Chapter 1
PROTECTION MALOPERATIONS ON THE ESKOM TRANSMISSION SYSTEM

1.1   Introduction

This research aims to show that incorrect operations associated with numerical distance protection relays utilized in boltedly earthed power systems during earth fault conditions can be resolved and/or compensated for. Incorrect protection relay operations can and does have a major impact on system security, dependability and reliability. Protection maloperation can result in multiple circuit breaker trips for a fault on an overhead line within a complex integrated system causing major power interruptions. This, in turn, has a direct impact on income generated by industries and the country as a whole. The cost of non-served electricity (electricity not provided to a customer(s)), is calculated based on the types of load affected, the system minutes lost and the cost per kilowatt-hour. The cost of non-served energy translates to income lost and an effective increase in running cost to Eskom.

Several maloperations, on the Eskom transmission system, have occurred where numerical protection relays are in use. This initially seemed to be restricted to short lines only, but recently this trend has also been observed on long lines. It is perceived that the operational behaviour of the protection relays differ for different parts of the network. This study will therefore focus on the topology of the network, and the evaluation of relay performance. Chapter 1 provides a high-level background of actual transmission network events that have occurred and highlights the protection operations associated with each event. The protection mal-operated in each case.

The following system fault examples are presented to illustrate some of the problems that were experienced in the Eskom transmission system. Note that unless explicitly stated otherwise, all impedances are shown in primary ohm per loop.

1.1.1 Example 1 on 275 kV: Georgedale – Klaarwater line

An A-phase-to-earth fault occurred on the adjacent feeder behind the relay position. The A-phase impedance locus enters the reverse characteristic in the third quadrant as expected, whilst the healthy C-phase enters the relay characteristic in the fourth quadrant and results in a zone 1 operation. The line has a total length of 27.54 km with primary impedance of 8.77 Ω. Figure 1.1 depicts the different impedance loci.
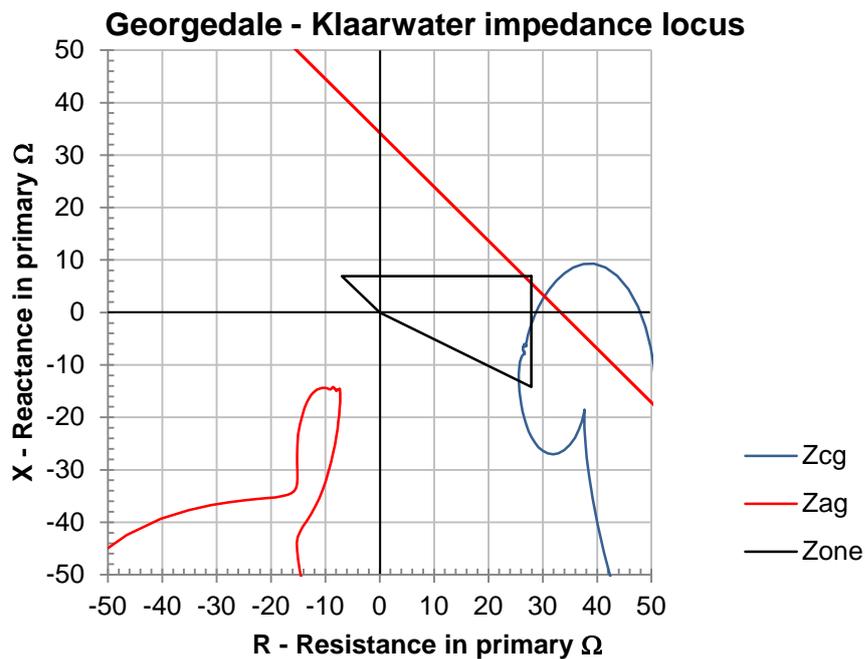

Figure 1.1: A-phase-to-earth fault in reverse on adjacent feeder

The relevant impedance zone settings can be summarized as follows

Zone 1

Reactive reach X1 = 6.95 Ω

Resistive reach R1 = 27.89 Ω

1.1.2 Example 2 on 400 kV: Hydra – Perseus line

An A-to-B-phase busbar fault developed, following a B-phase-to-earth busbar fault, which occurred at Perseus substation. This resulted in an overreach trip of the B-phase-to-earth underreaching element at the Hydra end of the overhead line. This is

a mid-compensated line with total compensation of 52.76%. The series capacitor is protected against overvoltage damage with a Metal Oxide Varistor (MOV) device.

Thorough checking of all related parameters and relay settings did not reveal the cause of the Hydra-Perseus feeder protection underreaching zone operation. The relay settings had been done in accordance with manufacturer's guidelines for series compensated lines. This line has an overall length of 283 km with primary impedance of 89.98 Ω. Figure 1.2 shows that the relay overreached the remote station busbar during the fault condition.
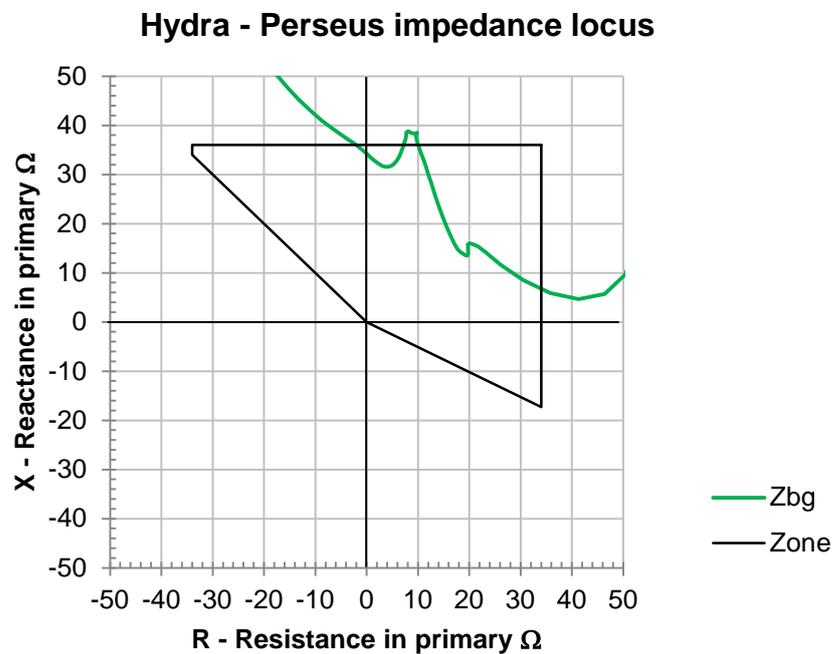

Figure 1.2: Red-to-B-phase fault at the remote busbar

The relevant impedance zone settings can be summarized as

Zone 1
Reactive reach X1 = 34 Ω
Resistive reach R1 = 36 Ω

1.1.3   Example 3 on 400 kV: Athene – Invubu line

A busbar fault that occurred at the remote end station (as seen in the forward direction from the relaying position), resulted in an overreach trip of the phase-to-earth underreaching element. Verification of all related parameters and relay settings did not reveal the cause. (All references to remote end used in this dissertation refers to the remote end station as seen in the forward direction from the relaying position).

The relay settings had been done in accordance with manufacturer's guidelines for non-series compensated lines. The line length is 21.84 km with primary impedance of 7.04 Ω. Figure 1.3 shows that the relay did overreach the remote station busbar during the fault condition.
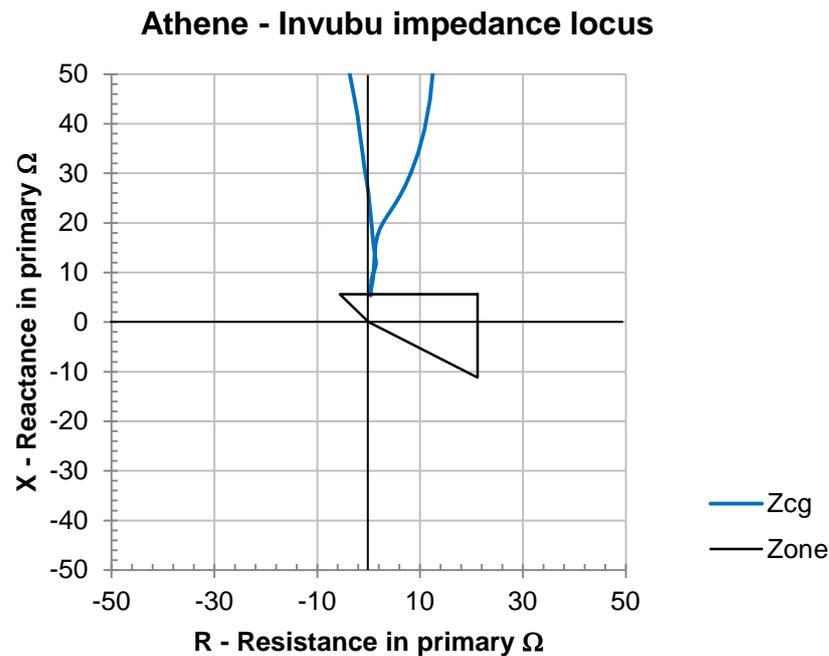

Figure 1.3: C-phase-to-earth fault on remote busbar

The relevant impedance zone settings can be summarized as

Zone 1

Reactive reach X1 = 5.60 Ω

Resistive reach R1 = 21.2 Ω

1.1.4 Example 4 on 88 kV (Relay measurement on 275 kV): Etna – Taunus line

An A-phase-to-earth reverse fault on one of the 88 kV feeders feeding from the medium voltage of the substation transformers occurred. The protection relay on the 275 kV feeder had measured the impedance locus on the healthy C-phase to be in the forward direction of the underreaching elements, resulting in an incorrect operation. This fault is similar to the one shown in example one with the only difference being that the fault occurred on a different voltage level. The line length is 18.56 km with primary impedance of 4.46 Ω. Figure 1.4 shows the C-phase entering the forward reaching characteristic for the A-phase reverse fault.
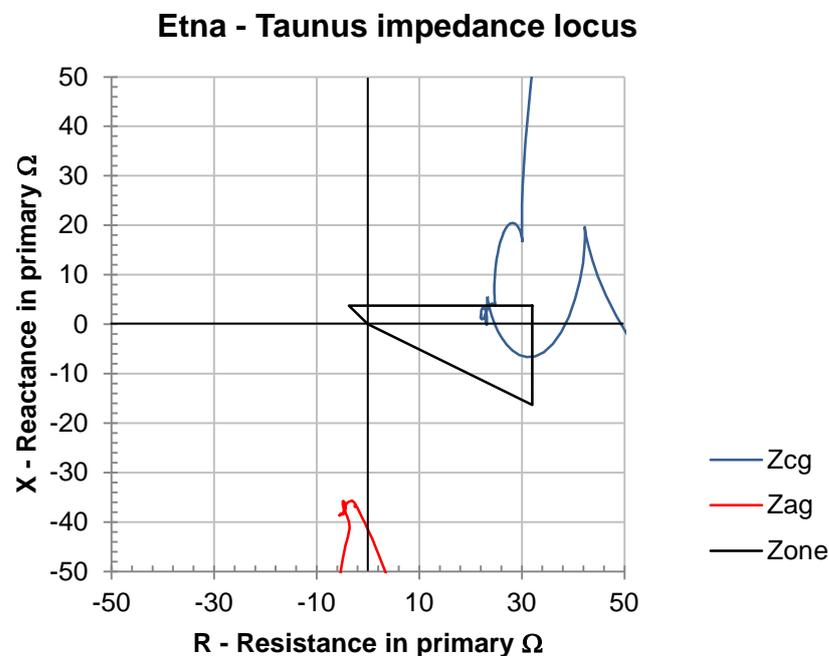

Figure 1.4: Reverse A-phase-to-earth fault on 88 kV network.

The relevant impedance zone settings can be summarized as

Zone 1

Reactive reach X1 = 3.75 Ω

Resistive reach R1 = 32 Ω

It is evident from these examples that the feeder impedance protection relays have mal-operated for different reasons in each case. These faults and the possible causes of relay maloperation will be evaluated and discussed in detail in the chapters to follow.

A holistic analysis approach will be followed. This will include

- Literature study covering fault conditions analysis, parallel connected sources, equal source voltages, superpositioning, Thevenin's theory and the calculation of line impedance,
- Numerical relay algorithms and algorithm result comparisson,
- Numerical relay operational analysis during fault conditions,
- Numerical relay analysis with the use of secondary injection test methods

The intent is to give the reader the opportunity to understand the complexity of overhead line impedance, numerical relay technology and appreciate the extent of this research, which was necessary to produce this dissertation.

1.2 Purpose of study

The purpose of this study is aimed at providing answers to the issues described above through enhanced knowledge of protection relay settings, the impact of line impedance and a thorough understanding of numerical relay operation. Solutions to these issues will contribute to increased protection relay reliability, which in turn will have a positive impact on system dependability. Improved system dependability will result in less power interruptions and therefore a more reliable system. Although the study will focus on single-phase-to-earth faults, due to their common occurrence in relationship to other combinations of faults, some attention will be given to phase-to-phase and phase-to-phase-to-earth faults.

It should be stated however, that although protection maloperations could lead to power interruptions, this is avoided in some cases due to different routes of supply. Some power interruptions have a serious economic impact, which not only effect Eskom and its direct customers, but also the economy of the country as a whole. It

follows therefore that should this research result in improved protection relay performance, a more reliable power network will be achieved, which in turn will benefit all role-players.

1.3   Issues to be addressed

The output of the research will provide answers related to protection relays that could benefit Eskom and other users of these relays in the industry. The following issues will be addressed:

- Overreaching of the protection on
    - Short lines
    - Series compensated lines
- Operation for reverse faults by forward reaching elements through healthy phase measurement.
- Relay compatibility evaluation

1.4   Approach leading to solutions

In order to understand the perceived or possible causes of these relay maloperations it is imperative that a thorough literature study be done to gain insight into the elements involved in the relevant fault loops that are prevalent during the types of faults that will be discussed. The literature study to follow in Chapter 2 will cover the theory involved in the relevant overhead line measured fault loops and will focus on overhead line conductor impedance calculations. An overview of the various elements involved in the calculation of the overhead line impedances, such as skin effect, skin depth, current density, etc. are discussed. Chapter 2 provides the reader with an introduction into the relay impedance measuring loops relevant for discussion in later chapters. Chapter 3 will introduce the reader to the theory and measurement algorithms involved with two of the numerical type impedance measurement relays in use on the Eskom Transmission system.

This chapter will also cover aspects of directional determination, series compensation, tripping characteristics, impact of fault resistance and load. The importance of Chapter 3 lies in the full understanding of the different relay measurement algorithms, the impact that external factors such as load has and the way in which the final measuring characteristics are presented.

Chapter 4 introduces the reader to a comparison between the two relays algorithms for faults within radial and complex networks and highlights the similarities and differences obtained through tabular and graphical representations. Armed with this understanding the following chapter, Chapter 5, then focus on the actual faults which occurred on the Eskom transmission system. Chapter 5 also highlights the investigations that followed, the results that subsequent to this research became apparent and the relay setting recommendations made aimed at ensuring correct operation of these relays during these system faults.

Chapter 6 is introduced to validate the two relays responses with the use of standard non-intrusive secondary injection test methods. These methods allow the engineer to inject three-phase voltages and currents into the relays under laboratory conditions and facilitate injection termination upon relay operation, thus ensuring no damage to the relays. The results obtained through these methods are electronically recorded and graphically displayed for further evaluation and future reference purposes. The impact of single-phase-to-earth faults are evaluated during different simulated system conditions. The results obtained from evaluating the impact of healthy phase current on relay measurements during remote breaker open conditions are compared with those obtained with the use of the so-called "Classic Method", where no current is injected on the healthy phases. The impact of load current on relay measurements is also evaluated during import and export load conditions.

Chapter 7 brings us to the final chapter where some conclusions are documented and recommendations for improved performance are made.