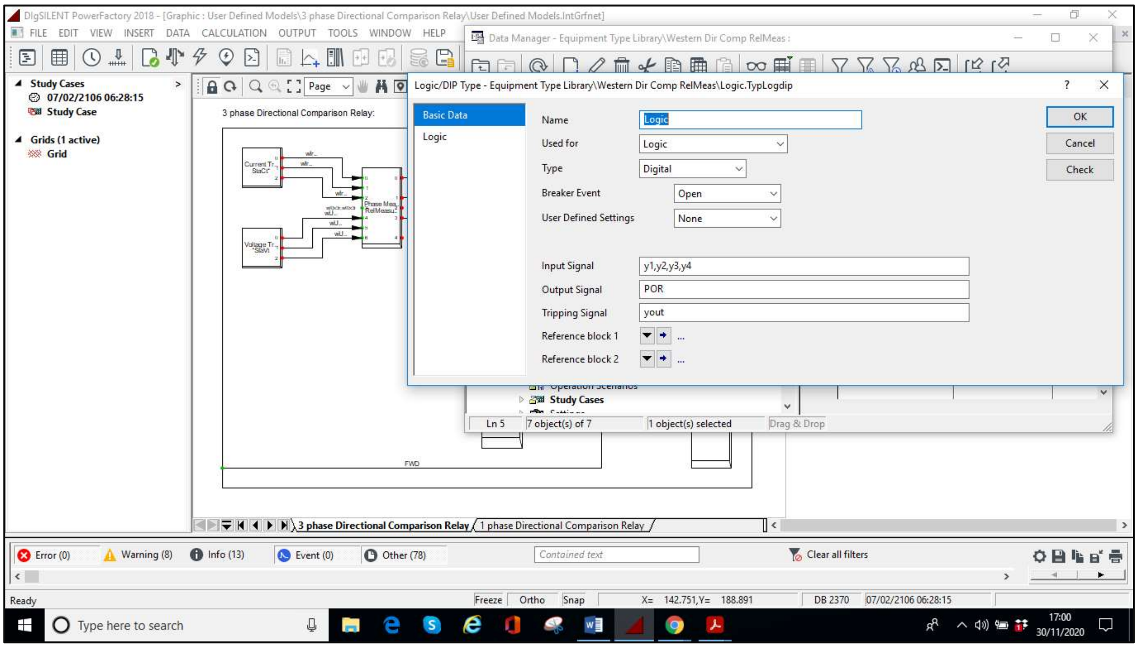


Appendix Figure 17: DIgSILENT Relay Creation – Connected Block Frame Diagram for Directional Comparison Relay.

In this case, the logic input to the relay is 'FWD' (received permissive command from remote relay. The logic outputs are *'yout'* (trip) and 'yFWD' (send permissive command to remote relay. The *'yout'* output is a direct output from the '*RelLogdip*' slot. Some prior knowledge of the output tripping logic is required in order to define the connections to the RelLogdip* tripping logic. In this case, tripping should occur if the local relay sees a forward fault above pickup and the remote relay indicates that it has measured the fault in the forward sense. As back-up tripping should occur if the (high set) time-delayed overcurrent element operates.

The required 'RelLogic' is therefore (((*I>* AND *send FWD*) AND (*receive FWD*)) OR (*I>>*)).

It is assigned according to the following two screen shots (Appendix Figure 18 & Appendix Figure 19).



Logic/DIP Type - Equipment Type Library\Western Dir Comp RelMeas\Logic.TypLogdip

Name: Logic

Used for: Logic

Type: Digital

Breaker Event: Open

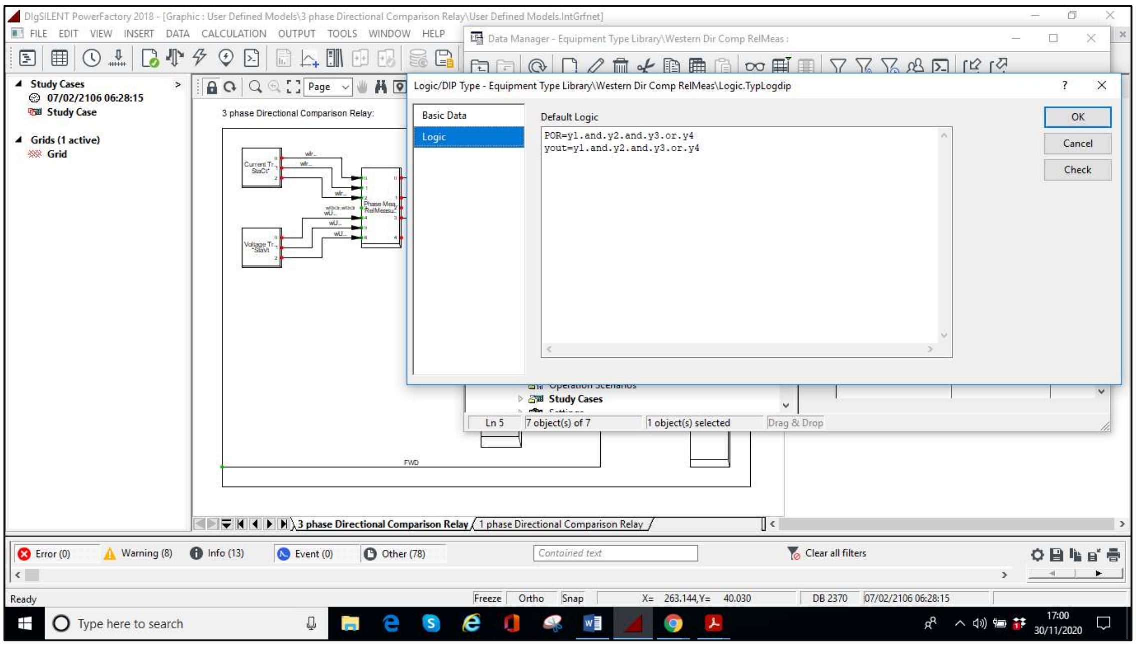
User Defined Settings: None

Input Signal: y1,y2,y3,y4

Output Signal: POR

Tripping Signal: yout

Appendix Figure 18: Allocation of *RelLogdip* Basic Data for Directional Comparison Model.



Logic/DIP Type - Equipment Type Library\Western Dir Comp RelMeas\Logic.TypLogdip

Default Logic

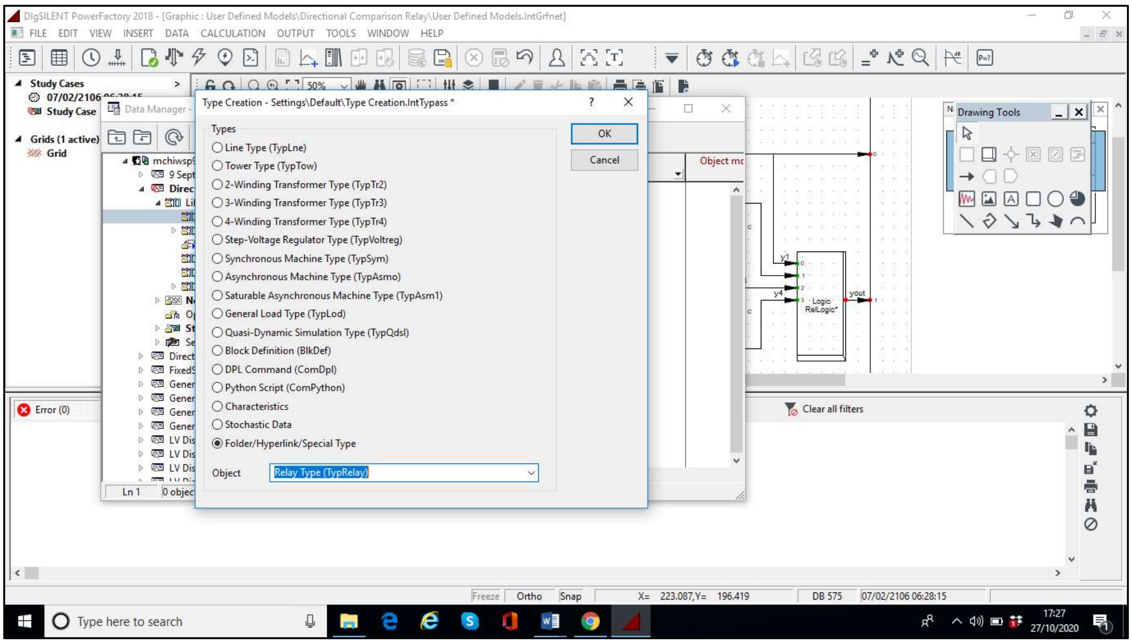
```
POR=y1.and.y2.and.y3.or.y4
yout=y1.and.y2.and.y3.or.y4
```

Appendix Figure 19: Allocation of RelLogdip Logic Equations for Directional Comparison Model.

The next stage in the process is to 'create the relay type'.

The new relay type (*TypRelay*) needs to be defined as do the details of the contained relay blocks.

To create the new relay type, firstly, create a new object of the type '*TypRelay*' inside the *Equipment Type Library* folder according to the following screenshot Appendix Figure 20.



Type Creation - Settings\Default\Type Creation.IntTypass *

Types

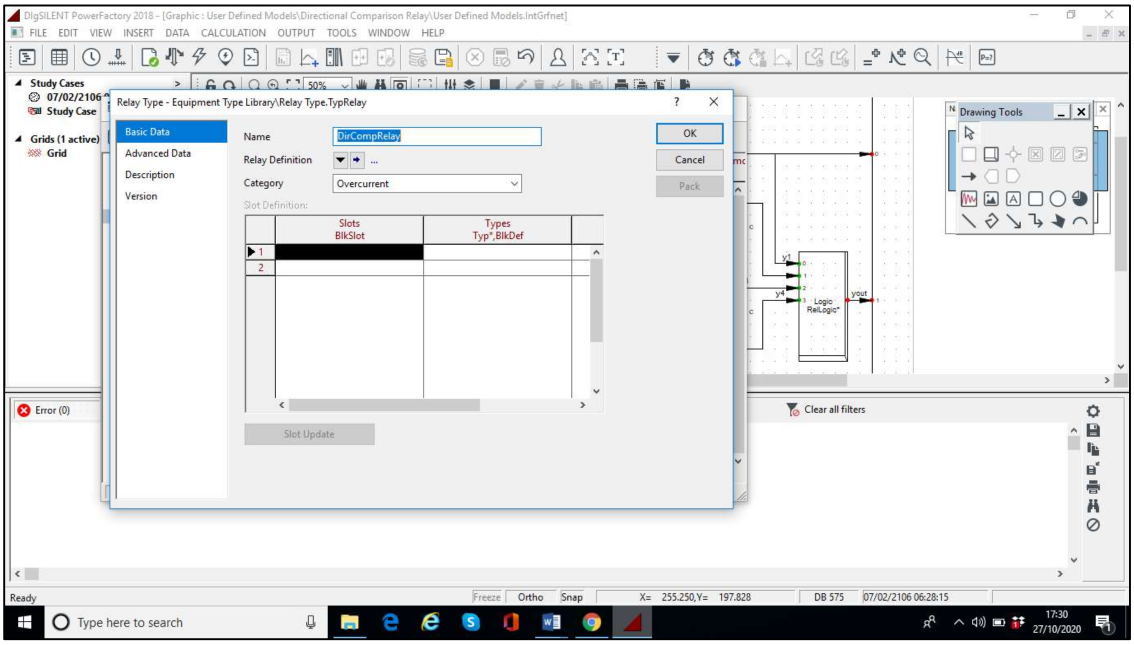
○ Line Type (TypLne)
○ Tower Type (TypTow)
○ 2-Winding Transformer Type (TypTr2)
○ 3-Winding Transformer Type (TypTr3)
○ 4-Winding Transformer Type (TypTr4)
○ Step-Voltage Regulator Type (TypVoltreg)
○ Synchronous Machine Type (TypSym)
○ Asynchronous Machine Type (TypAsmo)
○ Saturable Asynchronous Machine Type (TypAsm1)
○ General Load Type (TypLod)
○ Quasi-Dynamic Simulation Type (TypQdsl)
○ Block Definition (BlkDef)
○ DPL Command (ComDpl)
○ Python Script (ComPython)
○ Characteristics
○ Stochastic Data
● Folder/Hyperlink/Special Type

Object: Relay Type (TypRelay)

OK
Cancel

Appendix Figure 20: DIgSILENT Relay Creation –New Relay Type Selection.

The relay should be named. In this case it's called "*DirCompRelay*" as shown in the following screenshot (Appendix Figure 21).



DIgSILENT PowerFactory 2018 - [Graphic : User Defined Models\Directional Comparison Relay\User Defined Models.IntGrfnet]

Relay Type - Equipment Type Library\Relay Type.TypRelay

Name: DirCompRelay

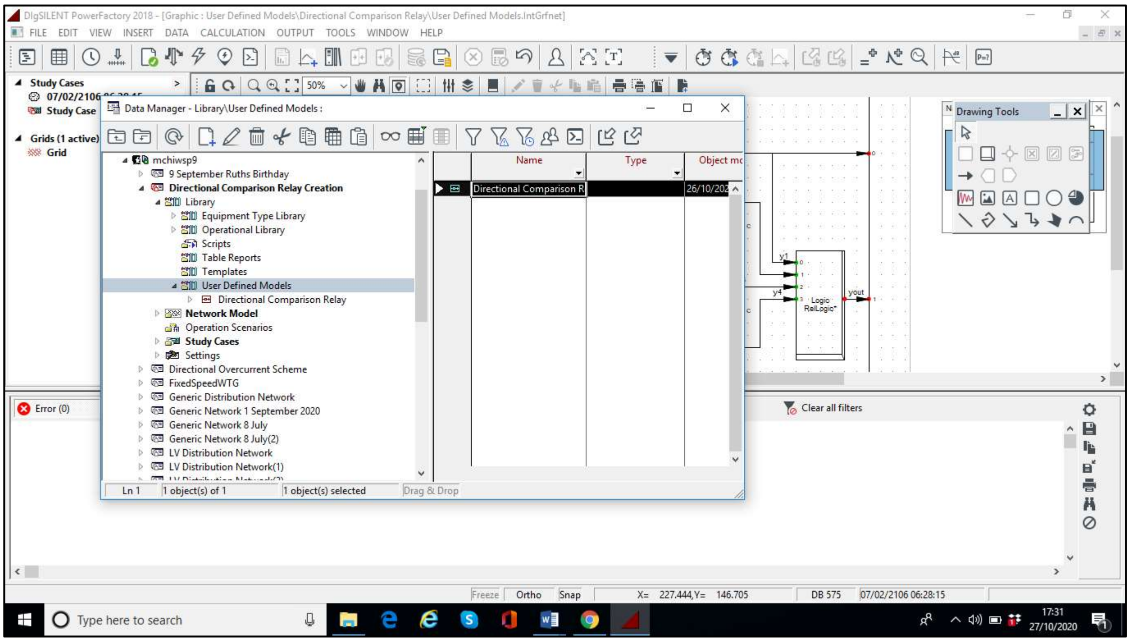
Category: Overcurrent

Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1		
2		

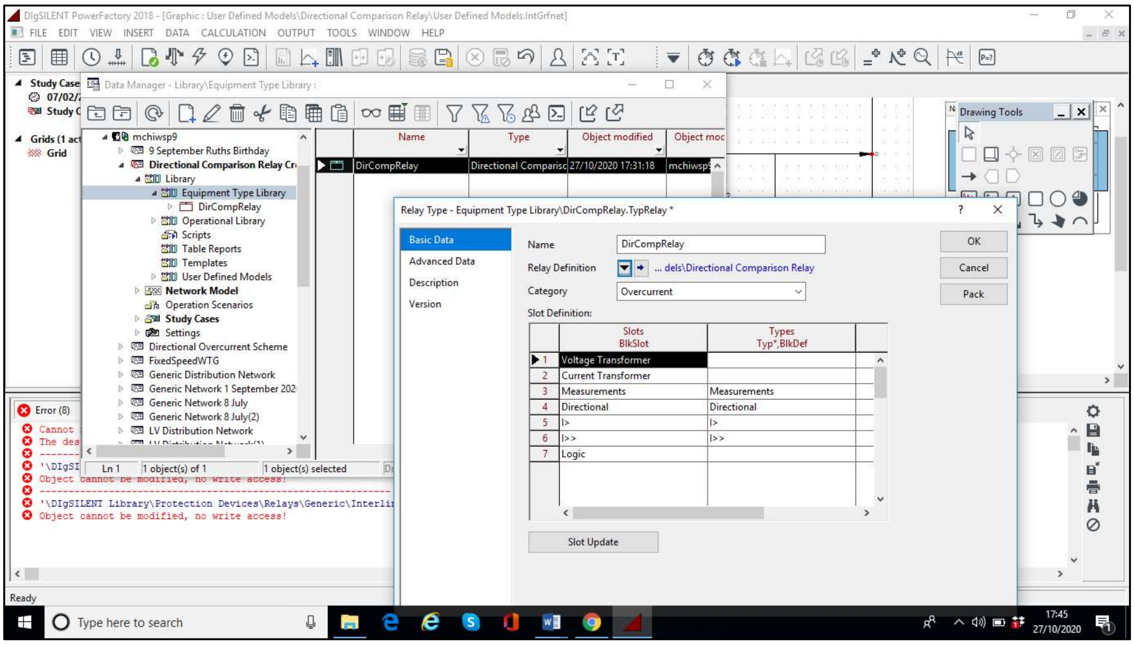
Appendix Figure 21: DIgSILENT Relay Creation –Naming the New Relay Type.

The Directional Comparison Relay frame that was created earlier in the *User Defined Models* folder now needs to be copied into the template library. The following screenshot (Appendix Figure 22) shows the file to be copied from the source location.



Appendix Figure 22: DIgSILENT Relay Creation –Locating the Newly Created Block Frame for use in the New Relay Type.

The Block Frame then needs to be pasted into the new relay type (*DirCompRelay*). Following storage into the library, the new relay (*DirCompRelay*) needs to be opened and the appropriate frame selected under the option *Relay Definition* (hint, pull down '*Select Project Type*') as per the following screenshot (Appendix Figure 23).



DIgSILENT PowerFactory 2018 - [Graphic : User Defined Models\Directional Comparison Relay\User Defined Models.IntGrfnet]

Data Manager - Library\Equipment Type Library :

Name	Type	Object modified	Object moc
DirCompRelay	Directional Comparisc	27/10/2020 17:31:18	mchiwsp9

Relay Type - Equipment Type Library\DirCompRelay.TypRelay *

Name: DirCompRelay

Relay Definition: ... dels\Directional Comparison Relay

Category: Overcurrent

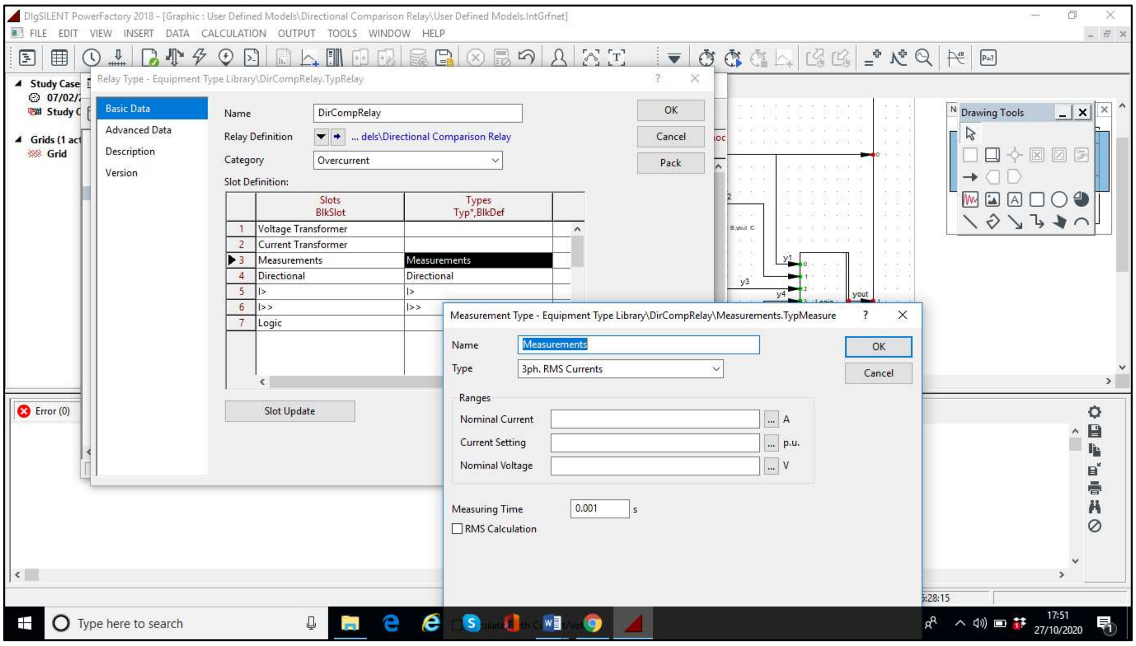
Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Measurements	Measurements
4	Directional	Directional
5	I>	I>
6	I>>	I>>
7	Logic	

```
Error (8)
Cannot
The des
--------
'\DIgSI
Object cannot be modified, no write access!
------------------------------------------------------------
'\DIgSILENT Library\Protection Devices\Relays\Generic\Interlir
Object cannot be modified, no write access!
```

Appendix Figure 23: DIgSILENT Relay Creation –Selecting the Newly Created Block Frame for use in the New Relay Type.

Now each of the slots in the block (e.g. *measurement, I>, I>>,* etc.) needs to be defined in detail. To do this, use the *Types Typ*BlkDef* field as shown in the following screen shots (Appendix Figure 24 through Appendix Figure 29).



Relay Type - Equipment Type Library\DirCompRelay.TypRelay

Name: DirCompRelay

Relay Definition: ... dels\Directional Comparison Relay

Category: Overcurrent

Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Measurements	Measurements
4	Directional	Directional
5	I>	I>
6	I>>	I>>
7	Logic	

Measurement Type - Equipment Type Library\DirCompRelay\Measurements.TypMeasure

Name: Measurements

Type: 3ph. RMS Currents

Ranges

Nominal Current: A

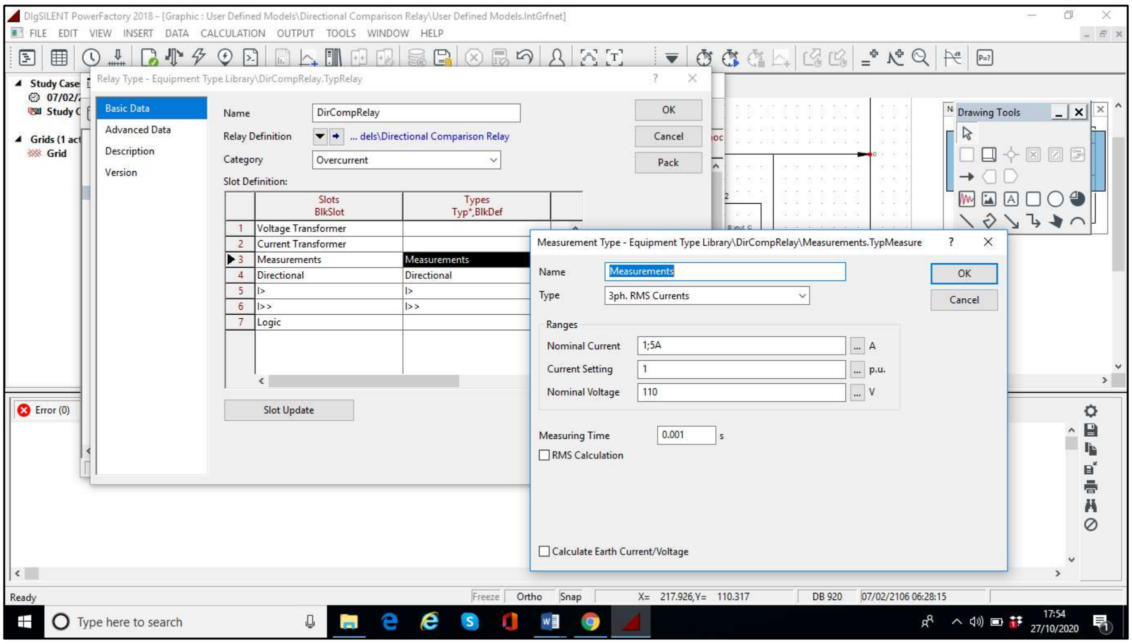
Current Setting: p.u.

Nominal Voltage: V

Measuring Time: 0.001 s

☐ RMS Calculation

Appendix Figure 24: DIgSILENT Relay Creation –Attributing Slot Values in the New Relay Type.



DIgSILENT PowerFactory 2018 - [Graphic : User Defined Models\Directional Comparison Relay\User Defined Models.IntGrfnet]

Relay Type - Equipment Type Library\DirCompRelay.TypRelay

Name: DirCompRelay

Relay Definition: ... dels\Directional Comparison Relay

Category: Overcurrent

Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Measurements	Measurements
4	Directional	Directional
5	I>	I>
6	I>>	I>>
7	Logic	

Measurement Type - Equipment Type Library\DirCompRelay\Measurements.TypMeasure

Name: Measurements

Type: 3ph. RMS Currents

Ranges

Nominal Current: 1;5A A

Current Setting: 1 p.u.

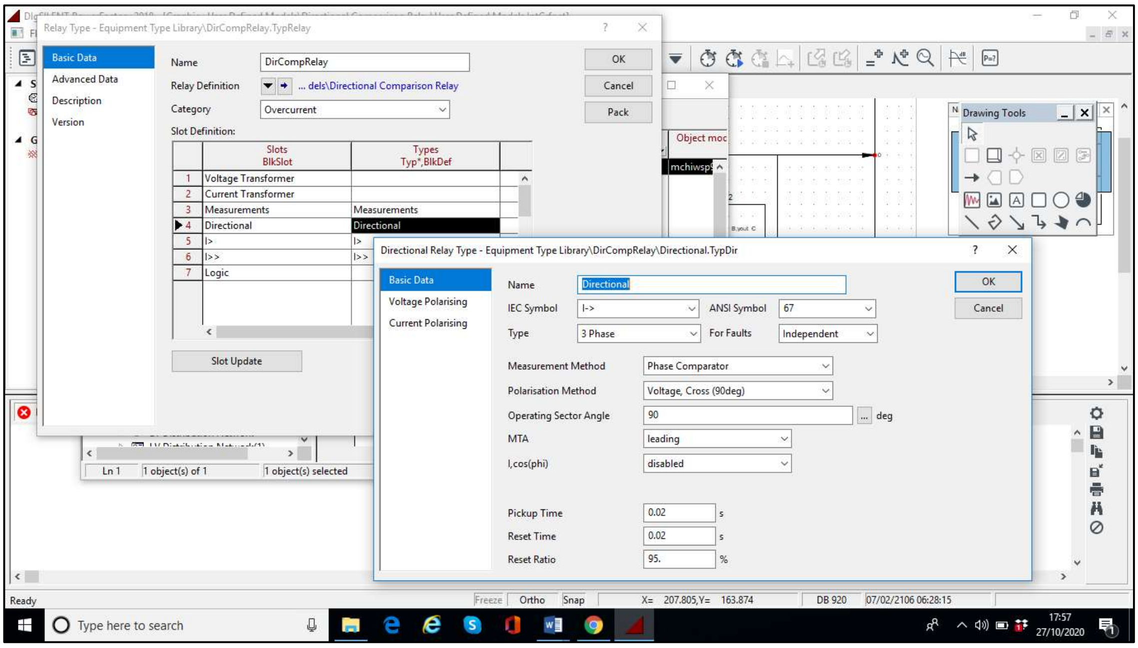
Nominal Voltage: 110 V

Measuring Time: 0.001 s

☐ RMS Calculation

☐ Calculate Earth Current/Voltage

Appendix Figure 25: DIgSILENT Relay Creation –Attributing Values in the Measurements Slot in the New Relay Type.



Relay Type - Equipment Type Library\DirCompRelay.TypRelay

Name: DirCompRelay

Relay Definition: ... dels\Directional Comparison Relay

Category: Overcurrent

Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Measurements	Measurements
4	Directional	Directional
5	I>	I>
6	I>>	I>>
7	Logic	

Directional Relay Type - Equipment Type Library\DirCompRelay\Directional.TypDir

Name: Directional

IEC Symbol: I-> ANSI Symbol: 67

Type: 3 Phase For Faults: Independent

Measurement Method: Phase Comparator

Polarisation Method: Voltage, Cross (90deg)

Operating Sector Angle: 90 deg

MTA: leading

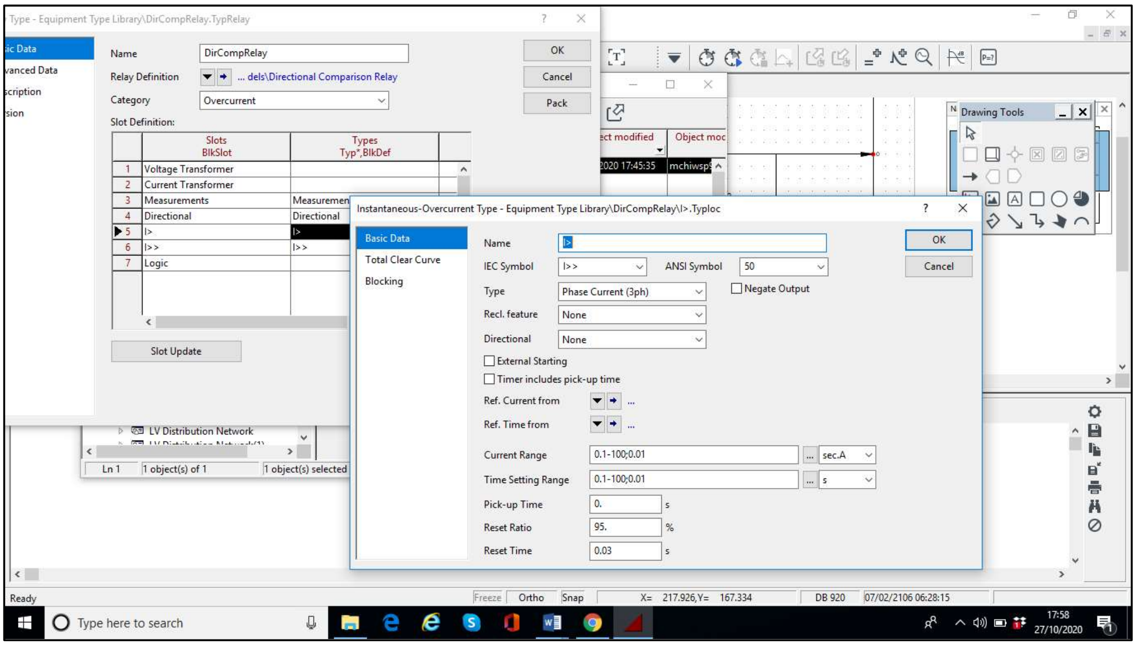
I,cos(phi): disabled

Pickup Time: 0.02 s

Reset Time: 0.02 s

Reset Ratio: 95. %

Appendix Figure 26: DIgSILENT Relay Creation –Attributing Values in the Directional Slot in the New Relay Type.



Type - Equipment Type Library\DirCompRelay.TypRelay

Name: DirCompRelay
Relay Definition: ... dels\Directional Comparison Relay
Category: Overcurrent

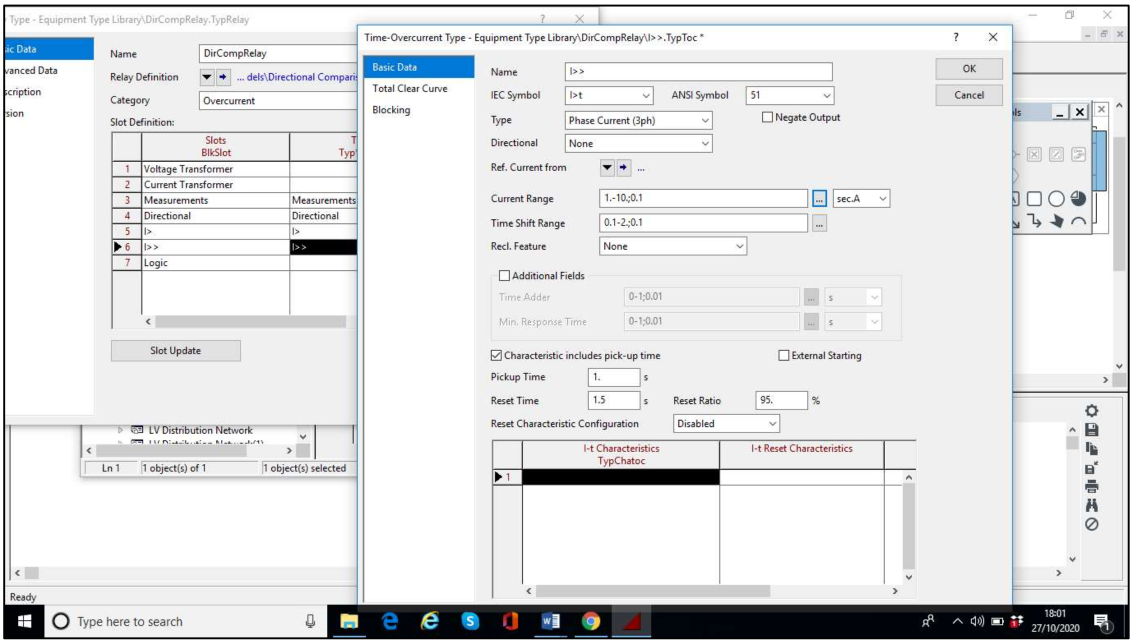
Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Measurements	Measuremen
4	Directional	Directional
5	I>	I>
6	I>>	I>>
7	Logic	

Instantaneous-Overcurrent Type - Equipment Type Library\DirCompRelay\I>.TypIoc

Name: I>
IEC Symbol: I>>
ANSI Symbol: 50
Type: Phase Current (3ph)
☐ Negate Output
Recl. feature: None
Directional: None
☐ External Starting
☐ Timer includes pick-up time
Ref. Current from
Ref. Time from
Current Range: 0.1-100;0.01 sec.A
Time Setting Range: 0.1-100;0.01 s
Pick-up Time: 0. s
Reset Ratio: 95. %
Reset Time: 0.03 s

Appendix Figure 27: DIgSILENT Relay Creation –Attributing Values in the *I*> Slot in the New Relay Type.

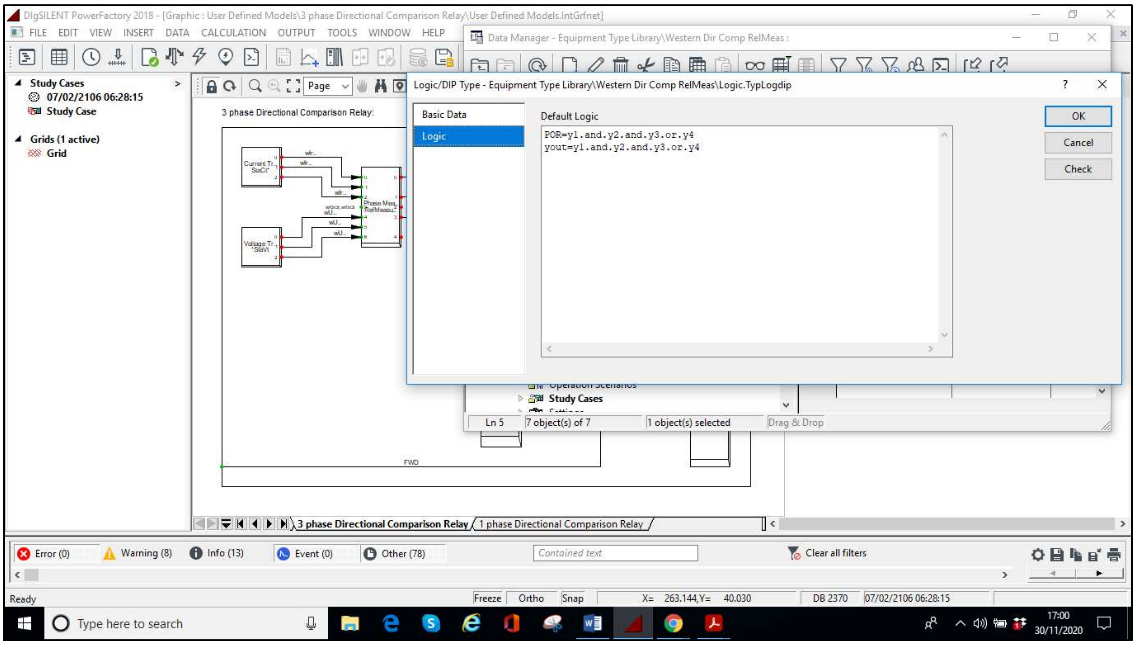


Time-Overcurrent Type - Equipment Type Library\DirCompRelay\I>>.TypToc *

Name: I>>
IEC Symbol: I>t
ANSI Symbol: 51
Type: Phase Current (3ph)
☐ Negate Output
Directional: None
Ref. Current from
Current Range: 1.-10.;0.1 sec.A
Time Shift Range: 0.1-2.;0.1
Recl. Feature: None
☐ Additional Fields
Time Adder: 0-1;0.01 s
Min. Response Time: 0-1;0.01 s
☑ Characteristic includes pick-up time
☐ External Starting
Pickup Time: 1. s
Reset Time: 1.5 s
Reset Ratio: 95. %
Reset Characteristic Configuration: Disabled

	I-t Characteristics TypChatoc	I-t Reset Characteristics
1		

Appendix Figure 28: DIgSILENT Relay Creation –Attributing Values in the *I*>> Slot in the New Relay Type.



DIgSILENT PowerFactory 2018 - [Graphic : User Defined Models\3 phase Directional Comparison Relay\User Defined Models.IntGrfnet]

Data Manager - Equipment Type Library\Western Dir Comp RelMeas :

Logic/DIP Type - Equipment Type Library\Western Dir Comp RelMeas\Logic.TypLogdip

Default Logic

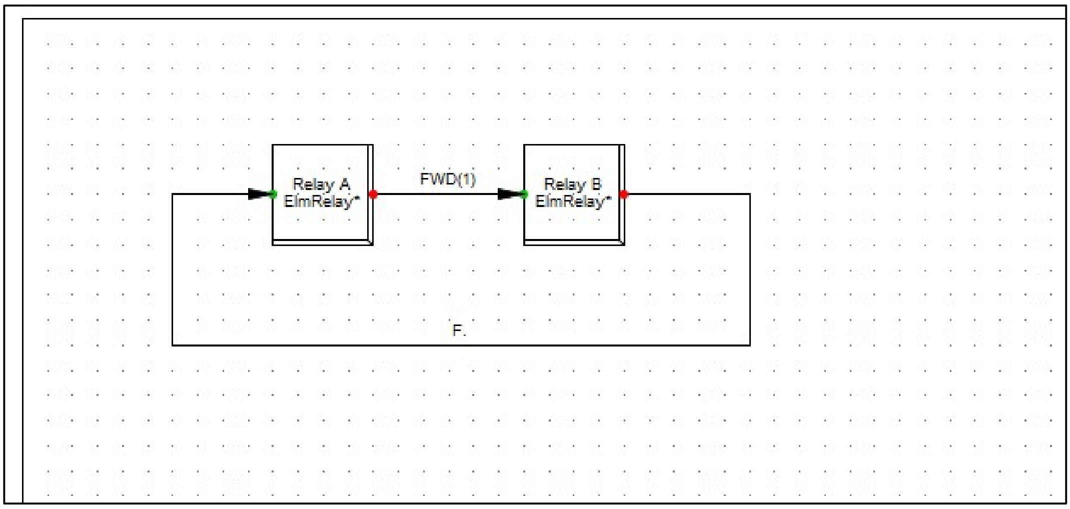
```
POR=y1.and.y2.and.y3.or.y4
yout=y1.and.y2.and.y3.or.y4
```

Appendix Figure 29: DIgSILENT Relay Creation –Attributing Values in the Output Logic (RelLogdip) Slot in the New Relay Type.

That completes the Directional Agent relay modelling, but to form a directional comparison unit scheme a Teleprotection (Communications Interlink) relay is also needed to link the *FWD* and the *yFWD* signals Directional Agents.

Teleprotection (Communications Interlink) DIgSILENT Model Creation

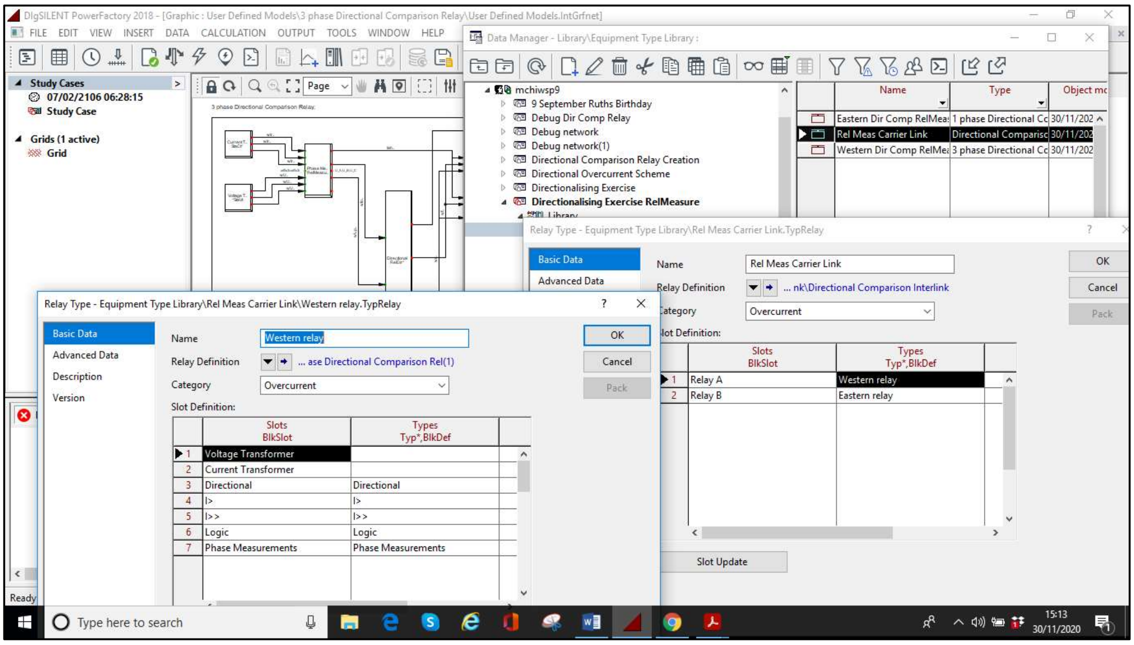
A similar process is applied to create the relay. The resulting Teleprotection (Communications Interlink) shown in the following Appendix Figure 30.



Appendix Figure 30: Teleprotection (Communications Interlink) Relay Model Schematic.

In this case, for Directional Comparison Interlink relay, the two blocks forming the Interlink are named Relays A and B. They are of type '*ElmRelay**'. The Directional Comparison Interlink relay is designed for use with the Directional Comparison relay designed herein. To combine the two element types is a scheme two directional comparison relay instances are required to populate the Interlink slots Relay A and Relay B.

When combining the directional relays with the Teleprotection (Communications Interlink) relay to form the directional comparison scheme, careful attention is required to ensure correct assignments into the slots of the Teleprotection (Communications Interlink) relay. The following Appendix Figure 31 guides the process.



Name	Type	Object mo
Eastern Dir Comp RelMea:	1 phase Directional Cc	30/11/202
Rel Meas Carrier Link	Directional Comparisc	30/11/202
Western Dir Comp RelMe:	3 phase Directional Cc	30/11/202

Relay Type - Equipment Type Library\Rel Meas Carrier Link.TypRelay

Name: Rel Meas Carrier Link

Relay Definition: ... nk\Directional Comparison Interlink

Category: Overcurrent

Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Relay A	Western relay
2	Relay B	Eastern relay

Slot Update

Relay Type - Equipment Type Library\Rel Meas Carrier Link\Western relay.TypRelay

Name: Western relay

Relay Definition: ... ase Directional Comparison Rel(1)

Category: Overcurrent

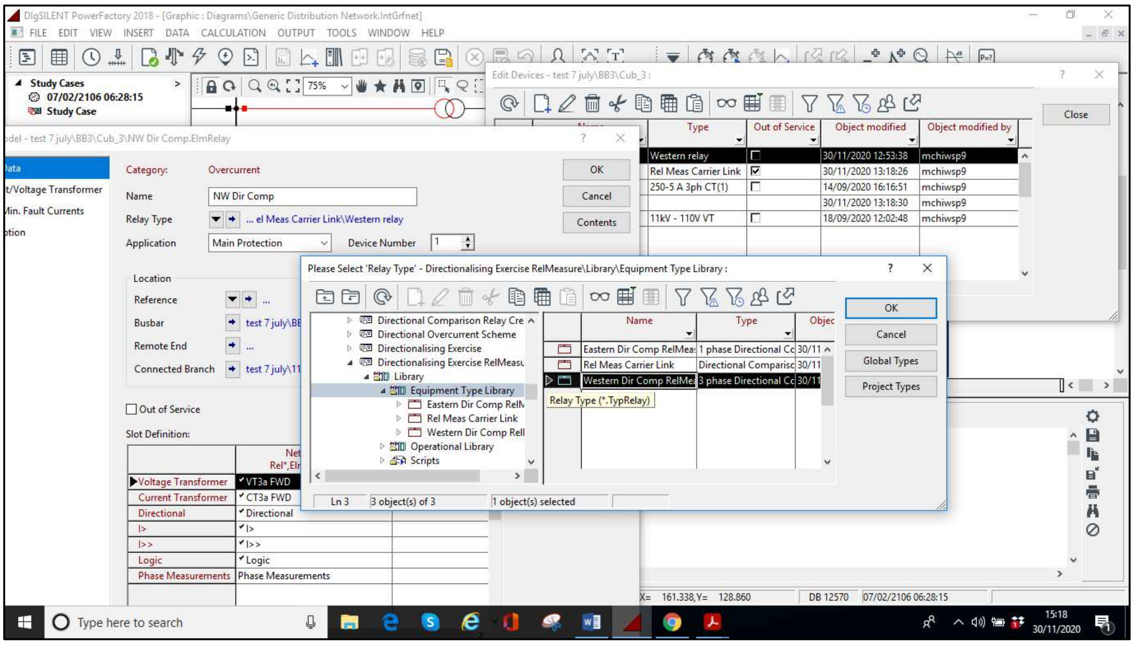
Slot Definition:

	Slots BlkSlot	Types Typ*,BlkDef
1	Voltage Transformer	
2	Current Transformer	
3	Directional	Directional
4	I>	I>
5	I>>	I>>
6	Logic	Logic
7	Phase Measurements	Phase Measurements

Appendix Figure 31: Allocation of Relay Slots in Teleprotection (Communications Interlink) Simulator.

Thereafter, use the 'Select Global Type' to select the directional relays and the interlink relay from the creation location and then assign the correct relay types in the application network diagram.

For the Western relay of Appendix Figure 31, the following Appendix Figure 32 outlines the allocation.


DIgSILENT PowerFactory 2018 - [Graphic : Diagrams\Generic Distribution Network.IntGrfnet]

Study Cases
07/02/2106 06:28:15
Study Case

odel - test 7 july\BB3\Cub_3\NW Dir Comp.ElmRelay

Category: Overcurrent
Name: NW Dir Comp
Relay Type: ... el Meas Carrier Link\Western relay
Application: Main Protection
Device Number: 1

Location
Reference: ...
Busbar: test 7 july\BB
Remote End: ...
Connected Branch: test 7 july\11

☐ Out of Service

Slot Definition:

	Net Rel*,Elr
Voltage Transformer	✓VT3a FWD
Current Transformer	✓CT3a FWD
Directional	✓Directional
I>	✓I>
I>>	✓I>>
Logic	✓Logic
Phase Measurements	Phase Measurements

Edit Devices - test 7 july\BB3\Cub_3 :

Type	Out of Service	Object modified	Object modified by
Western relay	☐	30/11/2020 12:53:38	mchiwsp9
Rel Meas Carrier Link	☑	30/11/2020 13:18:26	mchiwsp9
250-5 A 3ph CT(1)	☐	14/09/2020 16:16:51	mchiwsp9
		30/11/2020 13:18:30	mchiwsp9
11kV - 110V VT	☐	18/09/2020 12:02:48	mchiwsp9

Please Select 'Relay Type' - Directionalising Exercise RelMeasure\Library\Equipment Type Library :

- Directional Comparison Relay Cre
- Directional Overcurrent Scheme
- Directionalising Exercise
- Directionalising Exercise RelMeasu
  - Library
    - Equipment Type Library
      - Eastern Dir Comp RelM
      - Rel Meas Carrier Link
      - Western Dir Comp RelI
    - Operational Library
    - Scripts

Name	Type	Objec
Eastern Dir Comp RelMea	1 phase Directional Cc	30/11
Rel Meas Carrier Link	Directional Comparisc	30/11
Western Dir Comp RelMe	3 phase Directional Cc	30/11

Relay Type (*.TypRelay)

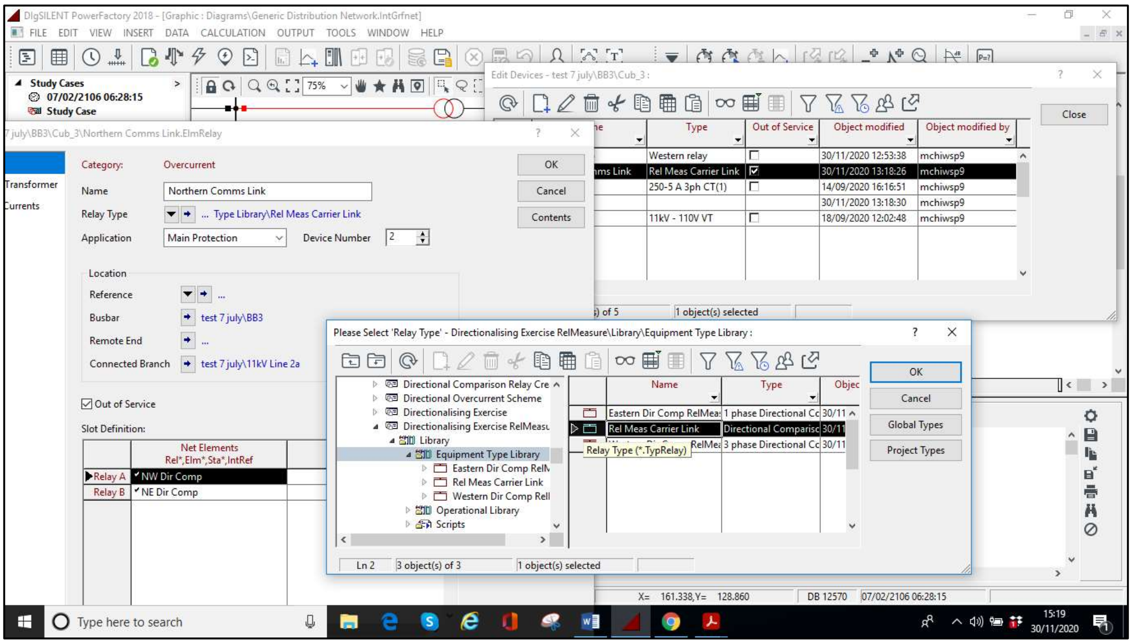
Ln 3 | 3 object(s) of 3 | 1 object(s) selected

X= 161.338,Y= 128.860 | DB 12570 | 07/02/2106 06:28:15

Appendix Figure 32: Allocating Relay Types in the Application Network Diagram for the Western Relay.

A similar allocation applies to the Eastern relay.

Following that, the Teleprotection (Communications Interlink) relay needs allocating according to the following Appendix Figure 33.



DIgSILENT PowerFactory 2018 - [Graphic : Diagrams\Generic Distribution Network.IntGrfnet]

Study Cases
07/02/2106 06:28:15
Study Case

7 july\BB3\Cub_3\Northern Comms Link.ElmRelay

Category: Overcurrent
Name: Northern Comms Link
Relay Type: ... Type Library\Rel Meas Carrier Link
Application: Main Protection
Device Number: 2

Location
Reference: ...
Busbar: test 7 july\BB3
Remote End: ...
Connected Branch: test 7 july\11kV Line 2a

☑ Out of Service

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef
Relay A	✓NW Dir Comp
Relay B	✓NE Dir Comp

Edit Devices - test 7 july\BB3\Cub_3 :

…e	Type	Out of Service	Object modified	Object modified by
	Western relay	☐	30/11/2020 12:53:38	mchiwsp9
…ms Link	Rel Meas Carrier Link	☑	30/11/2020 13:18:26	mchiwsp9
	250-5 A 3ph CT(1)	☐	14/09/2020 16:16:51	mchiwsp9
			30/11/2020 13:18:30	mchiwsp9
	11kV - 110V VT	☐	18/09/2020 12:02:48	mchiwsp9

…) of 5 | 1 object(s) selected

Please Select 'Relay Type' - Directionalising Exercise RelMeasure\Library\Equipment Type Library :

- Directional Comparison Relay Cre
- Directional Overcurrent Scheme
- Directionalising Exercise
- Directionalising Exercise RelMeasu
  - Library
    - Equipment Type Library
      - Eastern Dir Comp RelN
      - Rel Meas Carrier Link
      - Western Dir Comp Rell
    - Operational Library
    - Scripts

Name	Type	Objec
Eastern Dir Comp RelMea:	1 phase Directional Cc	30/11
Rel Meas Carrier Link	Directional Comparisc	30/11
…RelMe:	3 phase Directional Cc	30/11

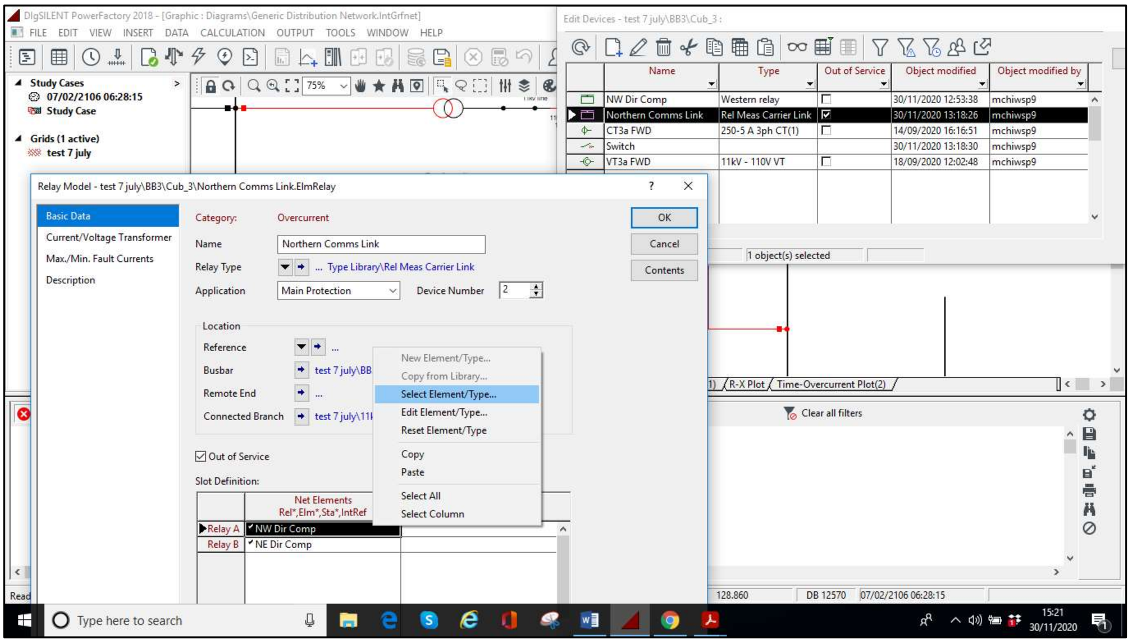
Relay Type (*.TypRelay)

Ln 2 | 3 object(s) of 3 | 1 object(s) selected

X= 161.338,Y= 128.860 | DB 12570 | 07/02/2106 06:28:15

Appendix Figure 33: Allocating Relay Types in the Application Network Diagram for the Teleprotection (Communications Interlink) Relay.

Next, on the Teleprotection (Communications Interlink) device in the application, the 'Select Element/Type' needs to be used as per the following Appendix Figure 34.



	Name	Type	Out of Service	Object modified	Object modified by
	NW Dir Comp	Western relay	☐	30/11/2020 12:53:38	mchiwsp9
▶	Northern Comms Link	Rel Meas Carrier Link	☑	30/11/2020 13:18:26	mchiwsp9
	CT3a FWD	250-5 A 3ph CT(1)	☐	14/09/2020 16:16:51	mchiwsp9
	Switch			30/11/2020 13:18:30	mchiwsp9
	VT3a FWD	11kV - 110V VT	☐	18/09/2020 12:02:48	mchiwsp9

Category: Overcurrent
Name: Northern Comms Link
Relay Type: ... Type Library\Rel Meas Carrier Link
Application: Main Protection
Device Number: 2

Location
Reference: ...
Busbar: test 7 july\BB
Remote End: ...
Connected Branch: test 7 july\11k

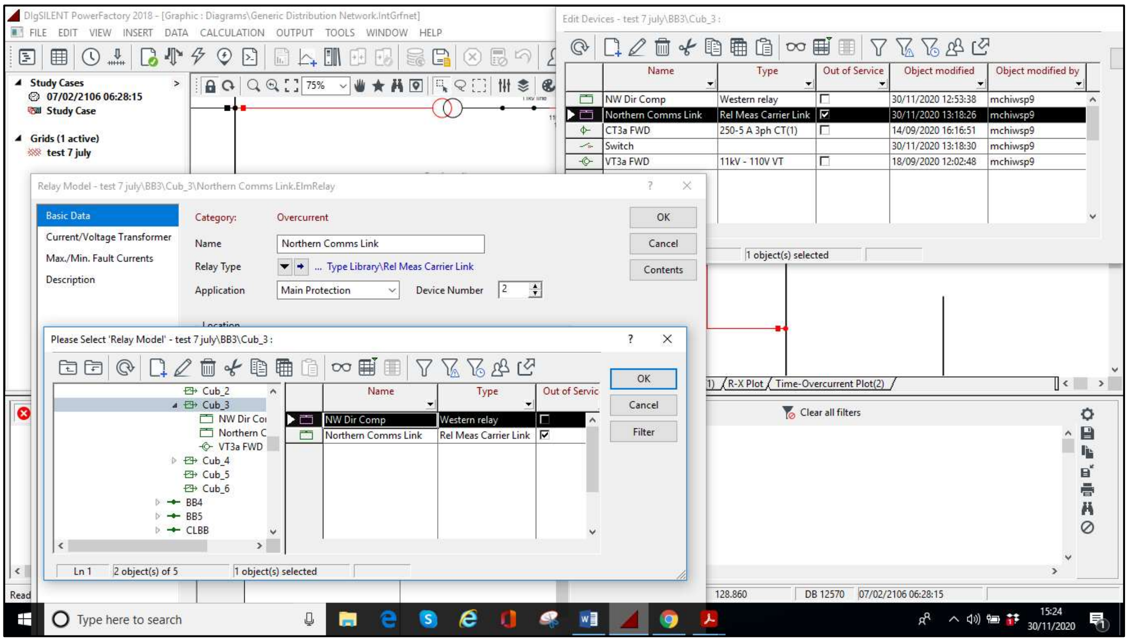
☑ Out of Service

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef
▶Relay A	NW Dir Comp
Relay B	NE Dir Comp

Appendix Figure 34: Selecting the Element Types in the Application Network Diagram for the Teleprotection (Communications Interlink) Relay.

Finally, the relay is located on the network according to the following Appendix Figure 35.



Edit Devices - test 7 july\BB3\Cub_3 :

Name	Type	Out of Service	Object modified	Object modified by
NW Dir Comp	Western relay	☐	30/11/2020 12:53:38	mchiwsp9
Northern Comms Link	Rel Meas Carrier Link	☑	30/11/2020 13:18:26	mchiwsp9
CT3a FWD	250-5 A 3ph CT(1)	☐	14/09/2020 16:16:51	mchiwsp9
Switch			30/11/2020 13:18:30	mchiwsp9
VT3a FWD	11kV - 110V VT	☐	18/09/2020 12:02:48	mchiwsp9

1 object(s) selected

Relay Model - test 7 july\BB3\Cub_3\Northern Comms Link.ElmRelay

Basic Data
Current/Voltage Transformer
Max./Min. Fault Currents
Description

Category: Overcurrent
Name: Northern Comms Link
Relay Type: ... Type Library\Rel Meas Carrier Link
Application: Main Protection
Device Number: 2

OK Cancel Contents

Please Select 'Relay Model' - test 7 july\BB3\Cub_3 :

Cub_2
Cub_3
NW Dir Co
Northern C
VT3a FWD
Cub_4
Cub_5
Cub_6
BB4
BB5
CLBB

Name	Type	Out of Servic
NW Dir Comp	Western relay	☐
Northern Comms Link	Rel Meas Carrier Link	☑

OK Cancel Filter

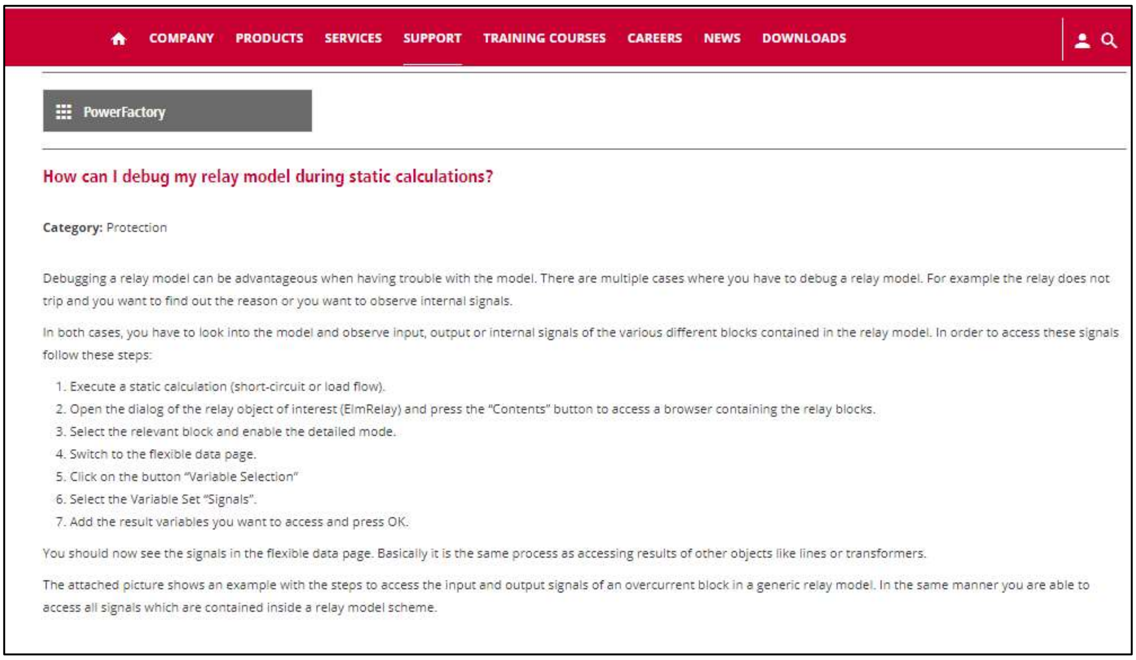
Ln 1 | 2 object(s) of 5 | 1 object(s) selected

Appendix Figure 35: Locating the Allocated Element in the Application.

Model Debugging

The DIgSILENT environment provides elementary tools with which to debug/test the created models. Debug assistance can be found at the following link:- https://www.digsilent.de/en/faq-reader-/how-can-i-debug-my-relay-model-during-static-calculations.html

From which the following two screenshots (Appendix Figure 36 & Appendix Figure 37) are provided for assistance.



How can I debug my relay model during static calculations?

Category: Protection

Debugging a relay model can be advantageous when having trouble with the model. There are multiple cases where you have to debug a relay model. For example the relay does not trip and you want to find out the reason or you want to observe internal signals.

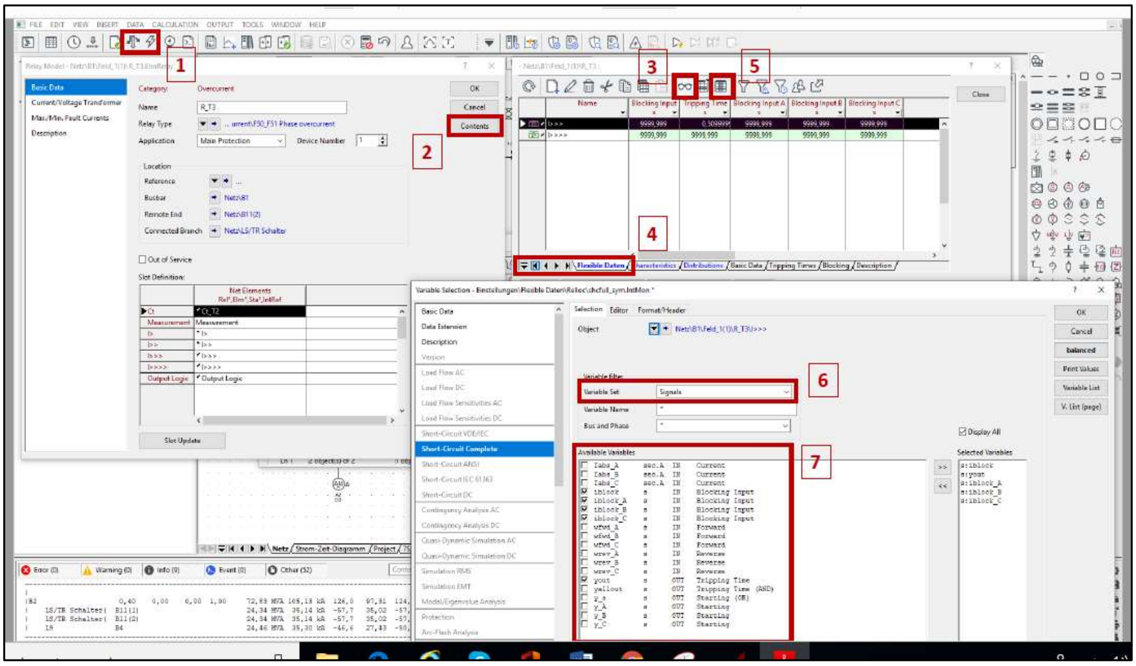
In both cases, you have to look into the model and observe input, output or internal signals of the various different blocks contained in the relay model. In order to access these signals follow these steps:

1. Execute a static calculation (short-circuit or load flow).
2. Open the dialog of the relay object of interest (ElmRelay) and press the "Contents" button to access a browser containing the relay blocks.
3. Select the relevant block and enable the detailed mode.
4. Switch to the flexible data page.
5. Click on the button "Variable Selection"
6. Select the Variable Set "Signals".
7. Add the result variables you want to access and press OK.

You should now see the signals in the flexible data page. Basically it is the same process as accessing results of other objects like lines or transformers.

The attached picture shows an example with the steps to access the input and output signals of an overcurrent block in a generic relay model. In the same manner you are able to access all signals which are contained inside a relay model scheme.

Appendix Figure 36: DIgSILENT Model Creation Debug Assistance Page.



Appendix Figure 37: DIgSILENT Model Creation Debug Assistance Screen.