INVESTIGATION INTO OPEN PHASE FAULTS ON TRANSMISSION CIRCUITS.

by

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Dr. Akshay Kumar Saha as the candidate’s Supervisor I agree/do not agree to the submission of this thesis.

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Abstract

Open phase faults are not commonly encountered on the South African power transmission systems. However, when these faults do occur it results in major power system interruptions and spurious tripping of healthy (circuits without faults) circuits to trip without giving any indication of the type or location of the fault. This results in lengthy restoration times to find the open phase fault without any fault detection devices. The intention of this study was to investigate open phase faults and assess the impact thereof. An investigation was conducted on an open phase fault on the bus-section of the transmission high voltage yard at Koeberg Power Station. The investigation utilised the Koeberg network configuration, power system data, and protection settings in order to simulate the fault and validate the results with the simulation model. The simulation model was tested by simulating short circuit faults with the current feeder circuit protection scheme characteristics and settings. The results of the investigation confirmed that the current feeder protection schemes do not take open phase fault detection into account. The back-up earth-fault protection which is normally utilised to detect and trip for high resistance faults, did indeed detect and trip for open phase faults where the unbalance currents summation was above the minimum setting threshold of 300 A although the fault clearing times was extremely long. However, this was not the case for all instances. The feeder tripped due to zero sequence currents instead of negative sequence currents. In addition the impact of open phase faults was investigated on the Koeberg generator circuit to confirm that the generator would be protected against negative sequence currents and trip based on the generator protection philosophy, the coordinated and configure generator protection settings. The literature research comprised of the present feeder protection philosophies, a review of currently used feeder protection schemes, available new feeder protection schemes, technologies available or technologies that have the potential to detect an open phase fault. An evaluation of the currently used protection schemes and new protection schemes available was conducted. Considerations with respect to the protection scheme flexibility, adaptability with regards to co-ordination and configuration of the protection scheme in conjunction with the feeder protection philosophies, modifications and additions to the current feeder protection schemes were considered.

Acknowledgements

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My gratitude to Mr J. H. Bekker, Eskom – National Control - for providing me with access to simulation software, South African national power network data, relay scheme data and protection configuration settings of relevant Eskom Transmission circuits.

To my family (Dharmita, Arshia, Kiara, Viveka & Taresh) for motivating and providing support to me during my studies.

Abbreviations

%	Percentage
$3I_0$	Residual current
$3U_0$ ($3V_0$)	Residual voltage
$3V_0$	Zero Sequence Voltage
ARC	Auto Re-Close
CCC	Charging Current Compensation
CPU	Central Processing Unit
CT	Current Transformer
DAS	Data Acquisition System
DC	Direct Current
DT	Definite Time
E/F	Earth Fault
EHV	Extra High Voltage
ERTU	Enhanced Remote Terminal Unit
HIF	High Impedance Fault
HMI	Human Machine Interface
HV	High Voltage
I_0	Zero Sequence Current
I_{Bias}	Current Bias
IDMT	Inverse Definite Mean Time
IED	Intelligent Electronic Device
$I_{nominal}$	Nominal Current
Km	Kilometre
KPI	Key Performance Indicator
kV	Kilo Volt
ms	Milliseconds
MV	Medium Voltage
NPS	Negative Phase Sequence
O/C	Overcurrent
OOS	Out Of Step

PD	Pole Discrepancy
PLC	Power Line Carrier
PSSE	Power Systems Simulation for Engineers
PST	Parameter Setting Tool
R	Resistance
RMS	Root mean square
SCADA	Supervisory Control and Data Acquisition
SIR	Source Impedance Ratio
T_d	Time Delay
TEF	Definite and inverse time delayed residual over current
TOC	Time Delay Over Current
VT	Voltage Transformer
X	Reactance
Z	Impedance
Z_{3F}	Zone 3 Forward
Z_{3R}	Zone 3 Reverse

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CHAPTER 1: INTRODUCTION

1. Chapter introduction and motivation of research topic

South African power transmission network present protection schemes cannot detect an open phase fault. Distance or impedance type of line feeder protection schemes are predominantly utilised with the rest being current differential protection [1]. Eskom (SA power utility) had focused on protection schemes to best protect the network based on the most common faults experienced and that could occur on the transmission and sub-transmission lines, since the majority of faults on the Eskom National Grid occur between single phase and ground or double phases and ground, known as shunt faults [1]. The shunt and phase to phase short circuit faults on the network result in a substantial increase in current flow towards the fault location and conventional over-current protection schemes are utilised to detect and protect against these low impedance faults [2]. Fault causes are mainly lightning discharges (over-voltages which initiate or result in flashovers), birds (actual contact and streamers) on overhead lines, veld fires, pollution caused by the environmental conditions and, to a lesser degree, contact with vegetation. Short-circuit faults result in a substantial increase in current hence, in the majority of applications, are easily detectable to alarm or trip the circuit [2].
As this type of faults give rise to unbalanced conditions on the network with little or no rise in current in the faulted or healthy phases, detection had become a growing concern within the utility business. Eskom Transmission had two major interruptions of supply in the last five years ([3] & [4]) give a detailed description of the fault. This type of fault is caused by direct lightning strike, a conductor burning off due to a hot connection or theft of a conductor, the latter being a common and a serious contributor [1]. Open circuit faults can exist on the transmission and sub-transmission system for a long time since they are not detectable.

Open circuit or series faults gives rise to unbalanced conditions on the network with little or no rise in current in the faulted or healthy phases thus detection has become a growing concern within the power network. South African power transmission national network had two major interruption of supply (interruption of supply of greater than one system minute is classified a major interruption in the last five years (references [3] & [4] give a detailed description of the fault.) This type of fault is caused by direct lightning strike, a conductor burning off due to a hot connection or theft of a conductor, the latter being a common and a serious contributor [1]. Open phase circuit faults can exist on the transmission system for a long time and without being detected [5].

Open phase circuit faults may be detected as voltage unbalance in radial feeds or single supply, open phasing of a supply results in single phasing of customers motors, customer experiencing problems during starting of three phase induction motors (pole slipping) or when random operations are performed on the network that result in the operation of protection due to unbalance current if the loading is adequately high [6].

However, the impedance feeder protection schemes have the capability to trip for negative phase sequence (NPS), however the NPS elements are not enabled (not marshalled to trip). Enabling of NPS elements causes a conflict with single-phase trip and auto-reclose philosophy. Single-phase trip and auto-reclose philosophy was developed to prevent an interruption to customers for an intermittent single-phase fault. The relay is marshalled in this configuration to eliminate tripping the feeder in totality (tripping 3 poles of the breaker) for a single phase fault (one phase to earth fault) [7].

1.1 Benefits of this study

A number of benefits are anticipated and are amongst others, a method for detecting, alarming and tripping open circuited transmission and sub-transmission feeders; reducing the unbalance (negative phase sequence) in the Eskom transmission and distribution network; reducing the thermal stress on Eskom's and customers' rotating (motors and generators) plant; improving the detection of conductor theft and qualifying the impact of an open phase circuit fault on the South African transmission national power network.

1.2 Research problem

It is hypothesised that the currently used transmission protection schemes in South Africa do not take into account of open phase circuit faults, hence, open phase faults cause major network interruptions when these faults occur due to spurious tripping of parts of the power transmission system without correct indication of the fault type or location.

1.3 Research questions

The fundamental research question:

What is the impact of open phase faults on the power network?

1.3.1 Can the present protection schemes detect open phase faults?

1.3.2 What are the possible solution options to enable detection of an open phase faults?

1.3.3 What changes will be required to the current EHV feeder protection philosophy to enhance or enable open phase detection?

1.4 Objectives

The objective is to justify that the problem statement is true by conducting an analysis of an open phase fault on transmission circuits and their behavioural characteristics that impact rest of the power network; performing simulations of the open phase fault using DigSilent Power Factory simulation software; conducting studies using the characteristics and functionality of the line feeder protection schemes with calculated and coordinated settings configured to verify operations of the protection during an open phase fault condition; and finally, recommending application based solutions.

1.5 Outline of chapters

Chapter 1: Introduction

The background to problems related to open phasing were described and explained with respect to the impact on the power system. By conducting simulations of the fault and presenting the results, the objectives of research problem (to analyse the phenomenon of open phase faults) will lead to the formulation of application-based solutions. The research questions are stated and the benefits of the research are emphasised.

Chapter 2: Literature survey

This chapter shares the information of the current power transmission system protection schemes used in correlation with the line feeder protection philosophy and future means of enhancing to ensuring open phase detection, alarming and tripping by studying numerous literature relating to this research topic.

Chapter 3: Research methodology

The methodology, techniques and the strategy of investigating the open phase fault condition and its subsequent impact on the power transmission system is outlined.

Chapter 4: Investigations and simulations

This chapter captures the investigation of an actual fault that occurred on the South African power transmission network with simulations of the open phase fault together with short circuit faults as a comparison and qualification of the simulation model. The protection relay characteristics were integrated into the simulation model to test the protection relay characteristics and settings with respect to short circuit faults and evaluation of these characteristics against an open phase fault.

Chapter 5: Results of investigation and simulations

Results of the investigation and simulations described in chapter 4 were recorded, analysed and assessed to conclude the hypothesis of this particular study.

Chapter 6: Recommendations and conclusion

Recommendations as an outcome of the literature studied in chapter 2 and the results of the simulations and investigation of chapter 4 together with the analysis of the results discussed in chapter 5 will be provided as possible mitigation should the hypothesis prove to be true. The conclusion of the research will be stated based on the analysis of the study.

1.6 Conclusion

The background and motivation of the research problem was presented together with the research questions that will provide direction into the analysis required in chapters 2, 4 and 5. The outline of the chapters presented a structured platform to enable the objective of the research to be achieved.

CHAPTER 2: LITERATURE SURVEY

2 Introduction

The objective of this chapter is to provide background information pertinent to the research topic, the current line feeder protection schemes utilised in South Africa, explanation and analysis of their operation characteristics and setting or marshalling. This chapter also provides a background into possible solutions that are available or are being developed by the various feeder protection scheme manufacturers.

2.1 Currently utilised line feeder protection schemes

A list of the feeder protection schemes presently used or available from protection scheme manufacturers is tabulated below and also gives a description of their protection functionalities and characteristics to illustrate the protection schemes limitations and or flexibility with regard to open circuit fault detection.

Table 2-1: Feeder Protection Schemes [1]

Relay Type	Manufacturer	Generation
Type –H	Reyrolle	Phase 1
P10/P40	Alstom	Phase 1
LZ32	ABB	Phase 1
THR	Reyrolle	Phase 1
R3Z27	Siemens	Phase 1
YTG	Alstom	Phase 1
SlypSlcn	GE	Phase 2
Micromho	Alstom	Phase 2
SLS	GE	Phase 2
TLS	GE	Phase 2
PXLN	Alstom	Phase 3
7SD512	Siemens	Phase 3
7SA513	Siemens	Phase 3
REL 561	ABB	Phase 4
REL 531	ABB	Phase 4

Phase 1 **-** Electromechanical relays and very early discrete electronic relays;

Phase 2 **-** Electronic relays;

Phase 3 **-** Digital relays; and

Phase 4 **-** Microprocessor based (Programmable) Intelligent Electronic Devices.

The list of feeder protection schemes in Table 2-1 was further broken down into type and generation of feeder protection currently in use. From Table 2-1, it was evident that the protections relays were of three feeder protection types namely, impedance or distance, current differential and directional overcurrent.

2.1.1 Impedance protection

Currently, transmission and sub-transmission line feeder protection schemes are predominantly of the impedance protection type [1]. The measurement principle of distance protection is that the relay calculates the ratio of the voltage and current at the precise location of the fault [8]. The ratio equates to the impedance (Z) and therefore measures the impedance of the line from the busbars to the location of the fault. In the case where the measured magnitude of fault impedance is less than to that of the line impedance, this implies that the fault is somewhere on the line. If the fault impedance is greater than the line impedance, then this implies that the fault is located beyond the line and the remote end substation.

The basic impedance based protection relays use only one phase current and a one phase voltage for the measurement of single-phase to earth faults [8]. With the advances in technology other currents and voltages of other phases had been integrated to the relay operating quantities for enhanced operation characteristics. As a result of changes in protection technology over the last few decades, various types of protection schemes are in operation on the South African power transmission system. Electromechanical "phase 1" (38%), electronic "phase 2" (32%), microprocessor base "Intelligent electronic devices" (IED'S) (30%) [25].

2.1.2 Current differential protection

Differential protection relays are used to detect faults by comparing electrical quantities at all terminals of a system element. Current differential relaying is the most common principle used for transmission line feeder protection [9], however current differential schemes can only be applied on short lines. For long lines (distances above 100km) the use of a communication channel has the disadvantage of being costly and reliability of the channels becomes a problem [9].

2.1.3 Directional Overcurrent

Directional overcurrent relays are used to detect phase or ground faults in a particular direction on a power transmission system and to initiate isolation of these faults [10]. They require a polarizing quantity as a reference. The directional overcurrent relay is widely used for earth fault protection. For ground faults all sequence quantities are available. The positive-sequence quantities are negatively impacted by load and therefore should be avoided when considering earth fault protection [10], leaving only zero and negative sequence quantities as possible inputs to a ground directional element. The polarization method used is specified as part of the relay type.

Polarization methods available are namely [10]:

Zero sequence voltage polarisation

A zero-sequence over-current relay simply measures the sum of the three phase currents as in the equation below:

$I_r = 3I_0 = I_a + I_b + I_c$ ---[Equation 2.1]

I_r = Relay zero sequence current

$3I_0$ = Residual current

I_a = Phase ‘a’ current

I_b = Phase ‘b’ current

I_c = Phase ‘c’current

These residual elements should never be set more sensitive than the normal system unbalance. System unbalances can be caused by conditions such as loading conditions and un-transposed transmission lines. A zero-sequence voltage polarized ground directional element uses V_0 or $3V_0$ as the polarizing reference.

$$3V_0 = V_a + V_b + V_c \text{ ---[Equation 2.2]}$$

Where:

$3V_0$ = Zero sequence voltage

V_a = Phase ‘a’ voltage

V_b = Phase ‘b’ voltage

V_c = Phase ‘c’ voltage

ZL_0 = Line sequence impedance

$3I_0$ = Residual current

$$Torque = |3V_0| * |3I_0| * Cos([\angle - 3V_0 - (\angle 3I_0 + \angle ZL_0)]) \text{ ---[Equation 2.3]}$$

The equation above represents the torque for a zero-sequence voltage polarized directional element [10].

The sign of the torque is positive for forward faults and negative for reverse faults. If the polarizing voltage magnitude becomes too small, its angle becomes unreliable. The main problem with this zero sequence voltage polarisation is that if the zero-sequence voltage magnitude presented to the relay for a remote fault is too low, the torque produced by the zero-sequence voltage directional element may be too low to cross its minimum torque threshold. The solution to low polarizing voltage magnitude applications is to use a current polarized directional element. A zero-sequence current polarized ground directional element measures the phase angle difference between the line residual current ($3I_0$) and an external polarizing source current (I_{POL}). Dual polarized zero-sequence directional element is the combination of a zero-sequence voltage polarized directional element and a zero-sequence current polarized directional element. This element provides more flexibility than a single method of zero-sequence polarization [10].

Negative-sequence polarized directional elements have the following advantage when compared to zero-sequence voltage polarized directional elements. Negative-sequence directional elements are insensitive to zero-sequence mutual coupling associated with parallel transmission line applications.

Positive sequence voltage is usually applied to a relay phase with a directional unit polarized by the healthy phase to phase voltage.

2.1.4 YTG line feeder protection relay scheme

The YTG relay is an impedance-based type of protection, a three phase relay with a mho characteristic [11]. The YTG relay caters for phase faults and earth faults. The zones of protection of this relay can be shown on the IX, IR Figure 2-1below [11].

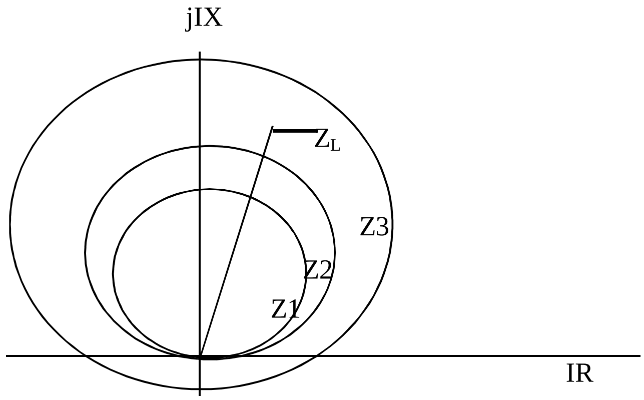

Figure 2-1: Three zones of protection for YTG type relay [11]

Polarising technique

Due to a lack of operation for zero voltage unbalanced faults, a YTG relay utilises a polarising voltage that is equal to 2% of the healthy phase voltage plus the faulted phase voltage for zone 1 and zone 2 faults [11]. The technique is also known as partial cross-polarisation of the mho characteristic. For zone 3 an offset mho characteristic relay is used. Cross polarisation has the effect of increasing the steady state mho characteristic in such that it covers for better resistance coverage [11]. For the YTG relay the effect of polarising is very small as only 2% of healthy voltage is utilised.

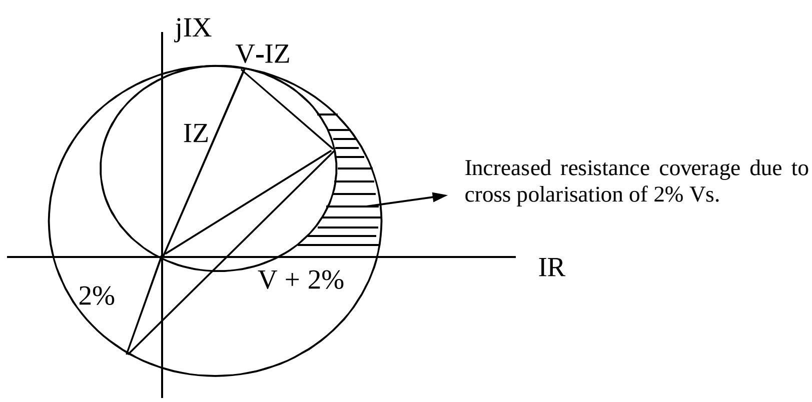

Figure 2-2: IR-IX Diagram with an Effect of Polarisation on GEC, type - YTG Relay [11]

Relay characteristic angle setting

The relay characteristic angle of the relay can increase the fault resistance coverage if it is set lower than the line impedance angle as shown in Figure 2-3. The setting ranges from 45^0 to 75^0. In the South African power transmission network, relay characteristic angle is set below the line angle to allow for better fault resistance coverage. Consider the following mho characteristic diagram for the explanation [11].

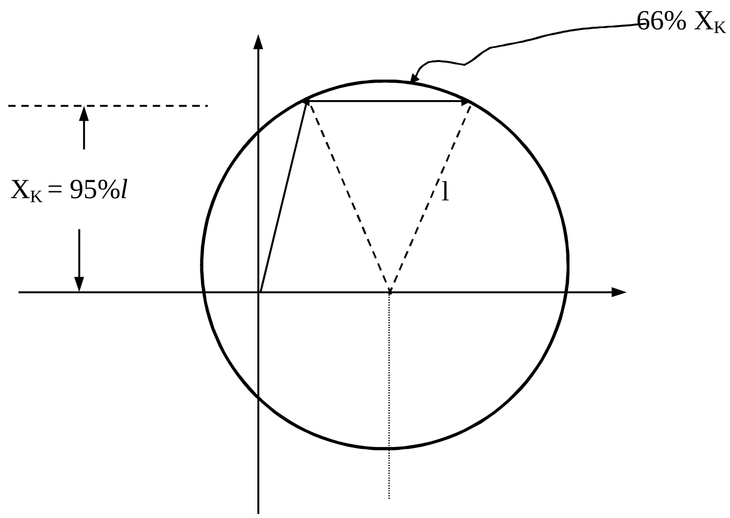

Figure 2-3: Effect of **GEC, type - YTG** Relay Characteristic [11]

2.1.5 TLS line feeder protection relay scheme

TLS protection scheme relays use multi input phase angle comparators to derive a variable mho type characteristic with self-polarization and memory action [12]. The distance function of the TLS relay uses a positive, negative and zero sequence voltage as the polarizing quantity for earth faults. The TLS relay has the variable mho, reactance and directional characteristics [12].

Fault resistance coverage capability

In order to enhance the resistance coverage of the relay, the characteristic timer angle adjustment is available which can be configured in three ways as namely [12], normal circle (if θ is equal to 90 degrees), lens (if θ is greater than 90 degrees), tomato (if θ is less than 90 degrees (Tomato shape provides better resistance coverage).

Lens characteristic

In applications of long line feeder with larger characteristics, discrimination of load and fault cannot be derived in the TLS; the TLS impedance protection could operate as a result of load encroachment [12]. The Lens characteristics however aids in improving stability of the function by enabling the relay characteristic to be shifted away from load area as demonstrated in Figure 2-4.

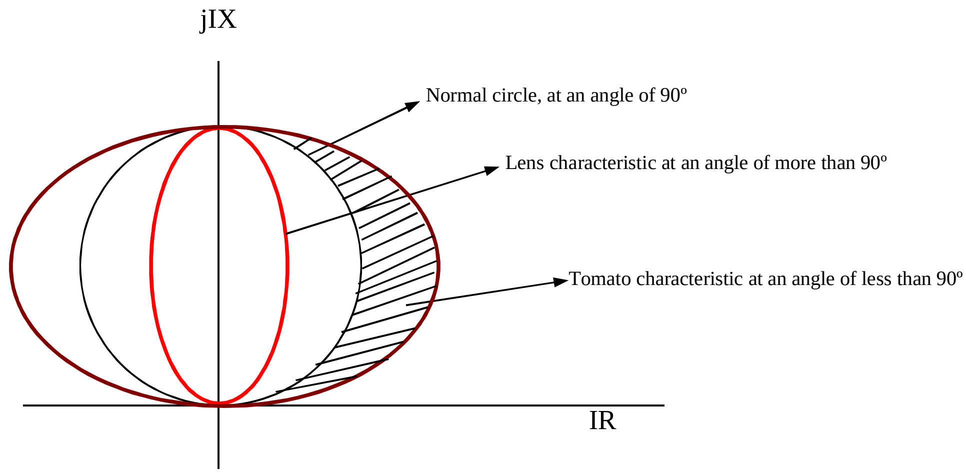

Figure 2-4: Effect of TLS Characteristic Timer Angle Adjustment [12]

Tomato characteristic

For short lines, the amount of fault resistance covered is very small and may result in the relay not tripping for high resistance faults on the line. The tomato characteristics allow the TLS relay shape to be adjusted to cover for more resistance as demonstrated in Figure 2-4 [12].

Reactance characteristic

This characteristic enhances the TLS relay scheme's ability to measure high resistance faults as only the reactive component of the line is measured [12].

2.1.6 R3Z27 line feeder protection relay scheme

R3Z27 is an impedance protection relay scheme which has measuring elements for each phase. TheR3Z27 protection relay scheme has an electrically separated contact with each phase for distance and direction measurement [13]. Figure 2-5 shows plain impedance normally used on long lines (line impedance greater than 25ohms).

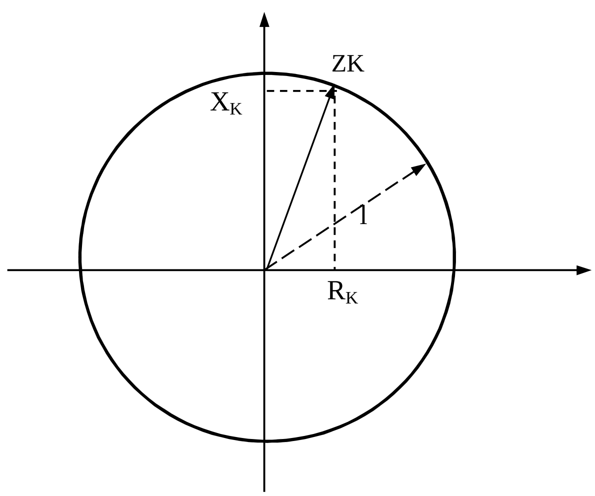

Figure 2-5: Plain Impedance Circle of R3Z27 Relay, l =Z (Radius) [13]

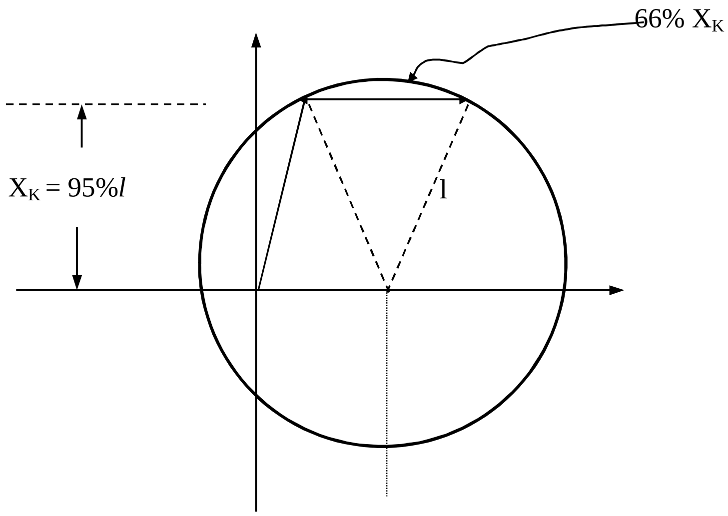

Figure 2-6: Modified impedance circle of an R3Z37 Relay, l =Z (Radius) [13]

Modified impedance with normal tolerance to arc resistance covers at least 66% of reactance (X) as depicted in Figure 2-6. This relay allows for the characteristic to be shifted along the R-axis by 66% of reactance (X) to be able to give better resistive coverage without changing the reactance (X) reach along the line [13].Improved tolerance to arc that covers 132% of reactance (X) is achieved with the modified impedance characteristic with an increased. Commonly utilised for short lines (line impedance less than 10ohms) [13].

2.1.7 LZ32 protection relay scheme

The phase angle comparator is the basic measuring element used in the LZ32 relay protection scheme with fully cross-polarized Mho characteristics [14].The measured impedance is shifted by 30 degrees for three phase faults to ensure an improved fault coverage. For single phase to earth faults, the polarizing voltage is phase shifted by 12 degrees in the leading direction [14].

2.1.8 Type H protection relay scheme

The basic measuring element used in type H protection scheme is the rectifier-bridge current-comparator or amplitude comparator. The phase angle comparator of a Type H relay is derived from the rectifier bridge current-comparator. Type H distance relays use a cross-polarized Mho with a memory action for zone 1 and zone 2. For zone 3 an offset mho characteristic is used. The polarizing voltage is derived from the faulty phase voltage and the small amount of the healthy phase voltage. For close up three-phase faults a back-up offset Mho characteristic is used [15].

2.1.9 SLYP/SLCN line feeder protection relay scheme

The SLYP/SLCN feeder protection scheme relays are more complex relays designed specifically for those lines with series capacitors. SLYP/SLCN use multi input phase angle comparators to derive different type's characteristics. SLYP/SLCN has the following mho characteristics: Self polarized mho relay with memory action, lenticular characteristics, Offset-mho characteristics and directional characteristics. SLYP/SLCN relays can also be set as a reactance relay [16].

2.1.10 Micromho line feeder protection relay scheme

The Micromho relays use multi-input phase angle comparators to derive a variable mho type characteristic. Micromho protection relay scheme has the following mho characteristics [17]:

16% cross - polarized mho, offset Mho and lenticular or lens Mho characteristic.

The sound phase cross-polarised voltage is converted to a square wave before combining with 16% of it with a sine wave self-polarizing voltage to give maximum fault coverage [17].

2.1.11 Siemens 7SA513 line feeder protection relay scheme

The Siemens 7SA513 feeder protection scheme is a numeric (microprocessor based protection sachem with digital processing) distance protection relay with a polygon characteristic [18]. The relay provides five measured current inputs and seven measured voltages. Three current inputs are intended for inputs of the phase currents of the protected line and the remaining for earth current. One voltage input is available for each of the line-to-earth and line-line voltages [18].

Earth fault detection is achieved by comparing the zero sequence current and the negative sequence current. $3I_0$ is measured and the value is compared with the negative phase sequence current for stability purposes ($3I_0$ should be at least 0.3 times the negative phase sequence current). The relay utilises cross polarisation method with the healthy phase voltage rotated 90 degrees. For directional determination, sound phase and stored reference or polarising voltages are used. Theoretical directional line is shown in the Figure 2-7. The position is dependent on source impedance as well as the load current carried by the line immediately before the fault. Consider Figure 2-8 for the directionality when the source impedance is considered for a forward fault which confirms that the fault is indeed in a forward direction.

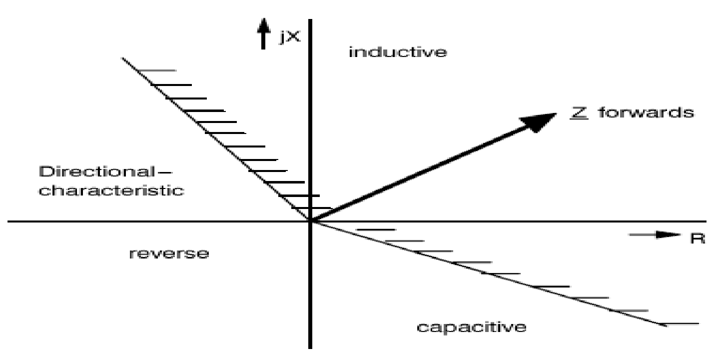

Figure 2-7: 7SA513 Directional characteristics [18]

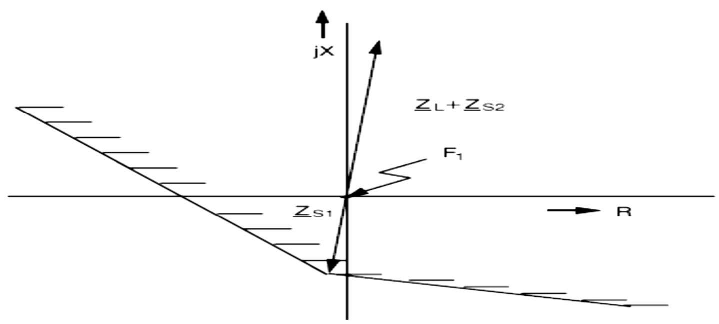

Figure 2-8: 7SA513 Directional characteristic with source impedance, forward fault [18]

Consider Figure 2-9 the following diagram for the directionality when the source impedance is considered for a reverse fault to assess and confirm the direction of the fault is in the reverse direction.

Z_L - Line impedance

Z_{S1} - Source impedance at source 1

F_1 - Fault on the forward direction

F_2 - Fault on the reverse direction

Z_{S2} - Source impedance at source 2

It can be clearly seen from figure above that the relay is stable for reverse faults.

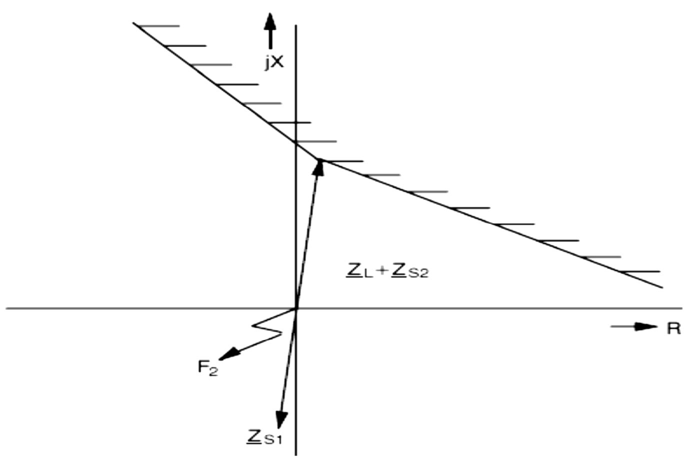

Figure 2-9: 7SA513 Characteristic with source impedance, reverse fault [18]

High-Resistance earth fault protection

The directional determination of the 7SA513 utilises the zero sequence voltage and dual polarisation methods. The features available for high resistance fault protection [18] are directional earth fault feature with non -directional back up, directional inverse time zero sequence voltage and directional earth fault comparison. The directional earth fault with non-directional back up can be used as a definite time or inverse time over current protection; definite time provides adjustable pick up stage and adjustable time delay and for inverse time an over current value and a time multiplier can be set. Directional inverse time zero sequence voltage function operates with an inverse time characteristics with a tripping time dependent on the magnitude of the zero sequence voltage. In the case of directional earth fault comparison, it is a directional protection function that has been extended to form a directional comparison.

This can be achieved with the aid of telecommunication systems. A carrier channel is essential for each direction, which transmits signals of the directional earth fault protection to the other end of the line. Tripping is only allowed if the relay operating setting has been satisfied and the signal was received from the other end. This function has an advantage that it can be used as a primary protection which allows for accelerated tripping of the circuit. Logic diagram is shown in Figure 2-10.

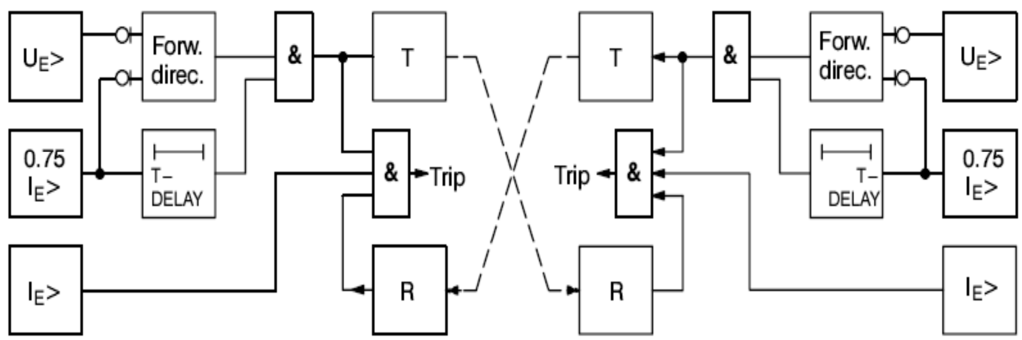

Figure 2-10: 7SA513 Directional earth fault protection logic diagram [18]

Instantaneous earth fault is also available as protection when the line with a fault is switched on to a live bus (either by auto-reclosure or switch on to fault). In this case it is imperative that tripping should happen immediately and this function is referred to as switch on to fault protection. The same principle can be achieved when the earth fault is detected, the current is above the setting pick up level and additional directional discrimination is achieved [18].

2.1.12 SEL-321 line feeder protection relay scheme

SEL-321 feeder protection relay scheme is a numeric distance protection relay with a Mho characteristic for phase faults as shown in Figure 2-11, and quadrilateral characteristic for earth faults as shown in Figure 2-12 [19]. This protection scheme has the functionality to provide adequate protection for line feeders with or without series compensation [19]. The South African line feeder protection philosophy criteria are met with this SEL-321 protection scheme. The load encroachment capability for conditions of high load currents that restricts the three phase relay element from being initiated and the enhanced single pole trip logic which has phase selection flexibility and integration with three phase tripping preventing high number of single pole tripping and reclosure operations are some of the features of the SEL-321 feeder protection scheme [19].

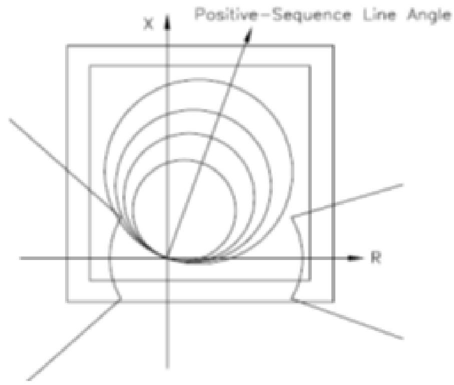

Figure 2-11: SEL phase characteristics [19]

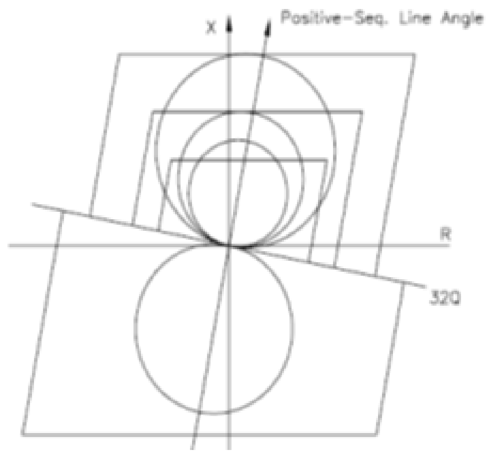

Figure 2-12: SEL earth fault characteristic [19]

2.1.13 ABB REL-531 protection relay scheme

ABB REL 531 feeder protection relay scheme operating principles is discussed in section 4.1.2.

Broken conductor detection

The BRC function detects a broken conductor condition by detecting the non-symmetry between currents in the three phases. The relay measures the difference between the maximum and minimum phase currents [20]. A comparison of the magnitude of the minimum current with that of the maximum current results in an output signal to enable tripping of the line feeder only if the setting criteria of the minimum current is less than 80% of the maximum current for a set time interval is achieved. At the same time, the highest current must be higher than a set percentage of the terminal rated current [20].

Instantaneous overcurrent

The instantaneous over current function is used as back-up protection for phase to earth faults occurring close to the terminal [20]. This enables a short back-up fault clearance time for the phase to earth faults with high fault current. The instantaneous, non-directional, earth-fault over current protection (IOC), which can operate in 15 ms (50 Hz nominal system frequency) for faults characterized by very high currents, is included in the REL 531 relay functionality [20].

Time delay overcurrent protection

The time delayed residual over current protection (TOC) which is an earth-fault protection, serves as a built-in local back-up function to the distance protection function. The time delay enable setting the relay to detect high resistance faults and still perform selective tripping [20].

Definite and inverse time-delayed residual overcurrent protection

Earth-faults with high fault resistances can be detected by measuring the residual current ($3I_0$). Directional earth-fault protection is obtained by measuring the residual current and the angle between this current and the zero-sequence voltage ($3V_0$) [20]. The earth-fault over current protection is provided with second harmonic restraint, which blocks the operation if the residual current ($3I_0$) contains 20% or more of the second harmonic component to avoid tripping for inrush current [20]. It is not possible to measure the distance to the fault by using the zero-sequence components of the current and voltage, because the zero-sequence voltage is a product of the zero-sequence components of current and source impedance. It is possible to obtain selectivity by the use of a directional comparison scheme, which uses communication between the line feeder ends [20].

Directional comparison

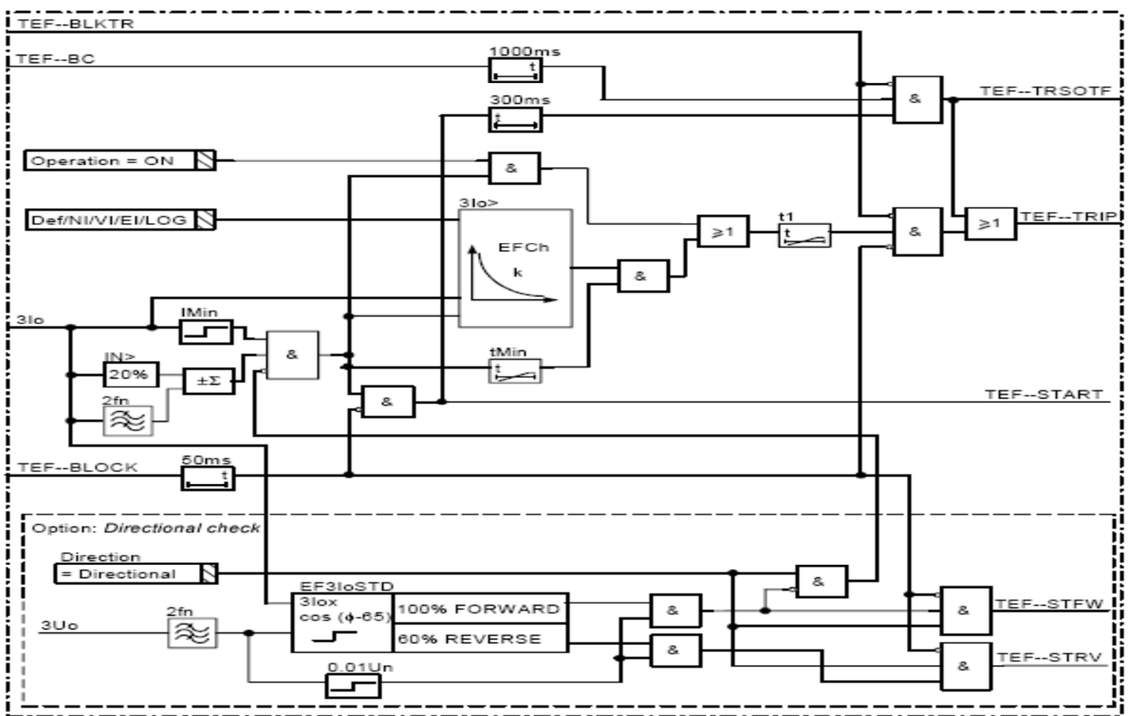

Figure 2-13: Simplified Logic Diag for REL531 Definite & Inverse Time-Delay Overcurrent Protection [20]

In the directional comparison scheme, information of the fault current direction is transmitted to the other line end. A short operating time enables auto-reclosing after the fault. During a single-phase reclosing cycle, the auto-reclosing device must block the directional comparison earth-fault scheme [20]. The logic diagram is shown on the Figure 2-13.

2.1.14 Alstom Micom P444 protection relay scheme

Alstom Micom P444 is a distance protection scheme for power transmission networks, which includes broken conductor detection function [21]. The protections features of this particular protection relay scheme are namely [21], phase and earth fault distance protection (21G/21P) (each has 5 independent zones of protection); instantaneous and time delayed overcurrent protection (50/51) consisting of four available elements are with independent directional control for the 1st and 2nd element, the fourth element can be configured for stub bus protection in breaker and a half arrangement; instantaneous and time delayed neutral overcurrent protection (50N/51N) consisting of two elements are available; directional earth fault protection (DEF/67N) which can be configured for channel aided protection including two elements which are available for backup definite earthfault (DEF); maximum of residual power protection or zero sequence power protection (32N). This element can provide protection element for high resistance fault, eliminated without communication channel; under-voltage Protection (27). Two stages, configurable to measure either phase to phase or phase to neutral voltage. Stage 1 may be selected as either IDMT (Inverse Definite Mean Time) or DT (definite time) and stage 2 is DT (definite time) only; over-voltage protection, (59) two stages, configurable to measure either phase to phase or phase to neutral voltage. Stage 1 may be selected as either IDMT (inverse definite mean time) or DT (definite time) and stage 2 is DT (definite time) only; directional or non-directional negative sequence overcurrent protection (67/46). This element can provide backup protection for many unbalanced fault conditions; switch on to fault (SOTF) protection (50/27), these settings enhances the protection applied for manual circuit breaker closure; trip on reclose (TOR) protection (50/27), these settings enhances the protection applied on auto-reclosure of the circuit breaker; power swing blocking (78), selective blocking of distance protection zones ensures stability during the power swings experienced on sub-transmission and transmission systems. The relay can differentiate between a stable power swing and a loss of synchronism (out of steps); voltage transformer supervision (VTS). To detect VT fuse failures, this prevents mal-operation of voltage dependent protection on AC voltage input failure; current transformer supervision (CTS) used to raise an alarm should one or more of the connections from the phase CTs become faulty; broken conductor detection (46BC) to detect network faults such as open circuits, where a conductor may be broken but not in contact with another conductor or the earth; circuit breaker failure protection (50BF) generally set to back-trip upstream circuit breakers, should the circuit breaker at the protected terminal fail to trip, two stages are provided.

The Micom P444 has the following non-protection features as well:

The auto-reclosure with check synchronism (79/25) permits up to 4 reclose shots, with voltage synchronism, differential voltage, live line/dead bus, and dead bus/live line interlocking available;

measurements, selected measurement values polled at the line/cable terminal are available for display on the relay or accessed from the serial communications facility; fault/event/disturbance records, available from the serial communications or on the relay display (fault and event records only); distance to fault locator, reading in km, miles or % of line length; and four independent setting groups to cater for alternative power system arrangements or customer specific applications [21].

The Alstom MiCom P444 open phase detection

It is possible to apply a negative phase sequence overcurrent relay to detect the series or open circuit condition of one phase. However, on a lightly loaded line, the negative sequence current resulting from a series fault condition may be very close to, or less than, the full load steady state unbalance arising from CT errors, load unbalance etc. In this case for low load the negative sequence element would not be energised and no tripping of the affected circuit [21].

The Alstom MiCom P444 relay incorporates an element which measures the ratio of negative phase sequence current (I_2) to positive phase sequence current (I_1). This will be affected to lesser extent than the measurement of negative sequence current alone. Since the ratio is approximately constant with variations in load current. Hence, a more sensitive setting may be achieved [21].

Setting Guidelines

When a conductor becomes open circuited, current from the positive sequence network will be series injected into the negative and zero sequence networks across the break [21].

In the case of a single point earthed power system, there will be little zero sequence current flowing and the ratio of $\frac{I_2}{I_1}$ that flows in the protected circuit will approach 100%. In the case of a multiple earthed power system (assuming equal impedances in each sequence network), the ratio $\frac{I_2}{I_1}$ will be 50%. It is possible to calculate the ratio of $\frac{I_2}{I_1}$ that will occur for varying system impedances, by referring to the following equations:-

$$I_{1F} = \frac{E_g(Z_2 + Z_0)}{Z_1Z_2 + Z_1Z_0 + Z_2Z_0}$$ --[Equation 2.4]

$$I_{2F} = \frac{-E_g Z_0}{Z_1Z_2 + Z_1Z_0 + Z_2Z_0}$$ --[Equation 2.5]

Where:

E_g = System Voltage

Z_0 = Zero sequence impedance

Z_1 = Positive sequence impedance

Z_2 = Negative sequence impedance

I_{1F} = Positive sequence current

I_{2F} = Negative sequence current

Therefore:

$$\frac{I_{2F}}{I_{1F}} = \frac{Z_0}{Z_0 + Z_2}$$ --[Equation 2.6]

It follows that, for an open circuit in a particular part of the system, $\frac{I_2}{I_1}$ can be determined from the ratio of zero sequence to negative sequence impedance. It must be noted however, that this ratio may vary depending upon the fault location. It is desirable therefore to apply as sensitive a setting as possible. In practice, this minimum setting is governed by the levels of standing negative phase sequence current present on the system. This can be determined from a system study, or by making use of the relay measurement facilities at the commissioning stage. If the latter method is adopted, it is important to take the measurements during maximum system load conditions, to ensure that all single phase loads are accounted for [21]. Note that a minimum value of 8% negative phase sequence current is required for successful relay operation. Since sensitive settings have been employed, it can be expected that the element will operate for any unbalance condition occurring on the system (for example, during a single pole auto-reclose cycle) [21]. Hence, a long time delay is necessary to ensure co-ordination with other protective devices. A 60 second time delay setting may be typical. The following table shows the relay menu for the Broken Conductor protection, including the available setting ranges and factory defaults:

Table 2-1: Alstom MiCom P444 Relay Setting Range [21]

Main Text	**Default Setting**	**Setting Range**		**Step Size**
		Min	**Max**	
Broken Conductor	Enabled	Enabled/ Disabled*		
I_2/I_1	0.2	0.2	1	0.01
I_2/I_1 Time Delay	60s	0s	100s	1s
I_2/I_1 Trip	Disabled	Enabled	Disabled	

* If disabled, only a Broken Conductor Alarm is possible.

Example Setting

The following information was recorded by the relay during commissioning [21]:

$I_{\text{full load}}$ = 1000A

I_2 = 100A

therefore the quiescent $\frac{I_2}{I_1}$ ratio is given by:

$$\frac{I_2}{I_1} = 100/1000 = 0.05$$

To allow for tolerances and load variations a setting of 200% of this value may be typical:

Therefore set $\frac{I_2}{I_1} = 0.2$

Set I_2/I_1 Time Delay = 2s to allow adequate time for short circuit fault clearance by time delayed protections and single phase auto-reclosing [21].

2.1.15 Current differential line feeder protection

Current differential feeder protection uses the principle of current balance, same as the well-known or proven transformer differential protection [22]. The feeder differential protection relays are of the numeric type. This technology has been used more frequently recently as these schemes cost less than the impedance protection scheme. The line differential protection function can be used on two terminal lines. It can be applied on MV, HV as well as on EHV overhead lines and cables [22]. The measurement is phase segregated, which gives correct phase selection for all types of faults, including simultaneous faults on double circuit lines and faults between lines at different voltage levels [22].

The differential protection is neither affected by voltage and current reversal at series compensated systems, nor by harmonics produced by HVDC or SVC installations. Unequal CT ratio in the two line ends can be compensated for [22]. Two binary signals can be exchanged between the terminals. The signals can be persistent, when used for other than tripping purposes. The differential protection requires a 56/64 kbit/s digital communication link, which can be achieved either by dedicated optical fibres or by multiplexed channels [22]. Communication is required in both directions or both ends of the line feeder.

The maximum transmission time for which the differential function will block is 15 ms [22]. For longer transmission times, the differential function will be blocked and an alarm "Communication Failure" will be given. The tripping function will not be blocked at route switching, as long as the communication time is <12 ms [22]. Neither will a false operation be caused by any changes in the communication time [22].The exchanged message is controlled by added check-sum information and corrupted telegrams are not evaluated.

2.2 Possible ways of detecting open phase faults

The literature that could aid in finding application based solutions was studied and discussed in great detail to gain the understanding.

2.2.1 Negative phase sequence protection

Negative sequence overcurrent elements are available in the microprocessor based impedance protection schemes. Negative sequence overcurrent elements do not respond to balanced load and can thus be set to operate faster and more sensitively than phase overcurrent elements for phase to phase faults [7].

2.2.2 Voltage transformer fuse failure

This logic function is implemented in the impedance relay to block the relay to trip the breaker. This logic was introduced to prevent impedance protection operating incorrectly for a VT fuse failure. This logic can be used to detect one phase open circuited for a radial feed but not for a ring feed network [21].

2.2.3 Line traps

Currently the Transmission and Sub-transmission feeders utilises line traps and carrier equipment on two phases of the feeder. Two line traps are installed on either side of the feeder, a total of four line traps for one feeder. The carrier equipment is interfaced with the protection schemes in accordance with the EHV feeder protection philosophy [23].

Possible Solution Option

Install line traps on all three phases on the local and remote ends of the feeder. The reason for this is the following [8] & [23] namely, if one of the phases is open circuited, the carrier signal will be lost or interrupted and the protection will trip all three phases of the feeder.

Advantages of line traps:

The carrier signal lost will be interpreted as an open phased condition; and tripping of the feeder will be initiated.

Disadvantages of line traps:

Additional cost to install one additional line trap with related equipment on either end of the feeders; and carrier failure will result in tripping of feeder incorrectly.

2.2.4 Detecting high-impedance faults caused by downed conductors

The reference [24] produced by ABB to detect High Impedance Faults (HIF's). The author's intention was to investigate the similarities between a downed conductor and an open phase condition taking into consideration that the downed conductors can come into contact with surfaces with impedances which could be significantly lower than the impedance of an open phase fault but the method or principles of detection could have the potential to also detect an open circuit fault condition [24].

Downed or open conductors are potentially life threatening. If the lines remain alive, human contact can result in serious injury or fatality. Arcing can also start fires. A HIF (high impedance fault) is typically a fault that occurs in the event of a live conductor making electrical contact with ground. Various types of surface are imaginable (a road surface, side walk, tree branch, etc). The commonality of these surfaces is that they reduce the flow of current towards the fault to a level so small that it cannot be reliably detected by conventional overcurrent protection schemes [24].

Typical HIF currents on a the distribution system can range from zero amperes for contact with asphalt and dry sand to fifty amperes for contact with wet grass to seventy five amperes for contact with reinforced concrete [24]. A problem however is the HIFs tend to exhibit not only low fault currents but random behaviour with unstable and wide fluctuations in current level. The fault signals have significantly high levels of harmonics and have high frequency components as shown in Figure 2-14.

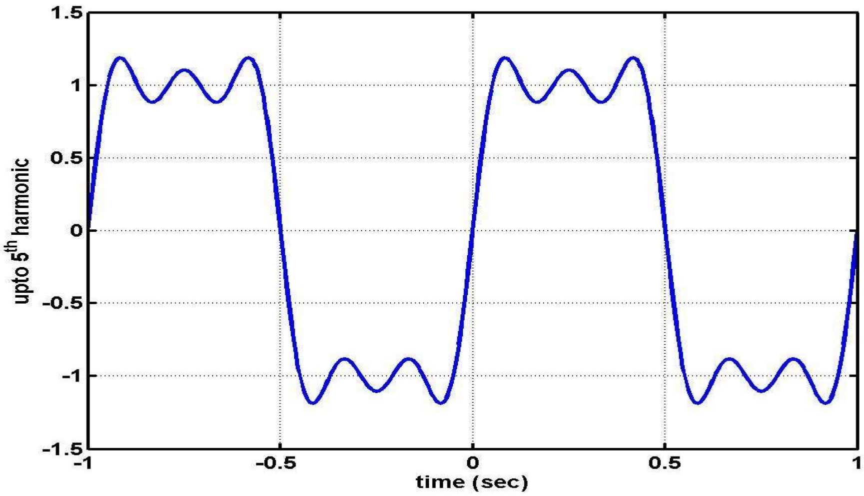

Figure 2-14: HIF Signal [24]

Most of the research conducted by ABB into HIF's had focused on developing sensitive but reliable fault detectors. The methods developed make use of, sequence components, neural networks, communication schemes and harmonic analysis. An additional problem is that not all HIF's can be detected regardless of the method used. For example if a conductor near the end of a radial feeder falls to the ground, very little current flows and the load loss is negligible [26]. This makes it difficult to detect the fault condition. It was apparent to ABB designers that it is practically impossible to detect all HIF's and achieve high security against false trips. Also, while communication schemes are extremely useful for detecting the loss of potential on a distribution line, they tend not to be cost effective as the communication make use of fibre optic cables and as the line length increases, the cost becomes significantly high [26]. With these challenges, it seemed virtually impossible in the past to devise a perfect system for detecting HIF's nevertheless ABB designers have taken on the challenge and have developed algorithms for this purpose [26].

Detection algorithms

In the last 5 years, ABB in conjunction with Lafayette College in the USA had managed to formulate new algorithms namely [26]:

Neural network algorithm

The neural network algorithm developed for HIF's is a two layer network, using back propagation with an adaptive learning rate. After low pass filtering, a three cycle window of data was normalised to unity before being used as input depicted in Figure 2-15. The target outputs for training were set to one for a HIF and zero for non – HIF [26].

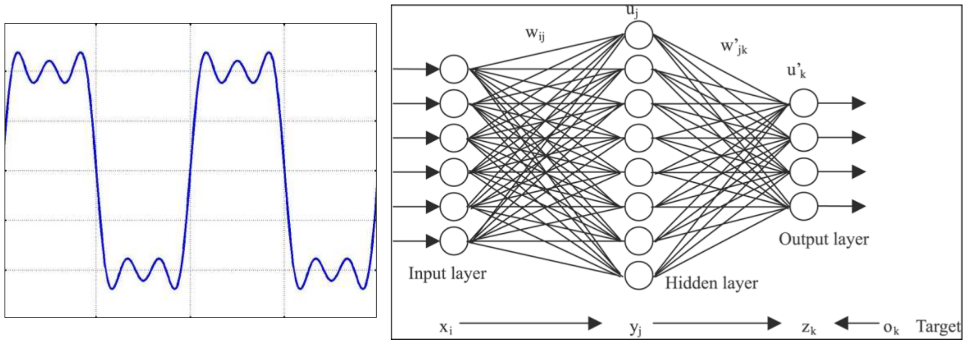

Figure 2-15: Neural Network Algorithm [26]

Wavelet algorithm

The wavelet algorithm was based on multi-resolution analysis of recorded current loads via discrete wavelet transform [26]. This algorithm delivers a description of load currents as they change with respect to time at different scales are associated with low frequency components and small scales are associated with high frequency signatures [26]. The wavelet transform decomposes the current signal into little wavelets that are localised both in time and frequency and are all scaled and dilated replicas of the same mother wavelet [26].

2.2.5 Line differential protection with an enhanced characteristic

This paper describes the operation principle of line differential protection [22]. The author explored this method to see whether these enhancements in the line differential protection could be used to detect open phased faults.

The advantages of this type of protection are as follows [22]:
Line differential protection with an enhanced characteristic is immune to power swings, series impedance unbalances and mutual coupling. Only require line currents to determine whether the fault is in the protected zone. Provides protection of cables, series compensated lines, three terminal and short transmission lines.

The disadvantages of line differential protection with an enhanced characteristic [22]:
Communication hardware cost is substantially more expensive compared to the tele-protection used by impedance type of protection schemes as the line differential protection uses fibre optic as means to communicate which require a high bandwidth communications channel.

2.2.6 Open-pole detection

On single pole circuit breakers there is a simple method to detect an open pole, the simplest being the use of the auxiliary contacts of the circuit breaker, namely, the normally closed and normally open contacts [8] These contacts are physically hardwired to the feeder protection scheme to provide circuit breaker status (circuit breaker open or closed), this can also be wired to the supervisory, control and data acquisition system (SCADA) remote indication and control [8]. However, protection schemes have integrated the pole discrepancy or pole disagreement detection and tripping [8]. Basically it uses one normally closed and one normally open contact of each single pole circuit breaker. The normally closed contacts are connected in parallel and the normally open are connected in parallel or shunt and the two groups are connected in series. This simple way of detecting an open circuit would be detected and indicated very effectively. However in this arrangement of using the auxiliary contacts is not always reliable or fail safe as contacts could become dirty or not make contact properly. The mechanical mechanism could be misaligned and would not change the position of the contacts resulting in incorrect status of circuit breaker indication which will trip the circuit breaker on pole discrepancy. The open pole detection arrangement would however only cater for open circuit conditions created by circuit breaker malfunctions and not aiding the detection of open circuited faults created by a conductor broken.

2.2.7 Negative phase sequence protection

Negative phase sequence (NPS) protection elements are available on 90% of the distance or impedance protection schemes presently in use. The negative phase sequence elements however have been disabled as it conflicts with the current extra high voltage (EHV) feeder protection philosophies. Specifically the single phase trip and auto-reclose functionality and it is also quite complex to correctly co-ordinate negative phase sequence protection [7]. However, Schweitzer Engineering Lab. Inc Pullman, Washington, USA and British Columbia Hydro Vancouver produced a paper that dealt with negative phase sequence (NPS) co-ordination called “Negative sequence overcurrent element application & co-ordination in distribution protection” by A.F. Elneweihi, E. O. Schweitzer & M. W. Feltis. This paper formulated a guideline that can be used for negative phase sequence (NPS) co-ordination [7].

The guidelines for coordinating negative sequence (NPS) overcurrent elements with phase overcurrent elements [7]:
Start with the furthest downstream negative phase sequence (NPS) overcurrent element (eg distribution feeder relay in a substation); identify the phase overcurrent device (e.g. line-recloser fuse downstream from the negative sequence overcurrent element that is of greatest concern for coordination. This is usually the phase overcurrent device with the longest clearing time; consider the negative sequence overcurrent element as an equivalent phase overcurrent element. Derive pickup, time dial, curve type, or time delay settings for this equivalent element to coordinate with downstream phase overcurrent device. As any phase coordination would be performed. Load considerations can be disregarded when deriving the equivalent phase overcurrent element settings; multiply the equivalent phase overcurrent element pickup setting by $\sqrt{3}$ to convert it to the negative sequence overcurrent element pickup setting in terms of $3I_2$ current; set the next upstream negative sequence overcurrent element to coordinate with the first downstream negative sequence overcurrent element and so on. Again coordination is not influenced by load considerations.

2.2.8 Analysis of open phase conductor

It was assumed a single open phase fault (with no part of the feeder making contact between other phases or ground) on a feeder that used impedance protection with negative phase sequence element. The purpose of the analysis was necessary to show the levels of negative sequence current generated for a single open phase fault. Also how negative sequence overcurrent element settings relate to these current levels [7].

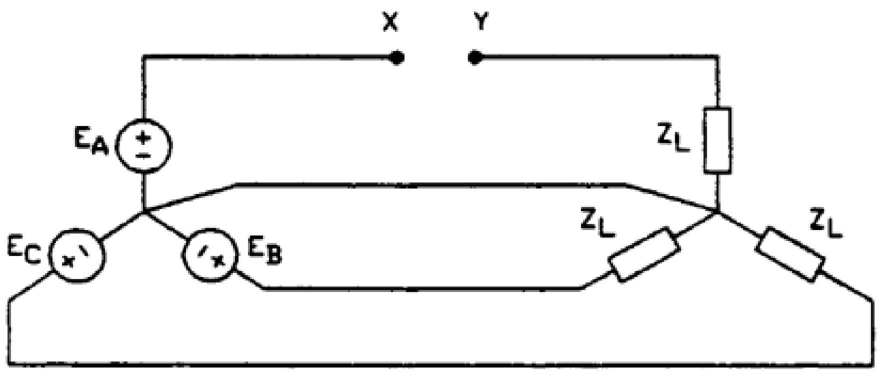

Figure 2-16: Showing the "A" Phase Open Circuit Fault in a Four-Wire Distribution System [7]

Where:

Z_L : Load impedance

Z_{1L} : Positive sequence load impedance

Z_{2L} : Negative sequence load impedance

Z_{0L} : Zero sequence load impedance

Z_{1s} : Positive sequence source impedance

Z_{2s} : Negative sequence source impedance

Z_{0s} : Zero sequence source impedance

I_1 : Positive sequence current

I_2 : Negative sequence current

I_0 : Zero sequence current

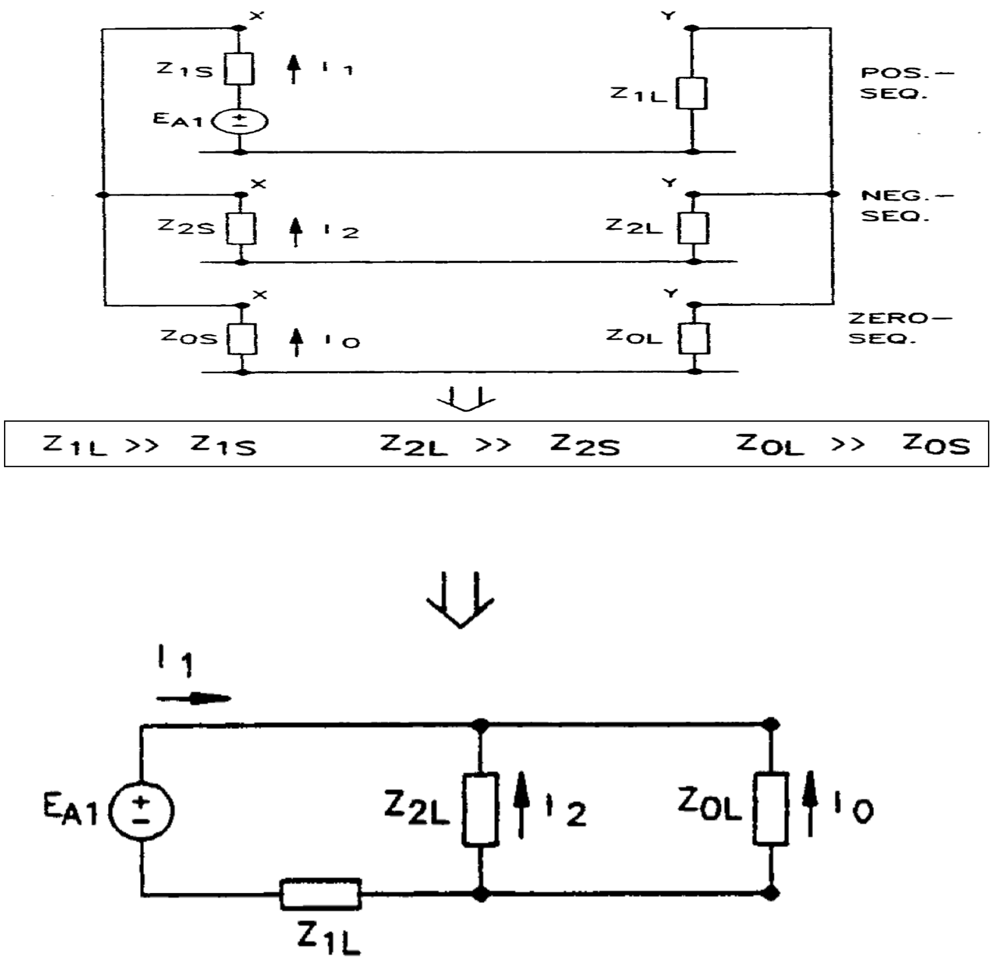

Figure 2-17: Equivalent Sequence Network for an Open Phase Fault on a Four-Wire System [7]

$I_1 = E_{A1}/\{Z_{1L} + [Z_{2L}Z_{0L}/(Z_{2L} + Z_{0L})]\}$

$= E_{A1}/(Z_{2L} + Z_{0L})/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L})]$ --[Equation 2.7]

$-I_2 = I_1 Z_{0L}/(Z_{2L} + Z_{0L})$

$= E_{A1}Z_{0L}/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L})]$ --[Equation 2.8]

Before the "A" phase conductor opened, the following equation held true for the balanced four-wire system.

$I_L = E_{A1}/Z_{1L}$ ---[Equation 2.9]

Combining equation (3) into equation (2) results in:

$-I_2 = I_L Z_{1L} Z_{0L}/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L}]$ ---[Equation 2.10]

$\left|3I_2\right| = \left|3I_L Z_{1L} Z_{01L} / [Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L} Z_{0L}]\right|$ --[Equation 2.11]

For example purposes, let $Z_{0L} = Z_{1L} = Z_{2L}$

Then, $\left|3I_2\right| = \left|I_L\right|$ ---[Equation 2.12]

Equation 2.12 indicates that the negative overcurrent element (operating on $3I_2$) detects the negative sequence current generated by the open phase conductor condition if its pickup magnitude is set equal to I_L (I_L continually varies within minimum and maximum load current levels) restating this relationship in terms of the "equivalent" phase overcurrent element pickup.

"Equivalent" phase element pickup = $\left|I_L / \sqrt{3}\right|$ =0.577 I_L ------------------------------------[Equation 2.13]

Discussion

From the reference [7], it was evident that negative phase sequence protection was capable of detecting an open phase condition. Negative phase sequence (NPS) element can be activated in the impedance feeder protection schemes. During a single open phase fault, the protection will detect an unbalance and trip the feeder. When using the negative phase sequence protection, care must be taken to cater for normal load unbalances and for single-phase trip and auto re-closing. If the negative sequence element operates, this will cause a three-phase trip. However, it is recommended that if the negative phase sequence tripping is delayed by using a timer set between 1.5 to 2 seconds then the suggested time will allow sufficient time for the circuit breaker to auto re-close for a single phase earth fault. The negative sequence co-ordination (grading) must be conducted to eliminate the possible tripping of healthy feeders [7].

Disadvantages of negative phase sequence tripping:

The co-ordination of negative phase sequence for transmission and sub-transmission is a great challenge; a possible hindrance to negative phase sequence (NPS) application is a lack of guidelines in power utilities on how to coordinate negative sequence overcurrent elements with other power system protective devices that operate on different electrical quantities ie. phase and zero sequence currents;

extremely long man hours would have to be spent on simulating faults using simulation software like Power system simulation for engineers (PSSE) and *Digsilent PowerFactory*; co-ordination would mean re-calculation of the network parameters and formulating new protection settings; implementation can only be made once the entire transmission and Sub-Transmission is re co-ordinated to prevent mal-operation of protection; this option would be rather tedious, uneconomical and almost impractical to implement.

2.3 Protection schemes considered during research simulations

The Table 2-1 listed numerous line feeder protection relays schemes however for the simulation studies conducted in chapter 4, taking the actual open phase fault incident [4] into consideration it was a conscious decision to choose the current differential protection scheme (ABB REL-561), numeric impedance or distance protection scheme (ABB REL-531). The reasons for the choice was to simulate the open phase fault condition experienced during the Koeberg incident [4]. These protection schemes are the latest version of line feeder protection schemes available in the South African power transmission system and coincidentally it was also the same line feeder protection schemes used on the Koeberg line feeders at the time of the incident [4].

The ABB REL-531 and ABB REL- 561 feeder protection schemes characteristics could be simulated using the *DigSilent PowerFactory* simulation software together with the protection configuration settings available from the South African power utility (Eskom). The added advantage was that the ABB REL-531 protection scheme had all the protection features and more that met the requirements by the Eskom extra high voltage (EHV) feeder protection philosophy [23]. The additional features was the “broken conductor” feature available. The ABB REL-561 is of the current type. These two relay protection schemes gave adequate options to test the functionality that all the other older technology schemes had with added flexibility of co-ordination.

The literature that was studied in this chapter had also become more apparent and better understood with the simulations conducted in Chapter 4.

2.4 Conclusion

A significant amount of literature was available for short circuit faults however literature for open phase faults was not as readily available. The currently used line feeder protection relays schemes was studied and discussed with reference to the line feeder protection philosophy. Various protection specialists, students and protection relay manufacturers have studied and made advancements into possible technologies and techniques of detecting open phase faults but no clear “one size fits all” solution to resolve the challenge of open phase fault detection.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3 Introduction of chapter

This chapter is paramount as it provides the techniques and methodology of the research conducted. Taking into consideration the research problem and research questions, the ultimate objective of qualifying the constraints of the current line feeder protection as well as the perceived or proven impact of open phase faults on the South African power transmission network were focussed on.

3.1 Research design

Quantitative Research Design was conducted using both non-experimental and experimental research techniques with the objective of being acquainted with the open phase fault impact on the network and the ability or shortcomings of the currently used protection relay schemes.

3.2 Non-experimental research technique

Present line feeder protection schemes, functionality and settings philosophies were studied and evaluated.

3.3 Experimental research technique

Modifications required on present relays schemes was investigated. Analysis of the phase iv and v microprocessor based relays to detect an open circuited condition was undertaken. Differentiation between a single-phase trip for a phase to ground fault and an open circuited condition was shown as a calculation.

3.4 Research methodology

The Literature survey was conducted by obtaining and studying related papers, the present South African EHV & HV feeder protection philosophy, protection relay schemes manuals, fault history and fault investigation reports. Simulations were conducted with current feeder protection schemes and settings.

3.4.1 Sourcing of literature

The power transmission protection relay schemes manuals (hard copies), EHV(extra high voltage) protection philosophy, fault investigation reports relating to open phase faults and protection performance and line feeder protection settings configurations were obtained from libraries, soft copies were sourced from protection relay manufacturers' websites, the South African power utility national control centre (Eskom).

3.4.2 Sequence of simulation studies

The simulation software used was *DigSilent PowerFactory* for the investigation and analysis of the open phase fault condition. Line feeder protection was accessed and selected for the respective feeder with the relevant protection relay scheme. The protection settings of the respective line feeders were configured and entered into the simulation model. The impedance relay characteristics were generated and plotted within the simulation model. The power system configuration before the open phase fault was completed on the simulator by ensuring that the simulation model matched the actual power system configuration at the time of the fault. The simulation was conducted by opening the relevant phases as described in chapter 4. The author initiated a three phase to ground fault on the busbar with an extremely high fault resistance (10 000 ohm) to simulate an open phase fault. The open phase fault incident was configured using the case study file which had the current South African national power network configuration and power plant data. The results were plotted on the relay characteristics and analysed. Voltage depression simulations were conducted with the result of the open phase fault simulation to evaluate the impact of the fault on the power network stability. Many tweaks including the load or scaling factor had to be reduced to 0.95 in the rest of the power network apart from the Cape network in order for the simulation to converge and solve which is described in chapter 4 as Duvha power as the reference bus overload. Consecutive simulations of open circuit faults were conducted to further analyse the effects of these faults on the power network. Short circuit faults were simulated as assurance that the simulation model used was authentic and correct. The results produced from the simulations were analysed and discussed in chapter 5.

3.5 Derivation of application-based solutions

From the literature review in chapter 2, the simulation and results in chapters 4 and 5, various solutions were recommended considering the practicality of the application, economic impacts, time to implement and cost effectiveness of solutions.

3.6 Conclusion of chapter

This chapter provided a taxonomy of the research study considering the research design, techniques, methodology, literature review of the research statement, the sequencing and methodology of the simulations. This provided evidence of the impact of open phase faults on the power transmission network, and an assessment of whether the current protection utilised was adequate to detect, trip, and provide possible solutions to mitigate these deficiencies.

CHAPTER 4: INVESTIGATION AND SIMULATION OF OPEN PHASE FAULTS

4 Chapter introduction

This chapter primarily deals with the investigation of open phase faults and the simulation of these faults on the South African transmission network at the Koeberg substation. The *DigSilent Power* Factory simulation software was used in the investigations. Protection relay schemes were configured and the relevant protection settings of the power line feeders and transformers were utilised in the software. The results were analysed with reference to the expected protection scheme operations, characteristics and protection philosophies.

4.1 Principle of operation, philosophy and functionality of the line feeder protection schemes

The purpose of this section is to provide the description and operating functionality of the Koeberg 400 kV line feeder protection and the EHV line feeder philosophy. The ABB REL 531and the ABB REL 561 line feeder protection schemes are utilized on the Koeberg 400 kV line feeders and will be discussed in detail in this chapter.

4.1.1 EHV line feeder philosophy

South Africa’s transmission power network line feeder impedance or distance protection uses redundancy of main protection, namely, Main 1 and Main 2. Main 1 and Main 2 are two feeder impedance protection schemes (ideally the two schemes should be from different manufacturers in order to enhance the dependability and reliability) [23]. The two main protection (Main 1 and Main 2) has an independent DC power source and a separate core of current and voltage transformers that would trip the circuit breaker, energising the respective Main 1 or Main 2 circuit breaker trip coils. Main 1 and Main 2 protections make use of two independent telecommunication mediums to ensure reliability and security of the protection [23]. The sending end impedance protection relay communication with the remote impedance protection relay is achieved by telecommunications [23]. Telecommunication primary device called “line traps” are installed on the centre phase of transmission and sub-transmission feeders to enable telecommunication between the sending and receiving end of the line feeder [23]. Back-up earthfault protection is also used to cater for high resistance faults that can occur on the line feeder for which the impedance scheme cannot operate.

The line feeder impedance protection scheme utilises impedance measurements which are categorised in zones of protection. Minimum of two zones are used, one under-reaching and one over-reaching zone. The practice is to have three zones of protection within the impedance protection scheme (zone 1, zone 2 and zone 3). The tripping times for the zones are configurable for reach of the line feeder and time. In the microprocessor based relay schemes, these zones are individually marshalled for directionality, time and characteristic of the impedance plain (mho or quadrilateral characteristic). Zone 1 is normally set to 80% of the line positive sequence reactance, zone 2 set to 120% and zone 3 is set to 150% [23].

Principle of distance protection

Typically, distance protection relays consist of three stages, mho, quadrilateral and reactance characteristics. The distance protection relay considers phase faults and earth faults. The three stages consists of zone 1 protection which typically covers 80% of the line, zone 2 covers 120 % of the line, zone 3 is configured to reverse reach which covers 20% of the line on the reverse direction and zone 3 forward which covers 150% of the line [8]. The zones of protection of this relay can be shown on the jIX, IR diagrams and Z_L is the line impedance as shown in Figure 4-1 and Figure 4-2.

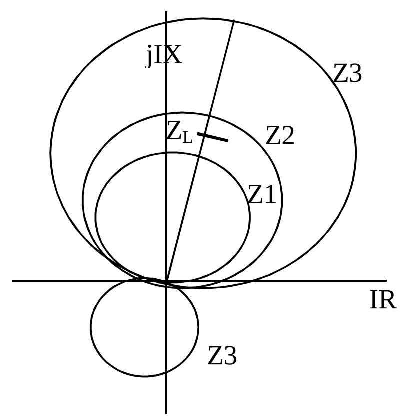

Figure 4-1: Three zones of protection for a mho or reactance characteristic relay [8]

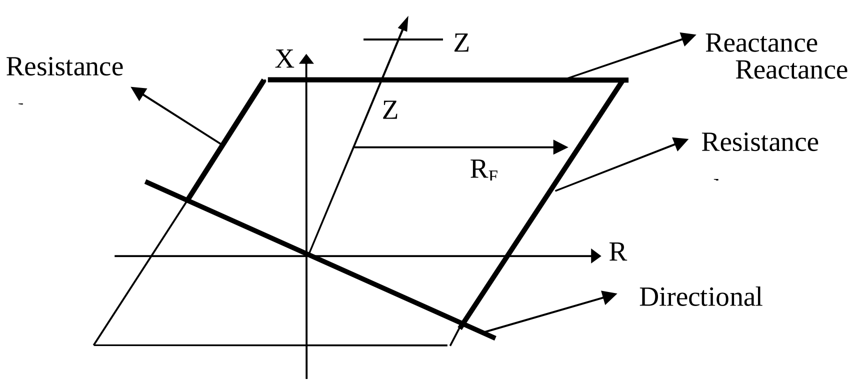

Figure 4-2: Three Zones of Protection for a Quadrilateral Characteristic Relay [23]

Zone 1 is to trip instantaneously as it is assumed that it covers the fault inside the line only. Zone 2 is to ensure that the remaining part of the line, which not covered by zone 1, is protected and zone 2 covers the remote busbars also. Zone 2 is normally delayed and is typically set to trip after 400 ms. Zone 3 has the forward reach and the reverse reach. The zone 3 reverse reach is to provide a backup for local busbar faults taking into account 20% measuring errors, infeed and high fault resistance. The zone 3 reverse reach must not overreach adjacent transformers taking into account 20% measuring errors and infeed. The zone 3 forward reach is the overreaching element that functions to provide a backup for the remote stations, but should not overreach zone 2 of shortest line adjacent to the remote end. Zone 3 is normally delayed by 1 second [23].

Zone reach settings

All setting calculations should incorporate a 20% measuring error, except for load encroachment where a 50% safety margin is applied to prevent unwanted tripping during disturbances and transient overload conditions [23].

Zone 1 setting

The zone 1 reach is based on line parameters considering the following limitations listed in order of priority. Zone 1 tripping is instantaneous, namely, without any intentional time delay. Zone 1 may be reduced to below 80 %, following further fault studies, in the following situations [23]; on series compensated lines, depending on the size and position of the series capacitor to avoid overreaching in cases of slow or lack of capacitor bypass, unless the relay incorporates other precautions; on teed lines, so as to not overreach the remote end of the teed line; on lines that have traction feeders teed off them, with many transformers in parallel, not to overreach these transformers; on lines that are used to supply small customers via capacitive coupling, not to overreach the capacitive divider; on relays that allow for a selection of resistive reach independent from other zones to ensure that the ground elements of zone 1 cover at least a resistance of 10 primary ohms; zone 1 must not encroach on the load characteristic with a minimum 50% margin. Usually this requirement is automatically covered once other zones with larger reaches are selected.

Zone 2 setting

The zone 2 time delay is normally set to 400 ms. In the event that zone 2 overreaches the zone 1 characteristics of the lines adjacent to the remote substation, a time discrimination must be provided. The local zone 2 timer setting is increased to 500 ms and the remote zone 2 timer setting is reduced to 250 ms.

The zone 2 reach is optimised based on fault studies done for a particular application considering the following limitations listed in order of priority: (The minimum setting of zone 2 is 120% of the line positive sequence reactance) [8]:

Zone 2 should not encroach onto the load characteristic with a minimum of a 50% margin ($1.5 * Z2 < Zload$); zone 2 should not overreach the transformers in parallel at the remote substation in adverse infeed conditions; zone 2 should provide maximum fault resistance coverage and should not be less than 10 primary ohms; zone 2 should not overreach the zone 1 setting of the shortest line adjacent to the remote end; in cases where zone 2 overreaches the zone 1 characteristics of the lines adjacent to the remote substation then the time discrimination must be applied between the relevant zone 2 settings [8].

Zone 3 forward setting

When a forward zone 3 is provided, its tripping can be used as a remote back-up where required. The Zone 3 time range is from 1 to 3 seconds. The zone 3 forward reach is calculated based on fault studies conducted by using the simulation software for a particular application considering the following limitations listed in order of priority [10]:

Zone 3 must not encroach the load characteristic with a minimum of a 50% margin (1.5 * Z3 < Zload);

zone 3 should provide the required level of back-up according to specific requirements or as negotiated with the relevant customer(s); zone 3 should not overreach transformers in parallel at the remote substation in adverse infeed conditions, unless specific back-up functionality is required; zone 3 should not overreach the remote zone 2 reach in adverse infeed conditions, unless time discrimination is applied; zone 3 phase-to-ground element should cover resistive faults with a preferred minimum of 20 and a maximum of 50 ohms primary. Always ensure that the back-up earth-fault protection is set to operate for at least a 50 ohms primary phase-to-ground resistive fault on the line. When the zone 3 elements are used as one of the power swing detection elements, allowance is to be made for the power swing blocking characteristics [10].

Settings of relay starting elements

Overcurrent starter settings

Set the overcurrent starter settings greater than 1.5 times the emergency load current, if the starter trips the circuit breaker, to avoid overload tripping. Set 1.2 times the emergency load current to achieve better sensitivity if the starter does not trip directly. If the overcurrent starter is the only starter for the relay, lower settings should be considered to ensure adequate sensitivity [10]; should pick up for faults at the end of the furthest reaching zone [10]; should accommodate healthy phase currents, under fault conditions, in excess of full load [10]. This arises in a multiple-earth system where proportions of the earth-fault current flow in the un-faulted phases such that the apparent impedance is decreased to such an extent making phase selection difficult. The overcurrent starter settings should be set to be sensitive enough to allow as much fault resistance coverage as possible.

Under impedance starter setting

The under impedance starter has two current settings, one is set for minimum voltage and the other is set at 100% voltage. The current setting for minimum voltage should ensure the required sensitivity. The pickup at 100% voltage should be set such that it only picks up at a current that is greater than [25] namely, for 1.5 times the emergency load current to avoid overload tripping if the starter trips the circuit breaker and for 1.2 times the emergency load current to achieve better sensitivity if the starter does not trip.

Auto-reclose (ARC) philosophy

The auto-reclosing philosophy was developed to ensure restoration of power as quickly as possible to prevent an interruption of supply. Generally the ARC is initiated after an instantaneous Zone 1 operation of protection for a line fault; however depending on the application, in some instances, Zone 2 protection may be marshalled to initiate ARC [8].

The single phase ARC cycle

When a single phase to ground fault occurs, single-phase trip is initiated on the respective phase thereafter a single phase ARC (auto reclose) is initiated. If the fault is still detected then the “three-phase” tripping is initiated while the protection blocks any ARC (auto reclose) further and has to be physically reset to close the breaker [25]. The dead time on the single phase ARC (auto reclose) is 1 second thereafter closing of the breaker is performed without synchronising check as the other two phases are closed.

The multi-phase ARC cycle sequence

During multi-phase fault condition, three-phase tripping occurs, then three phase ARC (auto reclose) is initiated closing breaker. If the fault is still detected, three-phase tripping occurs and the protection blocks any further ARC (auto reclose) preventing the closure of the feeder breaker. In order to close the breaker, the breaker must be physically reset to close the breaker [8].

Fast ARC for three-phase trip is not used by Eskom transmission to avoid stress to rotating machines (synchronous and asynchronous machines) at power stations and customer plant.

Additional features of the impedance protection scheme

Impedance protection has the following functionality as well [23]:

Current reversal guard applied in the case of parallel feeders; the switch-on-to-fault protection caters for single and three-pole switch-on-to-fault conditions, and covers the full line length. Switch-on-to-fault tripping is three poles and is effected via a high-set overcurrent threshold and/or the first overreaching zone in the forward direction; direct transfer tripping for EHV (extra high voltage) feeder protection applications, each of the tripping systems provides a direct transfer tripping facility with inputs derived from within the scheme or external to the scheme. Operation of this input initiates three-pole tripping without auto-reclose and initiates the circuit-breaker failure protection; voltage transformer (VT) fuse failure function prevents the impedance relay from unnecessary operation as a result of the loss of voltage due to VT fuses failure; transfer facility are available on most transmission substations with a transfer busbar (for circuit breaker maintenance purposes while the feeder is still energised) and a facility that transfers protection outputs from the feeder circuit breaker to the transfer coupler circuit breaker is provided; power swing blocking; overvoltage tripping; weak in-feed tripping and negative phase sequence (NPS) protection.

4.1.2 ABB REL 531 protection scheme

The ABB REL 531 feeder protection relay scheme is a numeric distance protection relay with a polygonal characteristic. The REL 531 allows for setting of line resistance, reactance and fault resistance for positive and zero sequence independently [20]. The main purpose of the REL 531 protection scheme terminal is the protection, control and monitoring of overhead lines and cables in solidly earthed networks with high requirements for fast operating times (less than one cycle). Typical characteristics of the REL 531 protection scheme can be shown on the Figure 4-3 and Figure 4-4 for phase and earth loop.

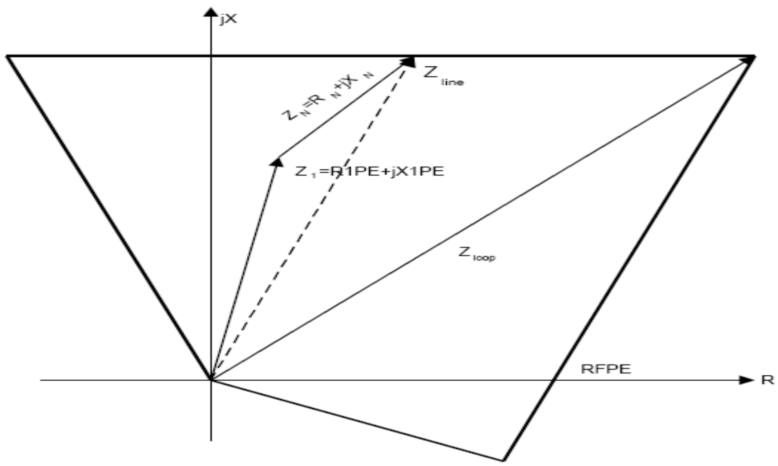

Figure 4-3: ABB REL 531 typical characteristic for phase loop [20]

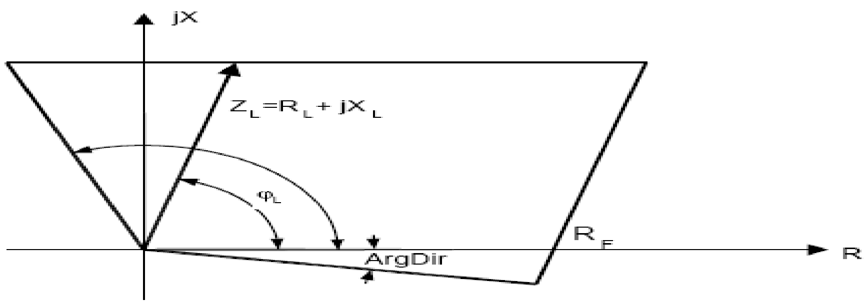

Figure 4-4: ABB REL 531 typical characteristics for phase to earth loop [20]

Where:

Z_N - earth return impedance

RFPE - Phase to earth fault resistance

XIPE - Zone 1 reactance setting for phase to earth loop

R1PE - Zone 1 resistive setting for phase to earth loop

Broken conductor detection function of ABB REL 531

The broken conductor detection function detects a broken conductor condition by identifying the non-symmetry between currents in the three phases. It does this by measuring the difference between the maximum and minimum phase currents. The relay compares the magnitude of the minimum current to that of the maximum current and gives an output if the minimum current is less than 80% of the maximum current for a set time interval. At the same time, the highest current must be higher than a set percentage of the terminal rated current [20].

Instantaneous overcurrent

The instantaneous residual overcurrent function is suitable as back-up protection for phase to earth faults close to the terminal. This enables a short back-up fault clearance time for the phase to earth faults with a high fault current. The instantaneous, non-directional, earth-fault overcurrent protection (IOC), which can operate in 15 ms (50 Hz nominal system frequency) for faults characterized by very high currents, is included in some of the REL 531 terminals [20].

Time delay overcurrent protection

The time delay residual overcurrent protection (TOC) which is an earthfault protection, serves as a built-in local back-up function to the distance protection function. The time delay makes it possible to set the relay to detect high resistance faults and still perform the selective trip.

Definite and inverse time-delayed residual overcurrent protection

Earth-faults with high fault resistances can be detected by measuring the residual current ($3I_0$). Directional earth-fault protection is obtained by measuring the residual current and the angle between this current and the zero-sequence voltage ($3V_0$). The earth-fault over current protection is provided with a second harmonic restraint, which blocks the operation if the residual current contains 20% or more of the second harmonic component to avoid tripping for inrush current. It is not possible to measure the distance to the fault by using the zero-sequence components of the current and voltage because the zero-sequence voltage is a product of the zero-sequence components of current and source impedance. It is possible to obtain selectivity by the use of a directional comparison scheme, which uses communication between the line ends [20].

Directional Comparison

In the directional comparison scheme, information of the fault current direction is transmitted to the other line end. A short operating time enables auto-reclosing after the fault. During a single-phase reclosing cycle, the auto-reclosing device must block the directional comparison earth-fault scheme. The logic diagram for the REL 531 protection scheme is presented in the Figure 4-5.

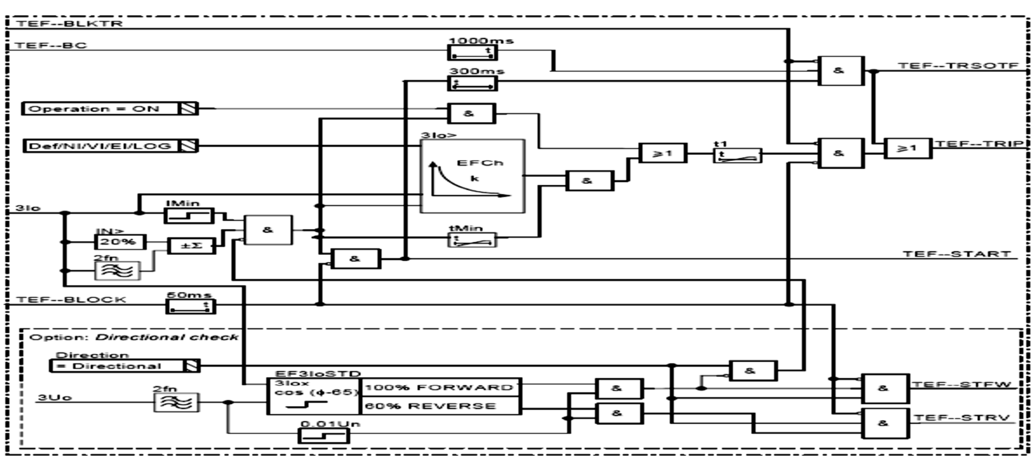

Figure 4-5: Simplified logic diagram - REL531 def & inv time-delayed residual overcurrent protection [20]

4.1.3 ABB REL 561 protection scheme

The ABB REL 561 protection scheme is the line differential scheme. The line differential function provides phase-segregated true current differential protection for transmission networks. The function compares the currents entering and leaving the protected overhead line or cable. This is done by exchanging the value of the three phase currents in both directions every 5 ms, while integrated in a common digital message. The currents are evaluated in both terminals on a per phase basis that prevents the problem of the current summation approach and provides phase selection information for single-pole tripping [9].

A dependable communication link is needed to allow exchange of the current information between the terminals at the line ends. Direct optical fibre or galvanic communication links are supported, as well as more complex digital communication systems like multiplexed and route switched networks. The transmission time is continuously measured to provide correct synchronization of local clocks. Two independent binary signals can be transmitted from one line side to the other through the differential communication link for direct inter-trip logics or information purposes. The function of the line differential function utilises the communication functionality and hardware for communication with remote end as used for the function “Binary signal transfer to remote end (RTC)”. The communication modules are available in three options namely, optical, pilot wire for short range and galvanic connection communication equipment which are designed to operate at 64 kbit/s. The simplified block diagram of the line differential protection function is shown in Figure 4-6.

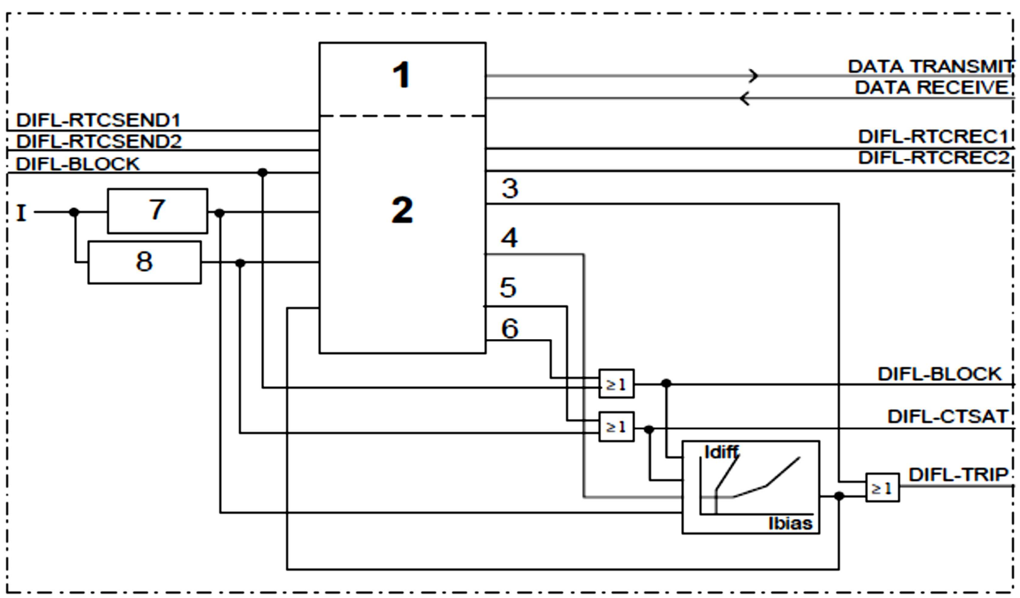

Figure 4-6: Simplified block diagram of line differential protection function [9]

Where:

1 - Communication interface

2 - Communication logic

3 - Remote trip

4 - Remote current value

5 - Remote saturation detection

6 - Remote block

7 - Fourier filter

8 - Saturation detector

Saturation detectors evaluate the phase current using the raw/ unfiltered samples issued every millisecond. The detection is based on the secondary current behaviour. At current transformer saturation as shown in Figure 4-7, the stabilisation is increased at both terminals in the saturated phase. Therefore, phase segregated "saturation" signals are included in the transmitted message. The ABB REL 561 differential function will never trip for an open circuit condition, instead, only for short circuit conditions. However the impedance function in the same relay will be susceptible to tripping for open circuit conditions depending on the impedances that are calculated.

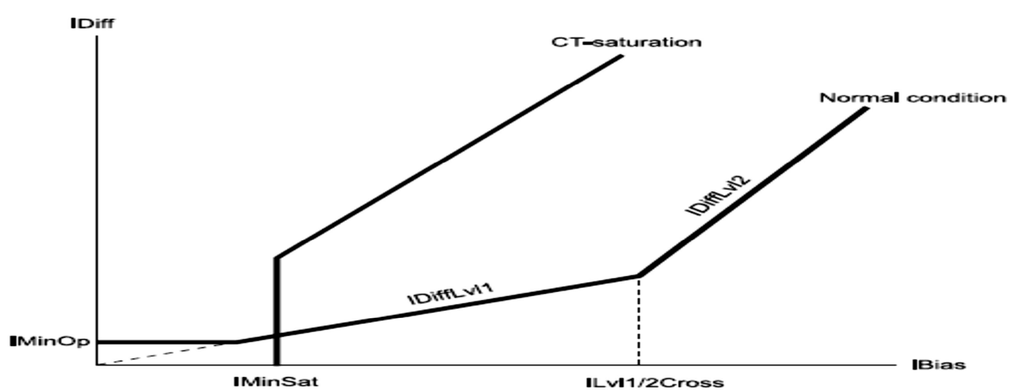

Figure 4-7: REL 561 Stabilisation characteristics [9]

Where:

IMinOp - Minimum differential operation current

IMinSat - Minimum phase current for saturation detection operation

IDiffLvl1 - Slope 1 stabilisation

IDiffLvl2 - Slope 2 stabilisation

ILvl1/2Cross - Slope 2 intersection

4.2 Background into an open phase fault at the Koeberg power station high voltage yard in South Africa

Eskom's Koeberg substation encountered an incident due to an open circuit fault on the red phase of the 400 kV bus section A isolator, on the 400 kV busbar no.1. A latent open circuit on the red phase of the Koeberg substation's 400 kV bus section isolator A was discovered after the switching operation of opening the bus coupler A. Prior to the opening of the bus coupler A, voltages were normal or healthy on both sides of busbar no. 1 bus sections. Due to insufficient travel of the red phase main contacts inside the gas insulated switchgear chamber, the contact did not make sufficient contact to complete the circuit resulting in the open phase. The Koeberg substation electrical circuit/single line diagram is shown in Figure

4-8. The generator transformer no.1 had been returned to service after out on routine maintenance. Hence all circuits had to be connected onto the 400 kV busbar no. 1 (circuits that were connected on busbar no.2 was switched over to busbar no.2.) The generator transformer no.2, coupling transformer no.1, Acacia no.1 line feeder and Muldersvlei no.2 line feeder were all switched from the 400 kV busbar no.2 to the 400 kV busbar no.1.

The 400 kV buscoupler A circuit breaker was thereafter switched open. Upon switching open the circuit breaker, the 400/132 kV coupling transformer no.1 132 kV breaker, the Koeberg - Acacia 400 kV line feeder breaker, the 400/132 kV coupling transformer no.2 132 kV breaker, the Koeberg - Muldersvlei no.2 400 kV line feeder breaker and the Koeberg - Muldersvlei no.1 400 kV line feeder breaker had tripped.

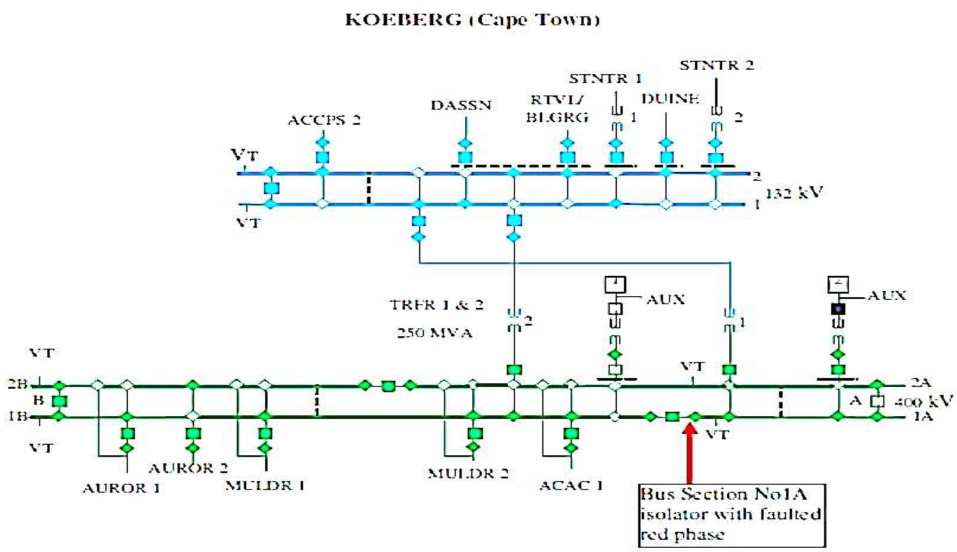

Figure 4-8: Koeberg power station high voltage yard single line

4.3 Simulation of the open phase fault at Koeberg substation

The simulation using *DigSilent PowerFactory* software was conducted with the current Koeberg 400 kV network configuration to analyse the impact of an open phase fault on the circuits connected on the Koeberg 400 kV busbars as a result of the blue-phase bus-section A isolator being open while red and white phases closed. It will also be used to verify that the present protection schemes protection elements will operate correctly for the protection settings applied to the protection schemes.

4.3.1 Configuration and simulation of the Koeberg substation open phase fault

The open phase fault at the Koeberg substation was simulated with the configurations as shown figure 4.9 in a combined load flow and short circuit simulation study. The Koeberg substation consists of a double 400 kV busbar with a bus-section on each 400 kV busbars for connection or isolation of the two parts of the same busbar; two bus-couplers between the 400 kV busbars to allow connection or isolation; two Koeberg generators connected through the generator transformer (24 kV/400 kV, 1050 MVA, Ynd 11) connected on either side of the bus-coupler A and bus-section A; four 400 kV line feeders (Koeberg-Acacia, Koeberg-Stikland, Koeberg-Ankerlig no.1 and Koeberg-Ankerlig no.2) and two coupling transformers (400 kV/132 kV/22 kV, 250 MVA) connecting the 400 kV Koeberg circuit to the 132 kV Koeberg circuit. The 400 kV

Koeberg network was configured with the circuits connected to the busbar no.1 as depicted in Figure 4-9. The blue phase of the 400 kV bus section A of busbar no.1 was switched to out of service (blue phase as opposed to red phase, due to software package limitations).

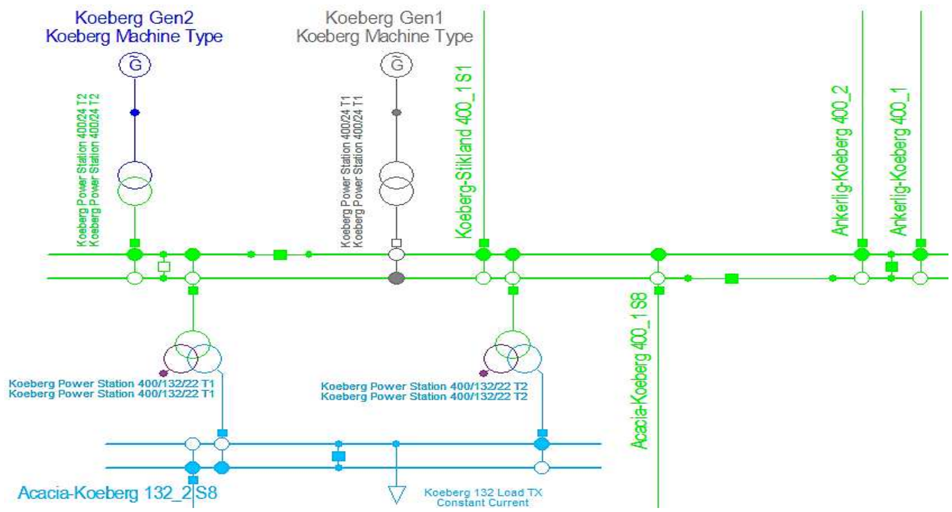

Figure 4-9: Koeberg power station single line diagram

The 400 kV feeder protection schemes were configured in the simulation software for all 400 kV feeders out of Koeberg substation. Koeberg-Acacia and Koeberg-Stikland 400 kV feeder were furnished with the impedance or distance protection relay ABB REL 531with back up earthfault protection. Koeberg-Ankerlig No.1 and 2, 400 kV line feeders consist of the line differential ABB REL 561 protection scheme. The current differential protection scheme principle was based on Kirchoff's current node law, namely that the total current flowing into a node should equal or balance the total current flowing out of the node, or else a short circuit has occurred.

The protection scheme type and settings were obtained from Eskom - National Control. The instrument transformers (current transformers and voltage transformers) had to be configured and ratios set. The protection settings were entered into their respective device data. The Koeberg 400 kV feeders protection relay phase (Ph) and ground (G) characteristic was plotted depicting the impedance zones of the feeder protection with the relevant 400 kV feeder or line impedance parameters. The Koeberg-Acacia 400 kV feeder ABB REL 531 distance protection relay characteristic plot as shown in Figure 4-10 and Figure 4-11. Zone 1, 2 &3 phase-phase and phase-ground characteristic respectively is depicted on the diagrams.

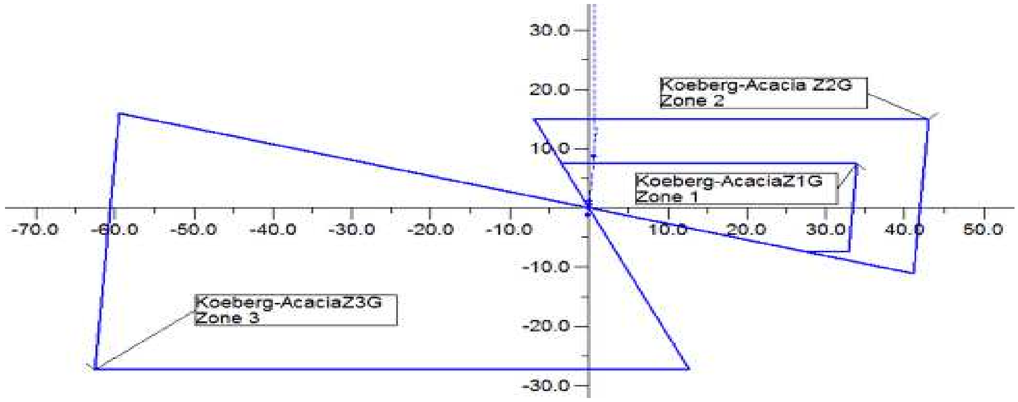

Figure 4-10: Koeberg-Acacia 400 kV feeder 1&2 protection relay phase-phase characteristic

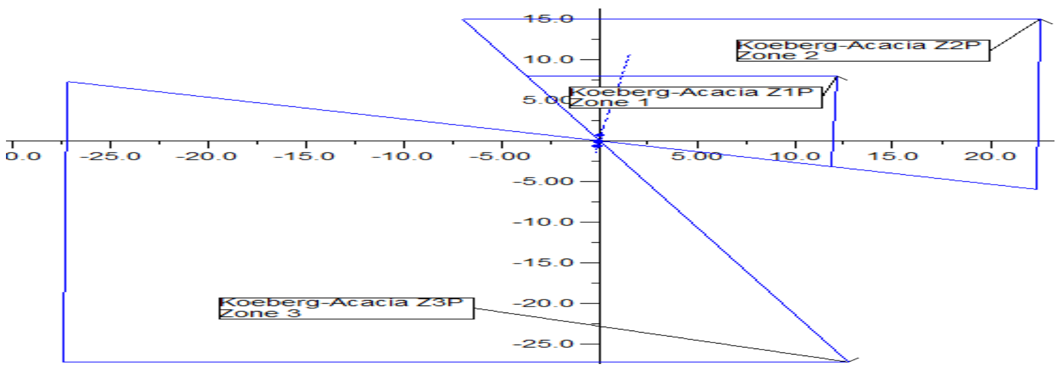

Figure 4-11: Koeberg-Acacia 400 kV feeder 1&2 protection relay phase-ground characteristic

The Koeberg-Stikland 400 kV feeder ABB REL 531 distance protection relay characteristic plot as shown in Figure 4-12 and Figure 4-13. Zone 1, 2 &3 phase-phase and phase-ground characteristic respectively is depicted on the diagrams. The Koeberg-Ankerlig no.1 and 2, 400 kV line feeder ABB REL 561 current differential protection relay step distance characteristic plot is shown in Figure 4-14 and Figure 4-15. Zone 1and 2 phase-phase and phase-ground characteristic respectively are depicted on the figures. The results are described and analysed in chapter 5. Faults within the relay characteristics will cause the relay to trip and open the associated circuit breakers. However faults that falls outside the relay characteristics cannot be detected. Open circuit faults are characterised by infinite resistance and therefore are almost impossible to be detected from the conventional impedance schemes.

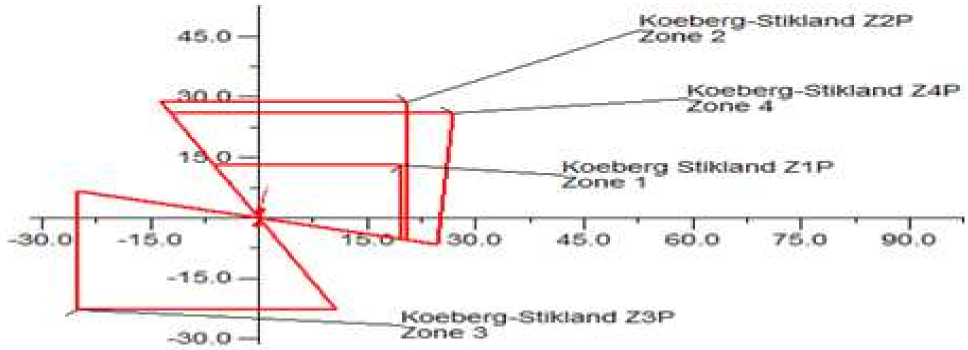

Figure 4-12: Koeberg-Stikland 400 kV feeder 1&2 protection relay phase-phase characteristic (above)

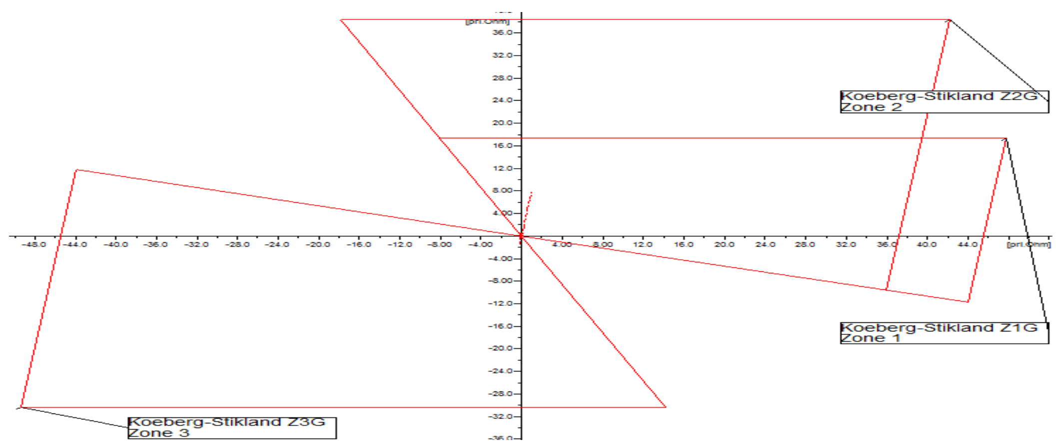

Figure 4-13: Koeberg-Stikland 400 kV feeder 1&2 protection relay phase-ground characteristic

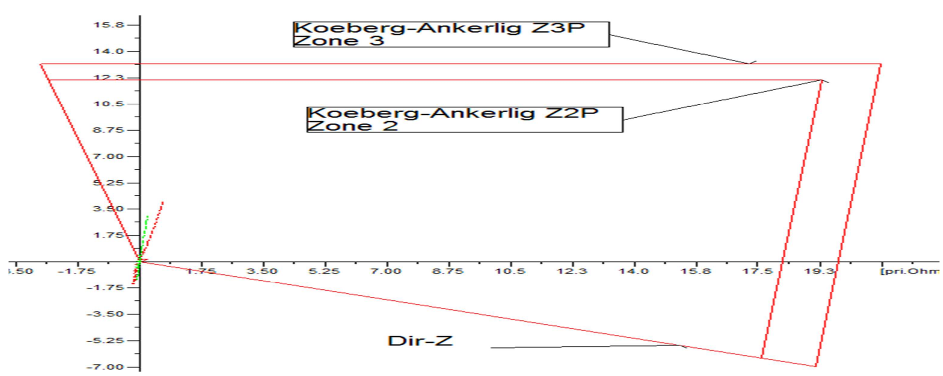

Figure 4-14: Koeberg-Ankerlig no.1&2 400 kV feeder 1&2 protection relay phase-phase characteristic

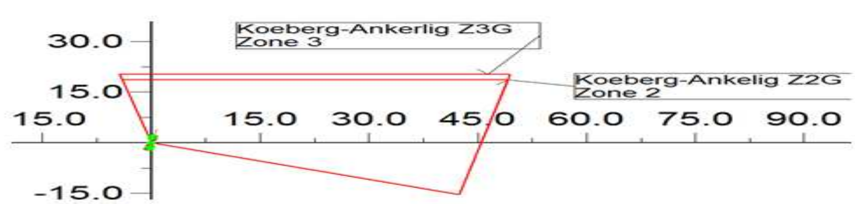

Figure 4-15: Koeberg-Ankerlig no.1&2 400 kV feeder 1&2 protection relay phase-ground characteristic

4.4 Koeberg-Acacia line feeder short circuit simulation

A three phase short circuit phase was simulated only on the Koeberg-Acacia line feeder in order to validate the integrity of the model used in the simulation. This was conducted to prove that the simulation converged, solved.

Figure 4-16 illustrates the result of a three phase short circuit fault that was initiated in the middle of the Koeberg-Acacia line feeder**.** It is evident that the fault was detected in zone 1 of the protection relay characteristic which is set at 80% of the line feeder which confirmed that the relay operated as defined by the settings for a three phase fault at 50% of the line feeder length.

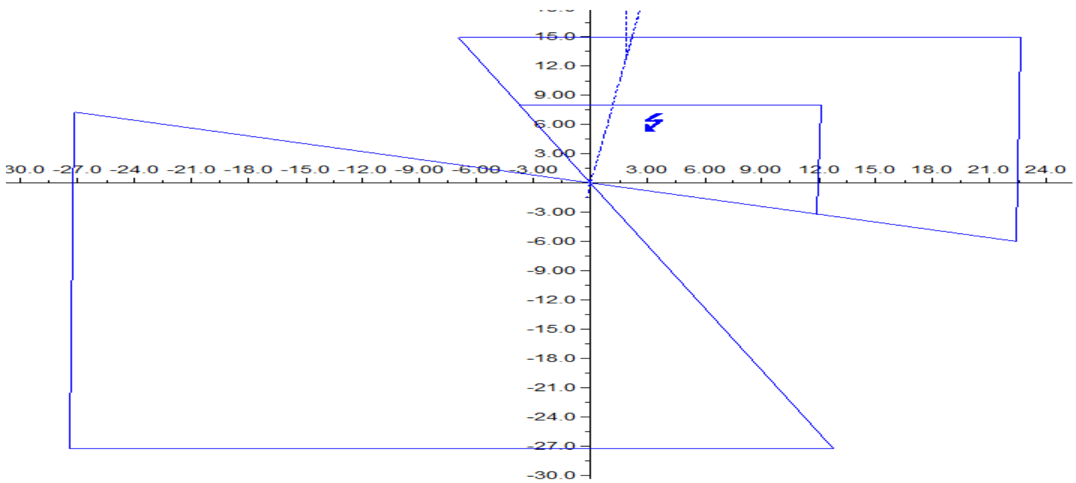

Figure 4-16: Koeberg-Acacia 400 kV feeder relay phase-phase characteristic with fault in Zone 1

4.5 Open circuit fault analysis of the 132 kV side of the Koeberg substation

The fault was simulated once more on the Koeberg 400 kV busbar no.1 with an open circuit fault on the red phase of the 400 kV bus section A isolator. However the simulation results showed that no fault current was flowing in the 132 kV side of Koeberg substation. This was due to the two auto-transformers between the Koeberg 400 kV and Koeberg 132 kV substation connecting the two Koeberg HV yards with a common star-point (auto-transformers are electrically connected). Please refer to Figure 4-9.

4.6 Simulation of an open phase fault on the Koeberg-Ankerlig line feeders

A simulation was conducted by applying an open phase fault on the Koeberg-Ankerlig No.1 and 2 line feeders with the Koeberg 400 kV configuration as shown in Figure 4-9. The Koeberg 400 kV bus-section A and B closed with the red phase open on the bus-section isolator, 400 kV bus-coupler A and B closed. The result was as shown in Figure 4-17 (with Koeberg-Acacia out of service) and Figure 4-18 (Koeberg-Acacia in service), which is assessed and discussed in chapter 5.

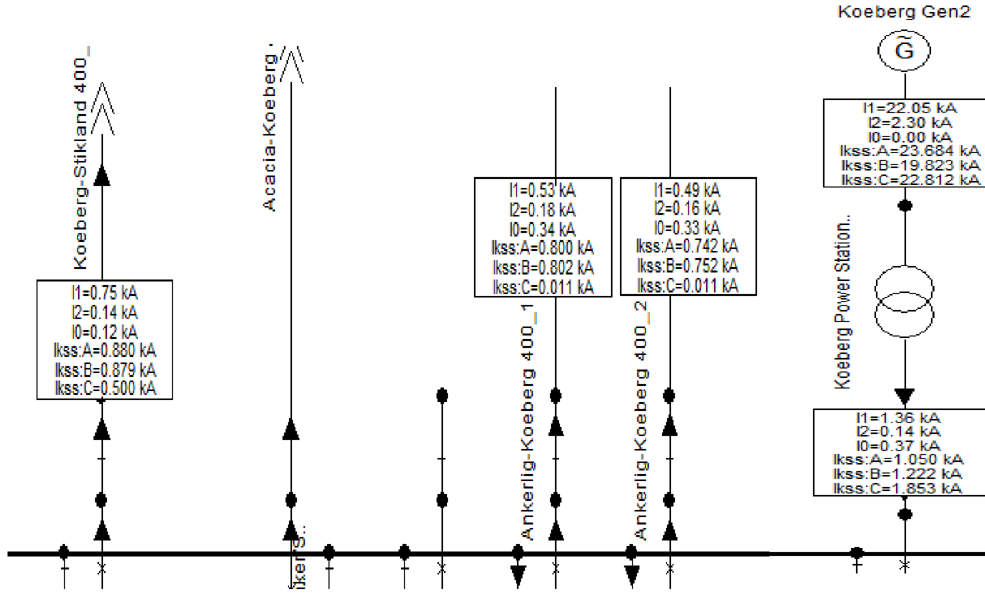

Figure 4-17: Results of open phase fault on Koeberg-Ankerlig no.1 & no.2 feeders

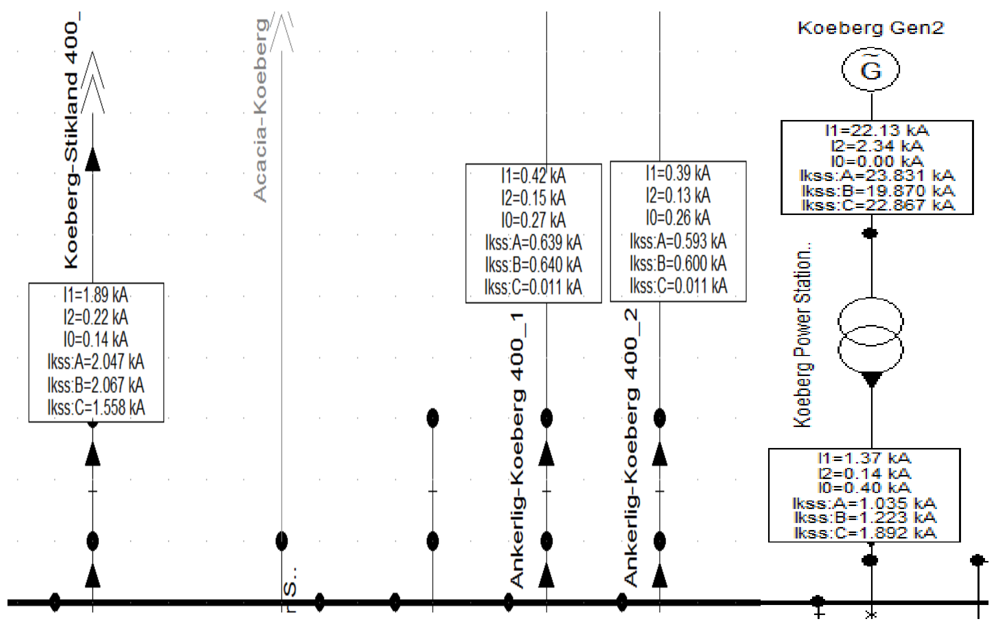

Figure 4-18: Open phase fault on Koeberg-Ankerlig no.1 & no.2 with the Koeberg-Acacia feeder in service

4.7 Voltage simulation during the open phase of the bus-section

The purpose of this simulation was to calculate the voltage depression due to the 400 kV feeders tripping as a result of the open circuit fault on the bus section. The simulation was significant to assess the voltage depression which could result in instability on the South African - Western Cape 400 kV local power network. A load flow simulation was initiated using the simulation software case study with the following circuits at Koeberg out of service: (the circuits tripped during the initial open phase on the Koeberg 400KV bus-section A isolator as per section 4.3).

- 400/132 kV coupling transformer no.1 132 kV breaker

- Koeberg-Acacia 400 kV line feeder breaker
- 400/132 kV coupling transformer no.2 132 kV breaker
- Koeberg-Ankerlig no.1 400 kV line feeder breaker
- Koeberg - Ankerligno.2 400 kV line feeder breaker

4.8 Conclusion

Short circuit, open circuit and voltage depression simulations were conducted in this chapter or various scenarios with the results analysed and discussed in chapter 5.

CHAPTER 5: RESULTS OF SIMULATIONS

5 Introduction

Simulation software was used to simulate the open phase fault incident at the Koeberg substation and compared the results of the impedance or distance line feeder protection and earthfault protection of all line feeders (not described and explained in chapter 4). The simulation of the Koeberg open phase fault incident was conducted as described in the previous chapter with the following results.

5.1 Koeberg-Acacia 400 kV line feeder

The Koeberg-Acacia line feeder has the ABB REL 531 distance protection scheme with the quadrilateral characteristic of Zones 1 and 2 for phase-phase and phase-ground set to trip in the forward direction of the line feeder and Zone 3 phase-phase and phase-ground is marshalled to detect a fault in the reverse direction to the line feeder. Zone 3 is used to detect and block tripping of the line feeder. The result of the open phase fault on the 400 kV Koeberg-Bus section No.1 blue or C-phase isolator is shown (in Figure 5-1) by the blue arrows on the phase-ground quadrilateral zone characteristics. It is evident that the fault is not in the protection's zone characteristics and hence this line feeder will not detect the fault as the starting current required by the relay was not fulfilled. It can therefore be concluded from this that the protection did not trip Koeberg-Acacia 400 kV line feeder.

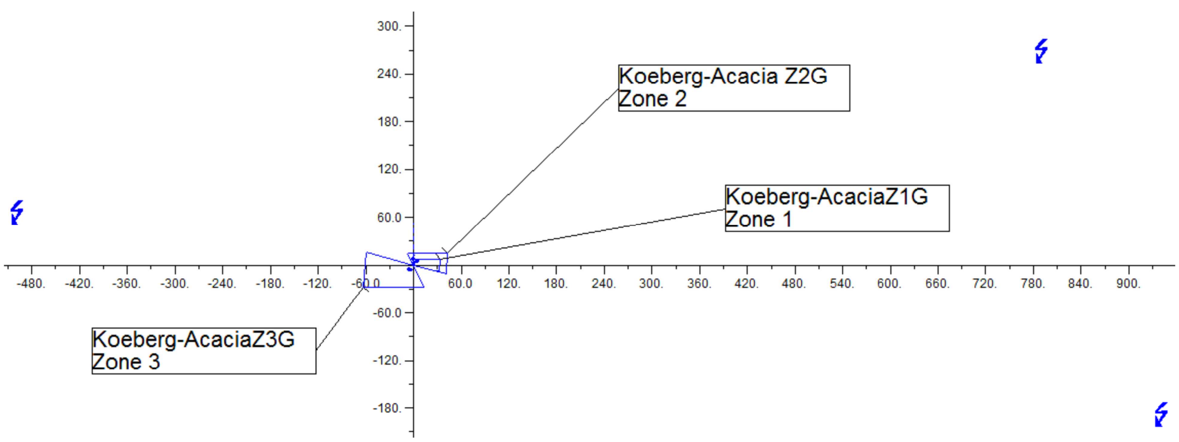

Figure 5-1: Koeberg-Acacia 400 kV feeder protection relay characteristic

5.1.1 The normal IDMT earth fault protection for Koeberg-Acacia

The earthfault characteristic was simulated and plotted as shown in Figure 5-2. Analysis of the earth fault current ($3I_0$ or $I_r = 3I_0 = I_a + I_b + I_c$ = 450.5 A) was detected by the ABB REL 531 earth fault element The time the earthfault relay would trip is 11.199 seconds with the setting of Ipset = 0.15 and Tpset = 0.35. In this case there was no earthfault on the feeder however the open phase on the bus-section gave rise to an unbalance with normal load currents. This resulted in the 400 kV Koeberg-Acacia line feeder tripping and isolation of the circuit.

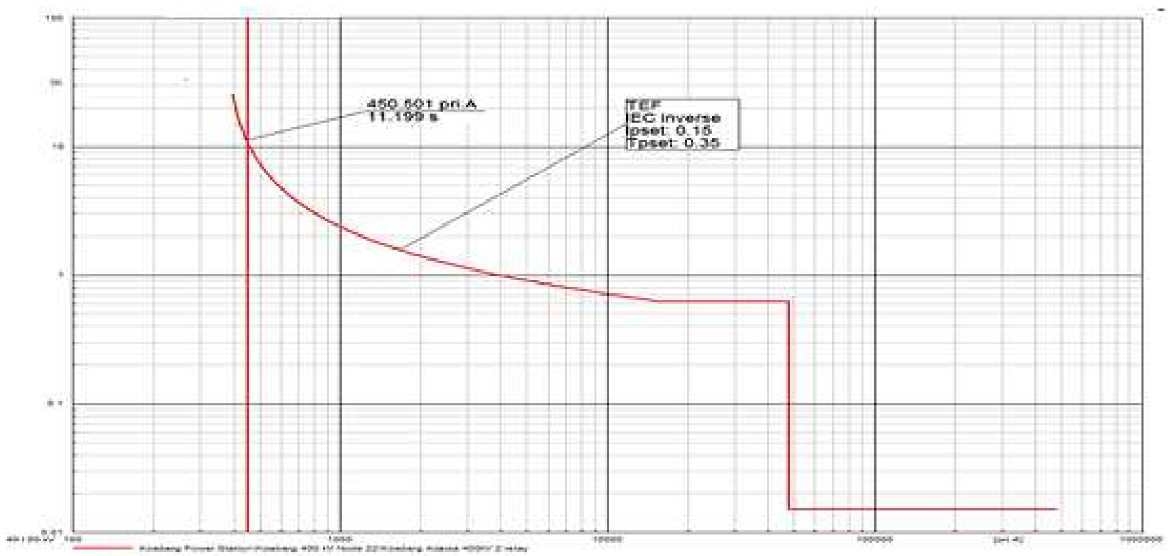

Figure 5-2: Koeberg-Acacia 400 kV line feeder IDMT earthfault (TEF) protection relay curve

5.2 Koeberg-Stikland 400 kV line feeder

The Koeberg-Stikland line feeder has the ABB REL 531 distance protection scheme, the same as the Koeberg-Acacia line feeder with the quadrilateral characteristic of Zones 1 and 2 for phase-phase and phase-ground set to trip in the forward direction of the line feeder and Zone 3 phase-phase and phase-ground set to detect a fault in the reverse direction to the line feeder. Zone 3 is used to detect and block tripping of the line feeder.

The result of the open phase fault on the 400 kV Koeberg-Bus section No.1 blue or C-phase isolator is shown by the red arrows on the phase-phase and phase-ground quadrilateral zone characteristics as shown in Figure 5-3 & 5-4 respectively. It is evident that the fault is not in the protection's zone characteristics and hence this line feeder will not detect the fault as the starting current required by the relay was not fulfilled. It can therefore be concluded that the Koeberg-Stikland line feeder was not isolated by the impedance protection scheme.

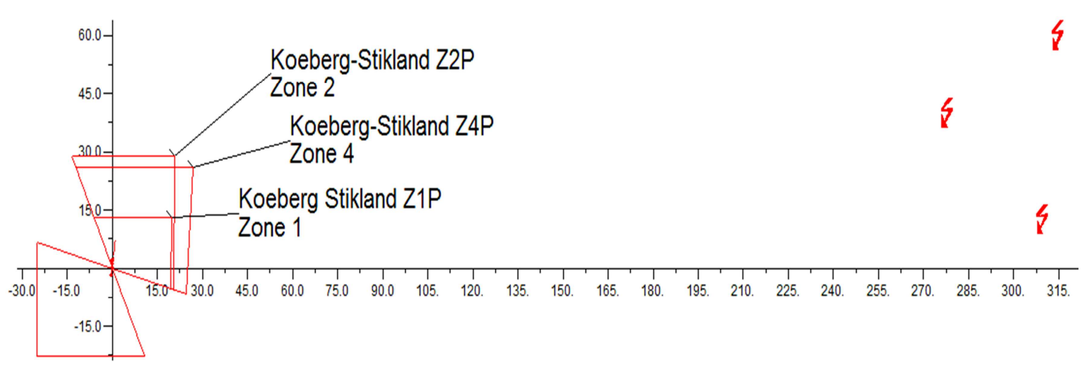

Figure 5-3: Koeberg-Stikland 400 kV line feeder protection relay phase characteristic

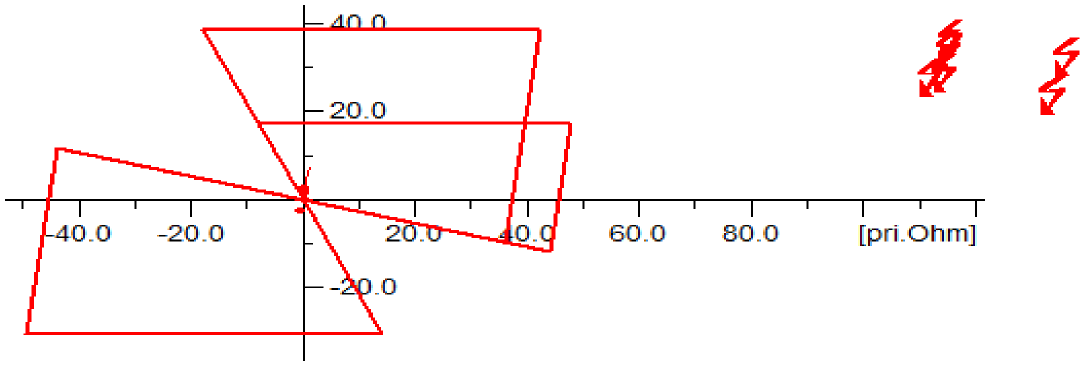

Figure 5-4: Koeberg-Stikland 400 kV line feeder protection relay phase-ground characteristic

5.2.1 The normal IDMT earth fault protection for Koeberg-Stikland

The earthfault characteristic was simulated and the result plotted as shown in Figure 5-5. Analysis of the earthfault current ($I_r = 3I_0 = I_a + I_b + I_c$ = 273.4A) was detected by the ABB REL 531earthfault element. The earth fault relay settings of Ipset = 0.2 and Tpset = 0.4.

In this case the earthfault current seen by the earthfault protection relay on the feeder was too low and was not within the IDMT characteristics of relay as depicted on Figure 5-5. This resulted in the 400 kV Koeberg-Stikland line feeder not tripping initially.

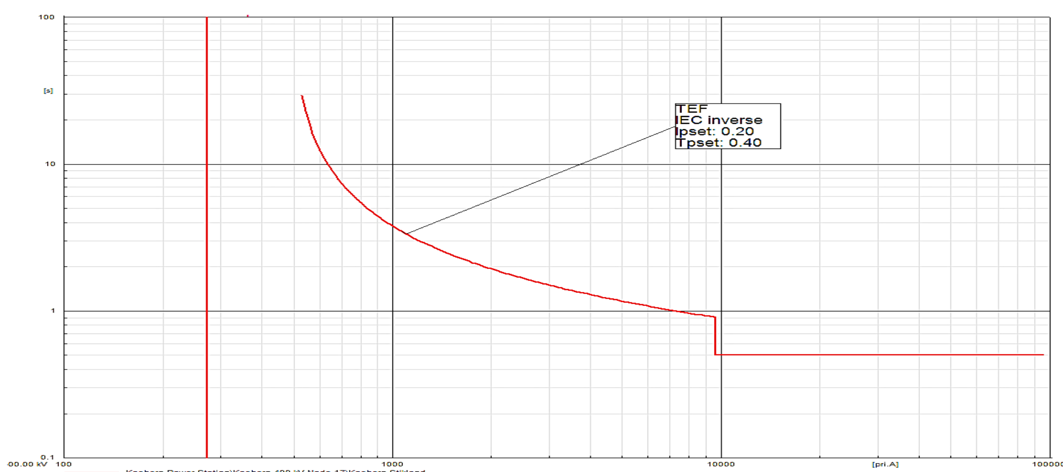

Figure 5-5: Koeberg-Stikland 400 kV line feeder IDMT earthfault (TEF) protection relay curve

A further simulation was conducted shown in Figure 5-6 to validate the integrity of the earthfault protection. Upon analysing this situation with the rest of the circuits connected to the bus-bar showed that both the Koeberg-Ankerlig line feeders tripped within 6 seconds.

5.3 Simulation with the Koeberg-Ankerlig line feeders out of service

A second simulation was conducted by opening the circuit breakers on both Koeberg-Ankerlig line feeders. The earthfault protection setting of Ipset = 0.2 and Tpset = 0.4.

$I_r = 3I_0 = I_a + I_b + I_c$ = 650.174 A. The time of the earthfault trip was 9.778 seconds as seen on Figure 5-6. This resulted in the Koeberg-Stikland line feeder tripping which correlates to the actual line feeder tripping during the incident.

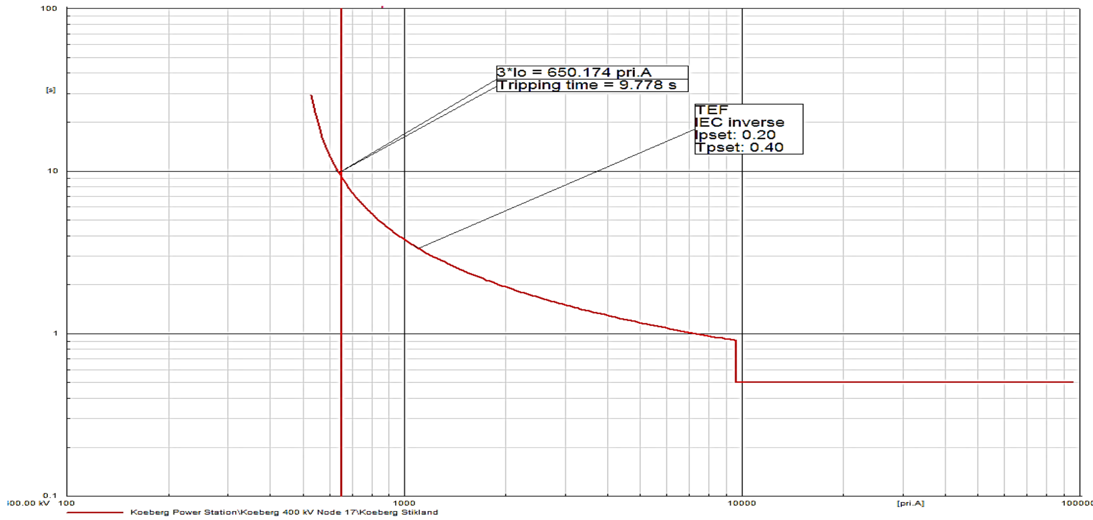

Figure 5-6: Koeberg-Stikland 400 kV line feeder IDMT earthfault (TEF) protection relay curve

5.4 Koeberg-Ankerlig 400 kV line feeder no.1&2

The Koeberg-Ankerlig 400 kV line feeder no.1&2 is protected by the ABB REL 561 as covered in Chapter 4. ABB REL 561 differential function will never trip for an open circuit condition, instead, only for short circuit conditions. However the impedance function in the same relay will be susceptible to tripping for open circuit conditions depending on the impedances that are calculated. The result of the open phase fault on the 400 kV Koeberg-Bus section No.1 blue or C-phase isolator is shown by the red arrows on the phase-phase and phase-ground quadrilateral zone characteristics as shown in Figure 5-7 and 5-8 respectively. It is evident that the fault is not in the protection's zone characteristics and hence this line feeder will not detect the fault as the starting current required by the relay was not fulfilled.

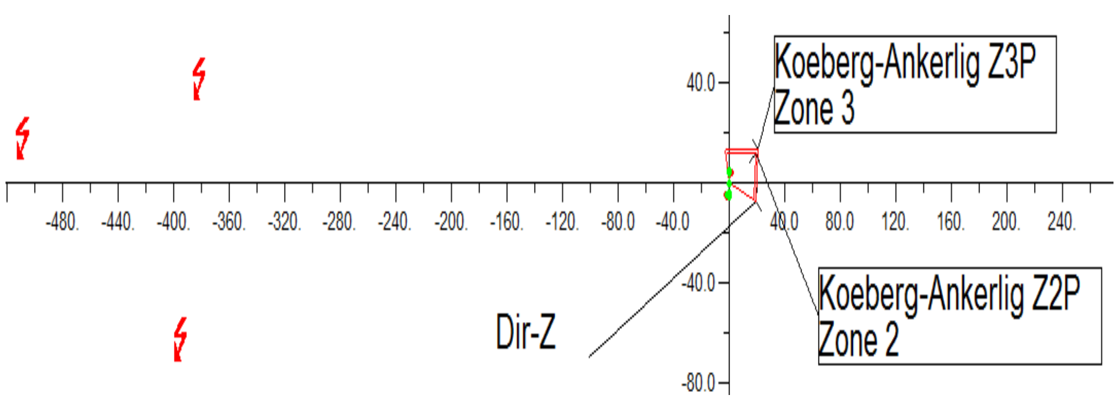

Figure 5-7: Koeberg-Ankerlig 400 kV line feeder no.1 & 2 protection relay phase characteristic

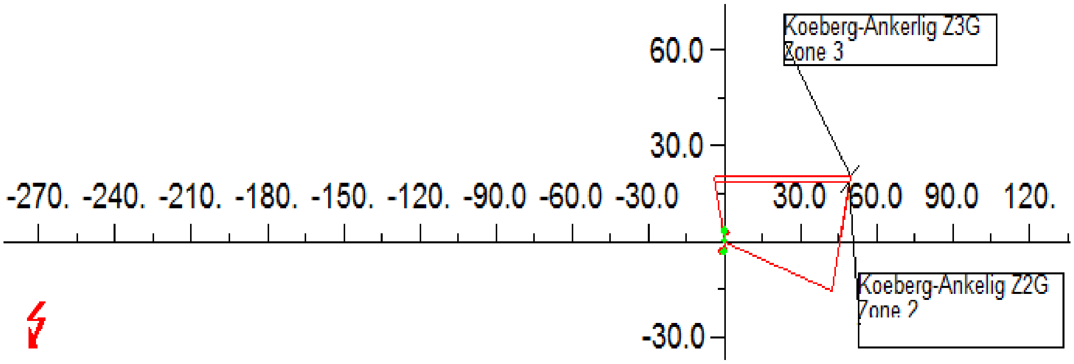

Figure 5-8: Koeberg-Ankerlig 400 kV line feeder no.1 & 2 protection relay phase-ground characteristic

5.4.1 The normal IDMT earth fault protection for Koeberg-Ankerlig

The open phase was simulated and the results of the earthfault characteristic were plotted as shown in Figure 5-9. Analysis of the earthfault current ($I_r = 3I_0 = I_a + I_b + I_c$ = 700.842 A) was detected by the ABB REL 531 earthfault element. The time that the earthfault relay would take to trip is 5.896 seconds with the setting of Ipset = 0.2 and Tpset = 0.3. In this case there was no earthfault on the line feeder however the open phase on the bus section gave rise to an unbalance with normal load currents. This resulted to the 400 kV Koeberg-Ankerlig line feeder no.1 and 2 tripping and isolating the feeder.

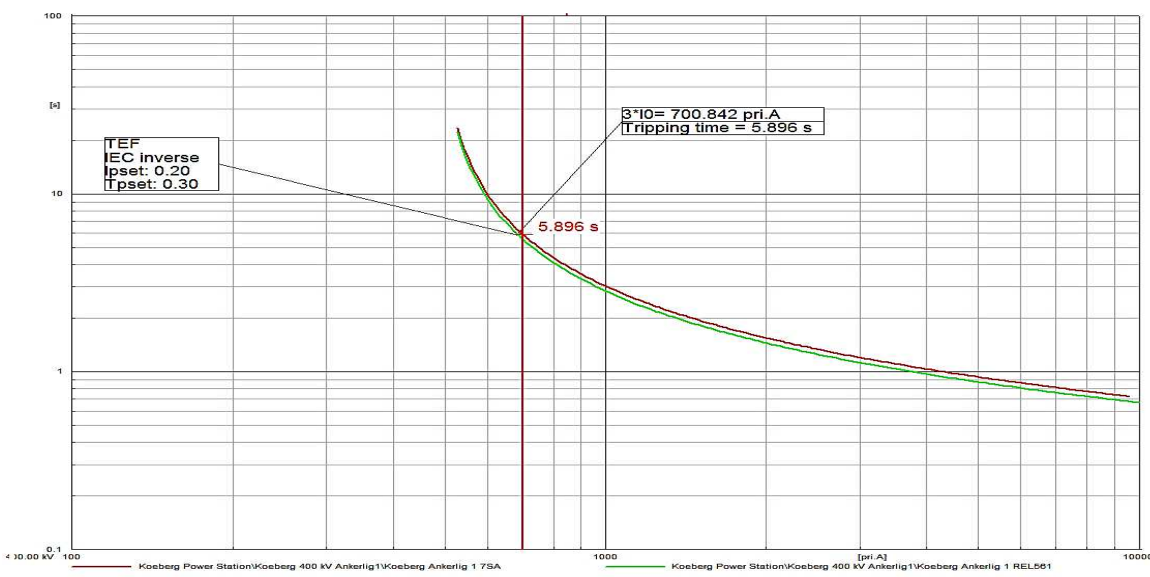

Figure 5-9: Koeberg-Ankerlig 400 kV line feeder no.1&2 IDMT earthfault protection relay curve

5.5 Koeberg-Coupling Transformer no.1&2 (400/132/22kV)

The normal IDMT earth fault protection for Koeberg-Coupling Transformer no.1 and 2 was simulated the plotted as shown in Figure 5-10. Analysis of the earthfault current ($3I_0$) as detected by earthfault element:

$I_r = 3I_0 = I_a + I_b + I_c$ = 450.507 A

The time it would take for the earthfault relay to trip is 11.65 seconds with the settings of Ipset = 0.15 and Tpset = 0.35. In this case there was no earthfault on the feeder however the open phase on the bus-section gave rise to an unbalance with normal load currents. This resulted to the 400 kV Koeberg-Coupling Transformer no.1 and 2 tripping and isolating the transformer from both the 400 kV and 132 kV Koeberg network.

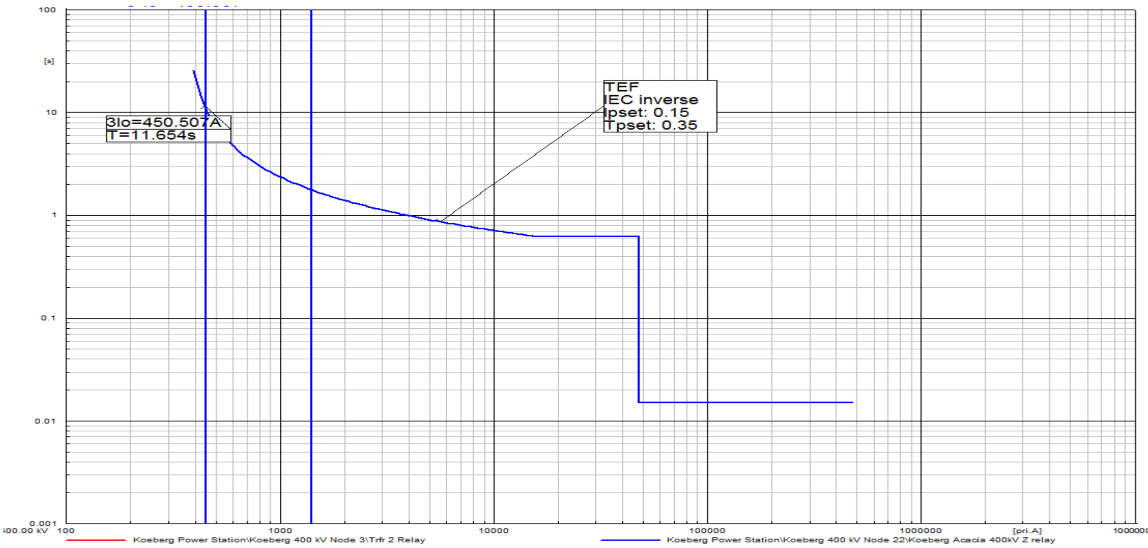

Figure 5-10: Koeberg-Coupling Transformer no.1&2 IDMT earthfault (TEF) protection relay curve

5.6 Results of the voltage depression simulation

The simulation study with the 400/132 kV coupling transformer no.1 132 kV, Koeberg-Acacia, 400 kV line feeder, 400/132 kV coupling transformer no.2 132 kV, Koeberg-Ankerlig, no.1 400 kV line feeder and the Koeberg-Ankerlig, no.2 400 kV line feeder out of service revealed that the voltage depression for the current power network configuration in Cape region was not significantly low. The result of the study is shown Table 5-1.

Table 5-1: Voltage measured on Cape region

Phase Voltage	kV	pu
VA	225.3	0.976
VB	229.6	0.944
VC	224.1	0.97

The largest voltage depression calculated as 5.6% of the simulation study was not significant to adversely impact the Cape network as opposed to a voltage depression of 21.8% of the actual incident at Koeberg power station. This was attributed to the equivalent or virtual loads used for the simulation due to the unavailability of the actual customer loads in comparison to the actual loads for the fault condition. In order to get the simulation to initiate and solve, the load factor was changed to 0.95. The investigation data was used to provide the root cause of the fault and actions taken to stabilize the Cape 400 kV. Although the voltage depression was 21.8% in the Cape geographical region the national system frequency was unaffected and remained at the fundamental frequency of 50Hz. Fortunately in this case the under frequency load shedding minimum criteria of 49.5Hz was not reached as shown in Figure 5-11.

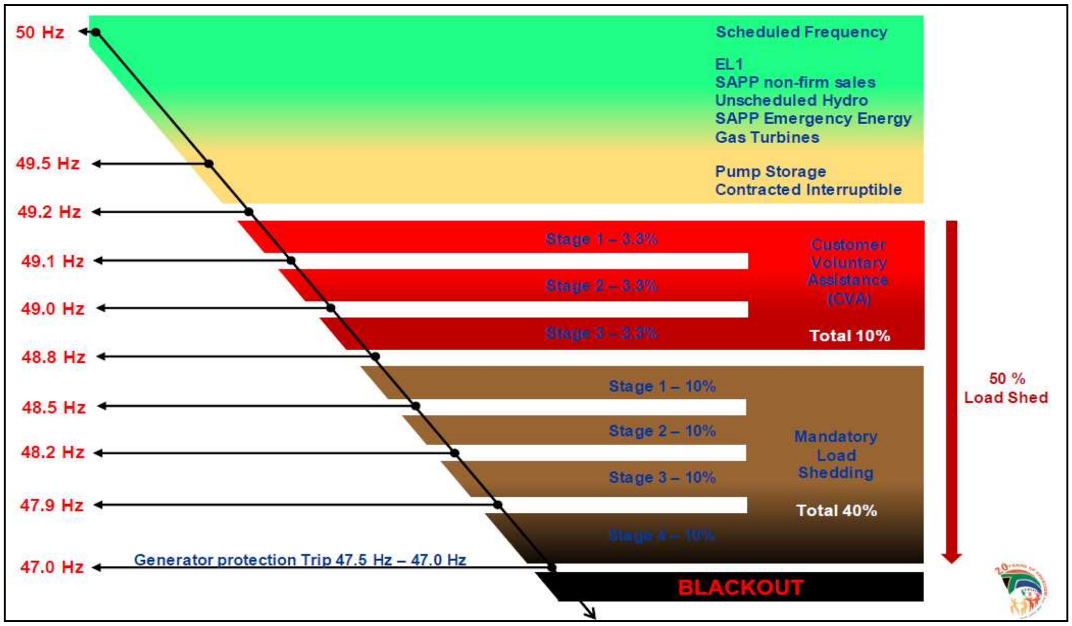

Figure 5-11: Under frequency load shedding stages [2] (above)

Table 5-2: Under frequency load shedding set criteria [2]

Stage	Frequency (Hz)	Delay (s)	Load Shed (MW)	Percentage (%)	Stage Total
CVA Stage 1	49.2	0.3	1666	4.94%	11.88%
CVA Stage 2	49.1	0.3	1130	3.35%	
CVA Stage 3	49.0	0.3	1212	3.59%	
Mandatory Stage 1	48.8	0.5	1884	5.58%	10.76%
	48.8	1.0	992	2.94%	
	48.8	1.2	107	0.32%	
	48.8	1.5	378	1.12%	
	48.8	2.0	272	0.8%	
Mandatory Stage 2	48.5	0.3	264	0.78%	9.90%
	48.5	0.5	1279	3.79%	
	48.5	1.0	557	1.65%	
	48.5	1.2	158	0.47%	
	48.5	1.5	118	0.35%	
	48.5	2.0	966	2.86%	
Mandatory Stage 3	48.2	0.2	83	0.25%	13.75%
	48.2	0.5	2858	8.47%	
	48.2	1.0	348	1.03%	
	48.2	1.2	115	0.34%	
	48.2	1.5	297	0.88%	
	48.2	2.0	940	2.78%	
Mandatory Stage 4	47.9	0.5	2201	6.52%	10.37%
	47.9	1.0	1135	3.36%	
	47.9	1.2	106	0.31%	
	47.9	2.0	57	0.17%	
Total			19 121	56.65%	56.65%

Table 5-1 provides the set criteria that the power utility Eskom in South Africa utilizes to expedite under frequency load shedding in order to ensure power system stability with the power system frequency of 50Hz maintained. The local system control in the Western-Cape region opted to stabilize the transmission network in the region by initiating manual load shedding and restore the voltage. This resulted in 1326 MW of local load that was shed to recover the voltage to the acceptable limit.

5.7 Simulation of an open phase fault on the Koeberg-Ankerlig line

The results of the simulation that was conducted by applying an open phase fault on the Koeberg-Ankerlig No.1 and 2 line feeders with the Koeberg 400 kV bus-section A and B closed with the red phase open on the bus-section isolator, 400 kV bus-coupler A and B closed is shown in Figure 4-17 and Figure 4-18 with and without the Koeberg-Acacia line feeder in service respectively.

Table 5-3: Earth fault currents with an open phase fault on the Koeberg-Ankerlig no.1 & 2 lines

Koeberg 400 kV Feeder	EarthFault Current without Acacia	EarthFault Current with Acacia
Stikland	414A	358A
Ankerlig No.1	810	1020A
Ankerlig No.2	810	1020A
Acacia	0	593A

5.7.1 Evaluation of results shown in Table 5-3 and Table 5-4

The objective of the evaluation of the results was to confirm that present line feeder protection is inadequately configured to trip the line feeders described below for an open phase fault. The main protection would not trip but the back-up protection, which caters for resistive faults, would operate on unbalance which is detected as zero sequence currents although its intended function was to detect high resistance ground faults. However the fault clearance time is too long (in electrical protection terms, in order to limit the adverse impact of electrical plant and equipment damage the protection is configured to isolate the fault within 1 second.

5.7.2 Koeberg-Stikland 400 kV

The Koeberg-Stikland line feeder showed an earthfault of 414 A and 358 A with and without the Koeberg-Acacia line in service respectively. Figure 5-12 shows the IDMT earthfault characteristic of the earthfault element with an Ipset = 0.2 and Tpset = 0.4. For the earthfault current of 358 A and 414 A the Koeberg-Stikland line feeder does not trip for the open phase fault half way down the both Koeberg-Ankerlig line feeders.

The feeder protection correctly does not trip the feeder. It will be seen in 5.6.1.3 that the Koeberg-Ankerlig no.1 and no.2 trips and isolates the open phase fault for both instances of Koeberg-Acacia line feeder in service and out of service.

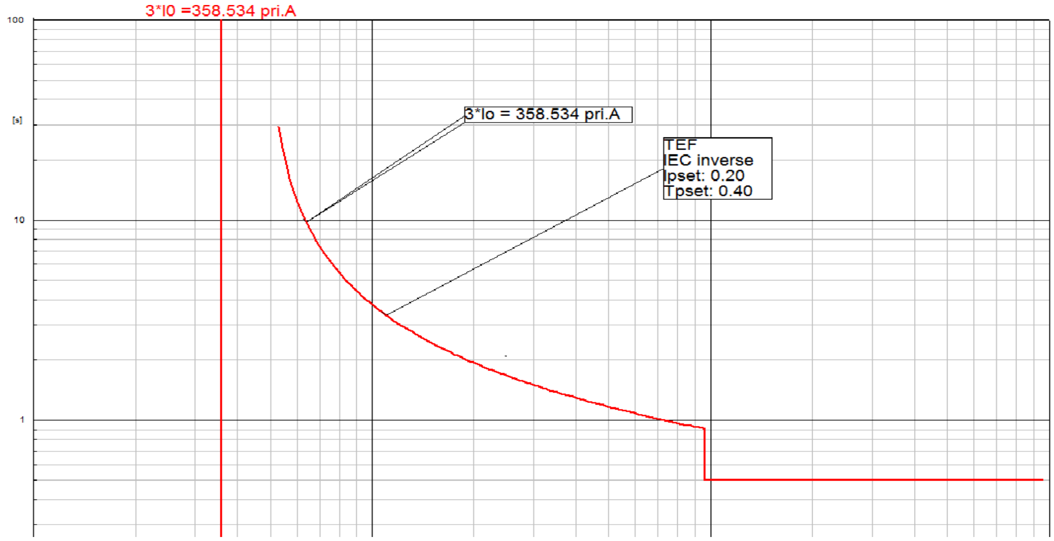

Figure 5-12: Koeberg-Stikland 400 kV line feeder IDMT earthfault (TEF) protection relay curve

5.7.3 Koeberg-Acacia 400 kV

The Koeberg-Acacia line feeder showed an earthfault of 593 A. Figure 5-13 shows the IDMT earthfault characteristic of the earthfault element with a Ipset = 0.15 and Tpset = 0.35. For the earthfault current of 593 A the Koeberg- Acacia line feeder does trip for the open phase fault half way down the both Koeberg-Ankerlig line feeders. The feeder protection correctly trips the feeder in 5.01s as shown in Figure 5-13.

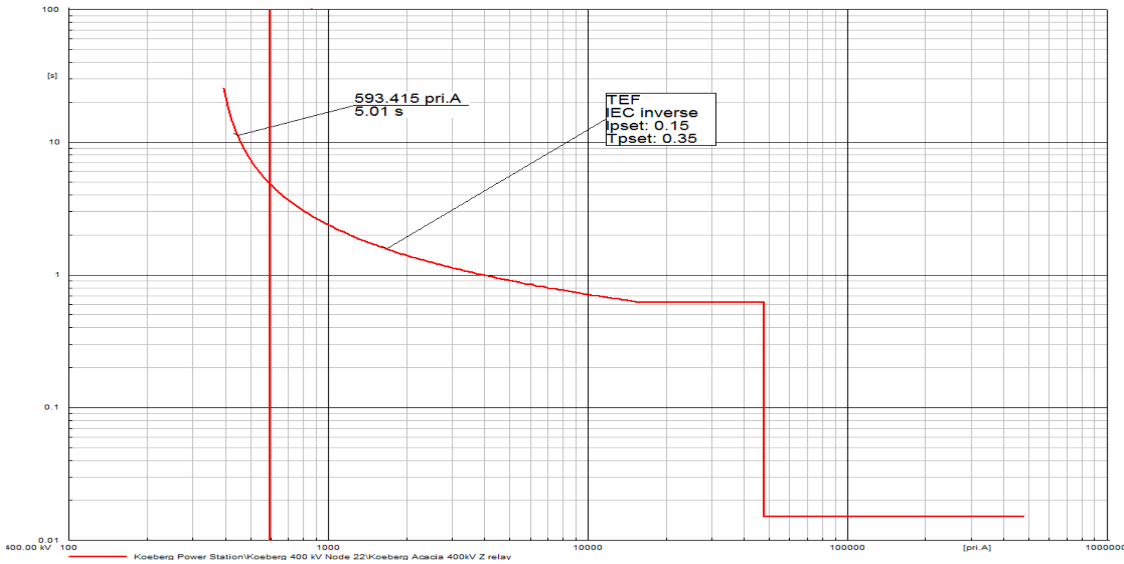

Figure 5-13: Koeberg-Acacia 400 kV line feeder IDMT earthfault (TEF) protection relay curve

5.7.4 Koeberg-Ankerlig No.1 &2 400 kV

The Koeberg-Ankerlig no.1& 2 line feeder experienced an earthfault of 1030 A and 814.5 A with and without the Koeberg-Acacia line in service respectively. Figure 5-14 and Figure 5-15 shows the IDMT earthfault characteristic of the earthfault element with an Ipset = 0.2 and Tpset = 0.3. For the earthfault current of 1030 A and 814.5 A the Koeberg-Ankerlig line feeder tripped correctly in 2.11s and 4.21s respectively for the open phase fault half way down the both Koeberg-Ankerlig line feeders.

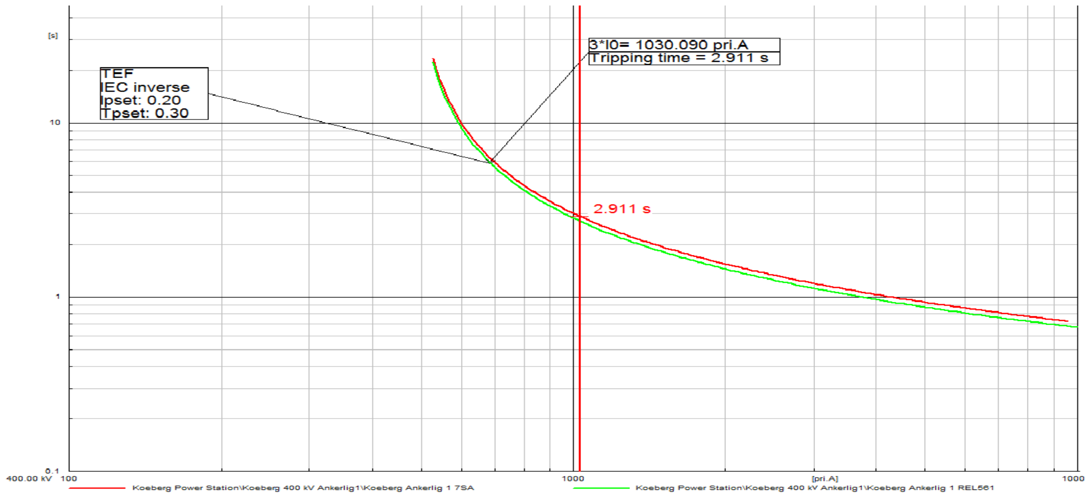

Figure 5-14: Koeberg-Ankerlig 400 kV feeder IDMT earthfault (TEF) with Acacia line feeder in service

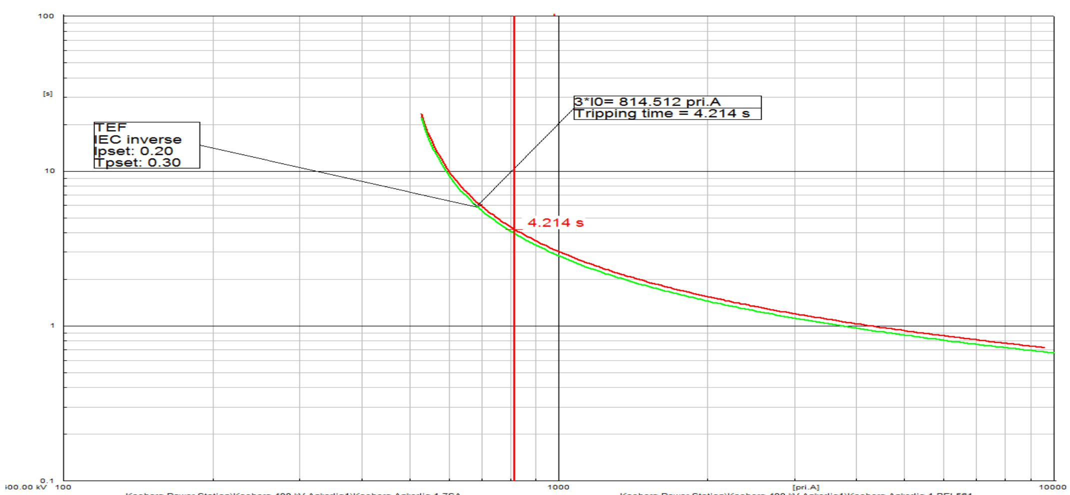

Figure 5-15: Koeberg-Ankerlig 400 kV feeder IDMT earthfault (TEF) curve without Acacia line feeder in service

5.7.5 Koeberg generator no. 2

The effect of the fault on the two Koeberg-Ankerlig 400 kV line feeders was assessed to validate tripping of the Koeberg generator no.2. The Koeberg-Gen 2 results as shown in Table 5-4 extracted from Figure 4-17 and Figure 4-18.

Table 5-4: Results of open phase fault on the Koeberg-Ankerlig no.1 and 2 feeders, generator sequence currents

Sequence Current	kA without Acacia in service	kA with Acacia in service
I_1	22.13	22.05
I_2	2.34	2.3
I_0	0	0

Table 5-5: Koeberg-Generator No.2 negative phase sequence settings

Negative Phase Sequence settings	
Alarm	1549A
DT-3s	2710A
IDMT - pick up	1549A

With reference to Table 5-5 it was confirmed that with a negative sequence current (I_2) of 2.34 kA and 2.30 kA that in both instances the IDMT pick-up setting of 1549 A was met and the negative phase sequence element was triggered resulting in a trip 5s and isolating the generator from the fault.

5.8 Root cause of the open phase incident

The 400 kV isolator is switched by means of a mechanical shaft coupling of the three phases as shown in Figure 5-16. The 400 kV bus section A isolator displaced shaft and gear mechanism that caused the open circuit is shown in Figures 5-17 and 5-18 below which show the coupling clamp over the joint between the square cylinder shaft and the square rod mounted with gears. The black marks indicate the original overlap position of the rod and the square shaft and the gear displacement from the housing. The space indicated by the ruler shows the displacement length that resulted from the shift. The dirty area is the part that was exposed all along and the clean area was the one that was normally covered inside the cylinder.

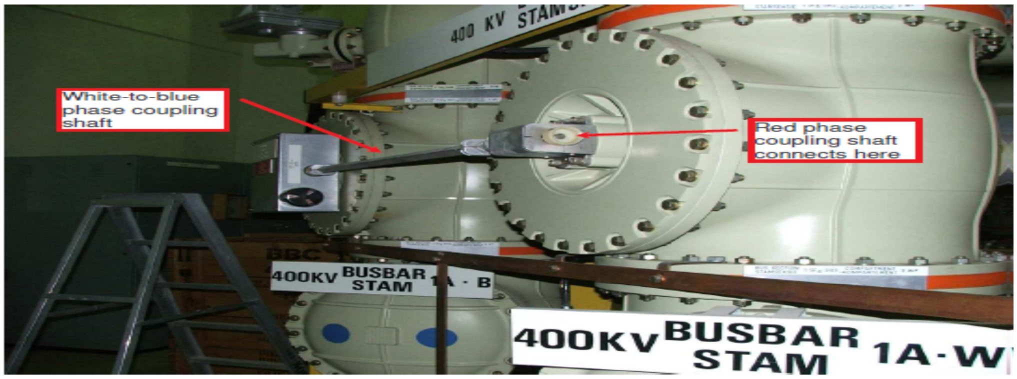

Figure 5-16: Overview of the isolator arrangement showing the coupling between the white and blue phases

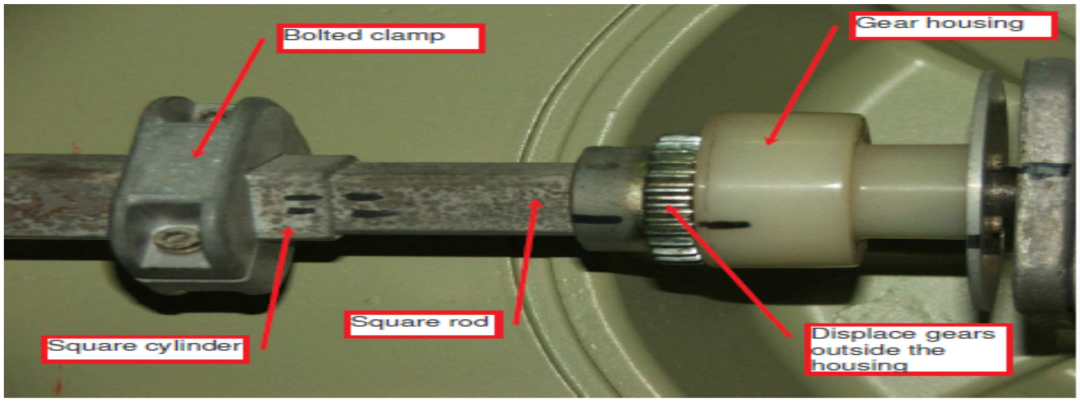

Figure 5-17: View of the coupling between the cylinder shaft, rod and displaced gears at the back of the rod


Figure 5-18: Measurement of the shaft displacement

The above fault occurred which could not be easily detected. Simulations were conducted to investigate the actual characteristics of the protection relay in order to explain the delay in clearing the fault. The author aims to formulate recommendations to the protection settings philosophy and protective devices in order to minimise the impact of such faults in future.

5.9 Conclusion

The results analysed in this chapter covered open phase faults on the bus-section and line feeder open phase faults. Impact of open phase faults was also conducted with respect to the generator and confirmed that the negative sequence protection on the generator detects the open phase fault. It was concluded that the typical line feeder protection being the impedance or current differential protection do not detect an open phase fault. In some instances the back-up earthfault protection picked up the open phase as an unbalance as a result of zero sequence currents measured but fault clearance was too slow.

CHAPTER 6: RECOMMENDATIONS AND CONCLUSIONS

6. Introduction

The investigation and simulations were conducted on open phase faults to evaluate the impact of these faults and to confirm that the presently utilised line feeder protection schemes utilised including back-up earthfault protection did not clear the open phase fault adequately. The author therefore recommends the following to reduce the impact of open phase faults and find ways to not only detect, but locate and trip for these faults.

6.1 Power line carriers

The power line carrier has the potential of being a practical solution with an addition of a set of PLC equipment on the third phase considering that the two outer phases of the power transmission line feeders are presently equipped with power line carriers. Minor modifications to the tele-protection and alarming circuits should be done however, the economics and modifications require some investigation in future.

6.2 Negative phase sequence protection

It is recommended that once the South African power utility has phased out all the phase I and phase II protection schemes on the sub-transmission and transmission line feeders the protection philosophies should be reviewed to incorporate the negative phase sequence protection element and it also should be configured to initiate a trip or alarm.

6.3 Detection of high-impedance faults caused by downed conductors

ABB researched solutions and developed the ABB REF 550 feeder scheme. This scheme can and will detect open phased conditions as well. The author recommends this scheme to be evaluated together with other feeder protection schemes for future use. The other functionalities and requirements must be evaluated by the relevant protection engineering specialists.

6.4 Integrated current phase comparator

This would be a very practical solution to implement. The cost might be low per unit however installing it on all feeders in Transmission might prove un-economical. This could be a very good application-based solution where installation of these “current phase comparators” would take place on lines feeding customers with sensitive equipment.

6.5 ABB REL 531 protection scheme

It would be recommended that this scheme be configured to detect open phased faults, trigger an alarm and/or trip. The latter being the more suitable option. Where tripping is initiated, care must be taken to set the BRC-timer to only trip after a minimum time of 3s. The Extra High Voltage (EHV) line feeder protection requirements of South Africa’s power utility Eskom are also satisfied with this scheme. For future replacement of EHV protection schemes as Eskom phase out the less reliable or obsolete protection schemes and new feeder installations. It is strongly recommended that this scheme or similar more modern schemes which has the full functionality and meets all the Eskom requirements be installed on the remainder of the line feeders.

6.6 Alstom Micom P444 protection scheme

This scheme has the functionality of detecting and tripping for an open phase fault. However, it is important that the power utilities protection engineers evaluate the total protection scheme functionalities by conducting integrity test on the protection scheme before taking a decision to use this scheme. The same that was recommended for ABB REL 531 protection scheme would also apply for this scheme, namely for single phase trip and auto-reclose, the broken conductor timer must allow sufficient time for the feeder circuit breaker to reclose. It is recommended by the author to set the timer to 3s since this would give sufficient time for the reclosure of a “genuine or true” single phase to ground fault.

6.7 Enhanced remote terminal unit (ERTU)

This option would be the most cost-effective and efficient method to detect an open phase condition. This option is a matter of reconfiguring the measurements transducer/s outputs to the protection panel and then to the ERTU. The measurements algorithm calculates the unbalance from the three current inputs and expresses it as percentage. If the percentage unbalance exceeds the prescribed or calculated maximum unbalance setting, the alarm will be initiated via the ERTU to the power utilities control room. The author considers this option as the practical and most economical yet the advantages of alarming and giving the power utilities controller the information of an open phased condition and the decision to trip the feeder will depend on the impact it is having on the network. Sometimes it would be more technically feasible to keep the feeder alive rather that to trip depending on the magnitude of the loading and type of customers connected to the supply.

6.8 Conclusion

It is concluded that the hypothesis, namely that open phase faults goes undetected with the present line feeder protection schemes on the power transmission network, is true. This causes major power system interruptions when they occur with long restoration times due to the challenge to identify the fault and physically locate the open phase fault. The impact of open phase faults cause spurious tripping of fault free line feeders and associated circuits (transformers, motors and generating plant). On the line feeders, the impedance did not detect faults, however, the back-up earthfault (used for high resistance fault detection) protection picked up the unbalanced currents as zero sequence currents in some cases where the protection setting of 300 A was exceeded. It must be noted that it is not correct protection operation although it was convenient that this protection triggered the open phase fault clearance but with long clearance times. It is imperative that these faults despite not commonly occurring be detected correctly when they occur.

It was interesting to notice that there was a difference in measurements taken by different relay manufacturers’ protection schemes and yet manufacturers are coming up with intelligent algorithms to deal with load currents and unbalances without compromising the integrity of being dependable, reliable and secure. A manufacturer opted to measure the phase currents in the three phase and take the differential between the highest and lowest phase currents, the highest phase should be greater than the minimum current setting value and the lowest phase current is below 50% of the minimum current setting value.

6.9 Future Research

The open phase faults investigated and discussed in chapter 5 indicated a need for open phase faults to be detected and require isolation of the fault to prevent spurious tripping of the power transmission network. Future research is required for modelling of negative phase sequence currents and method of negative sequence current protection grading, revision of EHV line feeder protection philosophy to enable the possibility of enabling the impedance negative sequence elements to trip, broken conductor algorithms modelling in order to test and validate the dependability of these functionalities available from impedance protection relay scheme developers or manufacturers, optimising the possible solutions and assuring that the solution considered to resolve open phase fault detection and tripping is reliable.

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