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ANALYSIS OF THE RELIABILITY FOR THE 132/66/22 kV DISTRIBUTION NETWORK WITHIN ESKOM's EASTERN CAPE OPERATING UNIT

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DISSERTATION

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DECLARATION

I, Athini Pantshwa, declare that the contents of this dissertation represent my own unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Nelson Mandela Metropolitan University (NMMU).

Signature:…………………………………..

Student Number:……………………………

ABSTRACT

A stable and reliable electrical power supply system is an inevitable pre-requisite for the technological and economic growth of any nation. Due to this, utilities must strive and ensure that the customer’s reliability requirements are met and that the regulators requirements are satisfied at the lowest possible cost. It is known fact around the world that 90% of the customer service interruptions are caused due to failure in distribution system. Therefore, it is worth considering reliability assessments as it provides an opportunity to incorporate the cost or losses incurred by the utilities customer as a result of power failure. This must be considered in the planning and operating practices.

The system modelling and simulation study is carried out on one of the district’s distribution system which consists of 132 kV, 66 kV and 22 kV network in Aliwal North Sector ECOU. The reliability assessment is done on the 22, 66 and 132 kV system to assess the performance of the present system and also predictive reliability analysis for the future system considering load growth and system expansion. The alternative which gives low SAIDI, SAIFI and minimum breakeven costs is being assessed and considered. The reliability of 132 kV system could be further improved by constructing a new 132 kV line from a different source of supply and connecting with line coming from another district (reserve) at reasonable break even cost. The decision base could be further improved by having Aliwal North Sector context interruption cost. However, the historical data which may be used in Aliwal North Sector to acquire interruption costs from the customers are being proposed.

The focus should be on improving the power quality on constrained networks first, then the reliability. Therefore for the Aliwal North power system network it is imperative that Eskom invest on the reliability of this network. This dissertation also analysed load reflected economic benefit versus performance expectations that should be optimized through achieving a balance between network performance (SAIDI) improvement, and total life cycle cost (to Eskom as well as the economy).

Reliability analysis conducted in this dissertation used Aliwal North power system network as a case study; the results proved that the system is vulnerable to faults, planned and unplanned outages. Reliability evaluation studies were conducted on the system using DigSilent software in conjunction with FME. These two models gave accurate results with acceptable variance in most indices except for the ENS where the variance was quite significant. It can be concluded that DigSilent results are the most accurate results in all three reliability evaluation scenarios for the Aliwal North Power System, best interpretation being that of DigSilent.

LIST OF ACRONYMS

AC	**Alternating Current**
ACSR	**Aluminium Conductor Steel Reinforced**
ANS	**Aliwal North Sector**
ASAI	**Average Service Availability Index**
ASUI	**Average Service Unavailability Index**
CAIDI	**Customer Average Interruption Duration Index**
CB	**Capacitor Bank**
CB	**Circuit Breaker**
COUE	**Cost of Unserved Energy**
DC	**Direct Current**
DMS	**Distribution Management System**
DPF	**DigSilent PowerFactory**
DSLI	**Distribution Supply Loss Index**
ECOU	**Eastern Cape Operating Unit**
ENS	**Energy Not Served**
ESKOM	**Electricity Supply Commission**
FMEA	**Failure Mode and Effect Analysis**
HL	**Hierarchical Level**
HMI	**Human Machine Interface**
IED	**Intelligent Electronic Device**

kV	**Kilo Volts**
MV	**Medium Voltage**
NERSA	**National Energy Regulator of South Africa**
NDP	**Network Development Plan**
NMMU	**Nelson Mandela Metropolitan University**
NRS	**National Regulator Standards**
OLTC	**On-Load Tap Changer**
PCC	**Point of Common Coupling**
pP	**powerPerfector**
QA	**Quality Assurance**
QOS	**Quality of Supply**
ROM	**Read Only Memory**
RSLI	**Retic (MV) Supply Loss Index**
SAIDI	**System Average Interruption Duration Index**
SAIFI	**System Average Interruption Frequency Index**
SCADA	**Supervisory Control and Data Acquisition**
THD	**Total Harmonics Distortion**
TRFR	**Transformer**
UDW	**Utility Data Warehouse**
VR	**Voltage Regulator**
VT	**Voltage Transformer**

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CHAPTER 1: RESEARCH PROPOSAL

1.1 Introduction

The term reliability constitutes a very broad meaning. In the engineering field, the term reliability means the capability of a system to perform its dedicated function, whereby the historical data assist to perform estimations of the future performance for that system. Electricity has been the basic need for economic institutions of the world and it furnishes day-to-day necessity for the growing population in the world. Due to the nature of electricity technology systems, the power demand at every specific moment needs to be met by consistent electricity supply to make sure of the continuous availability of the resources [8].

However, reliability of service has always been of primary importance to electric utility systems and there are many publications which describe various levels of activity and application. Hierarchically, power systems comprise three distinct parts: Generation, Transmission and Distribution. Power systems have evolved over decades with the primary emphasis of providing a reliable and economic supply of electrical energy to their customers [1]. Customer satisfaction with their electricity supply is an important issue in the new regulatory environment faced by electric power utilities and reliability has always been a major concern with electric power companies and with their associated agencies [1]. Spare or redundant capacities in generation and network facilities have been inbuilt in order to ensure adequate and acceptable continuity of supply in the event of failures and forced outages of plant, and the removal of facilities for regular scheduled maintenance.
Moreover, electrical distribution systems reliability analysis was considered as a tool for the planning engineers to ensure quality of service that is reasonable and to trade-off between different system expansion plans and cost of losses. When applied to a power network, reliability can be subdivided into the two basic aspects. This includes system security and adequacy. System adequacy relates to the system capacity in relation to energy demanded and system security relates to the dynamic response of the system to various disturbances such as faults [1].

1.2 Research Statement

In the planning phase of the power system network, reliability aspects are an important part of the decision making and processes. To be able to assess and simulate, reliability analysis is needed in the planning process. It has been found that after planning decisions has been made, Aliwal North Sector (ANS) power system network would still be inadequate for operations and maintenance requirements, due to the fact that there are no other alternative sources of supply for faults, planned and unplanned outages on the Dreunberg-Melkspruit 132 kV line. This line is responsible for the supply five substations. This further affects the reliability indices of the distribution network in the area.

1.3 Sub-problems

1.3.1 Sub-Problem 1

Power System reliability improvement may further expand to other network challenges such as power system load flow. If the network apparatus such as busbars, conductors and transformer are not operating at nominal values it may have a impact on life cycle and performance of the apparatus and that of the network.

1.3.2 Sub-Problem 2

The inability of the system to respond to sudden network disturbances such as electrical and non-electrical faults that could results in damages in the utility's power system equipment conductors, breakers, power transformers, voltage regulators etc. and in turn damaging customer appliances.

1.3.3 Sub-Problem 3

Power quality is one of the important components that are embedded within reliability study; customers may experience quality of supply problems such as voltage flickers, voltage swells, voltage regulation, voltage dips, voltage unbalance and total harmonic distortion. These challenges might be current, during commissioning and after reliability improvement is completed.

1.4 Research Objectives

- To analyse fault statistical data for the Aliwal North distribution network.
- To use the Aliwal North 132/66/22 kV network as a case study to evaluate system reliability.
- To develop an approach that will analyse the reliability indices.
- To apply reliability power system evaluation tools (DigSilent).
- To conduct load flow studies.
- To analyse the power quality issues on the Aliwal North network.
- To analyse the protection coordination on the Aliwal North network
- To quantify the benefit to cost analysis of improving the reliability of the system.
- Compare the results before and after reliability improvement.
- To select the best solution for the reliability improvement on the Aliwal North Network that meets all requirements.

1.5 Alternative Solutions

1.5.1 Solution 1

According to Eskom Eastern Cape Operating Unit Network Planning Engineer, the proposed solution as per the network development plan (NDP) for the Aliwal North Sector is to add 132 kV Riebeek feeder bay at Melkspruit Substation and strengthen Riebeek 66/22 kV Substation to 132/66/22 kV. This means building a new Melkspruit-Riebeek 132 kV line. See the area highlighted green in figure 1 below, shows the proposed developments in the network.

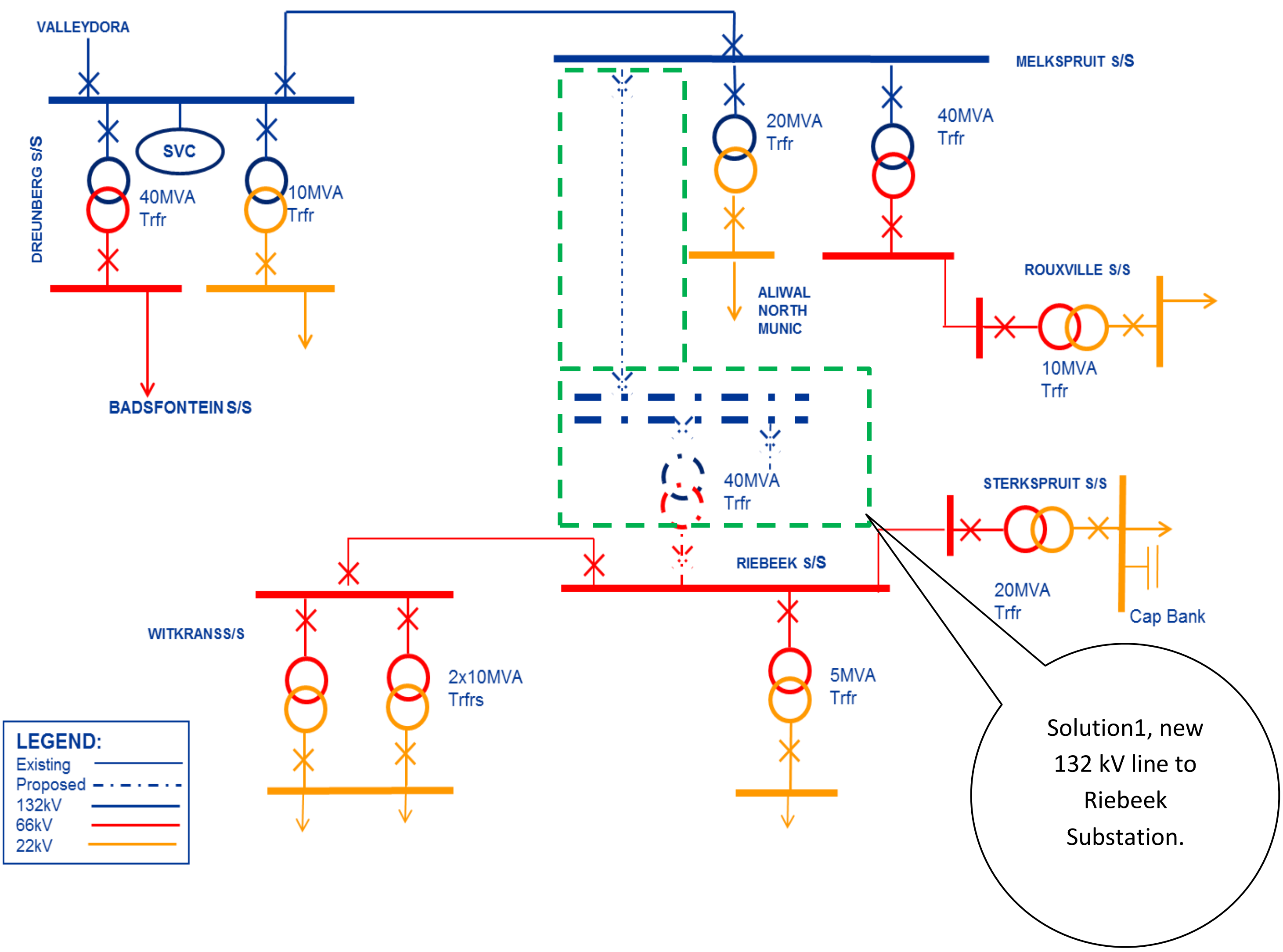


Figure 1: Proposed solution from ECOU planning department

1.5.2 Solution 2

To apply operational solution, by running the existing 132 kV line at 66 kV when a fault occurs in the busbar at Melkspruit Substation. So that power can be restored in other customers. Proposed solution is shown in dashed line, See figure 2 this kind of solution is operational and does not provide full solution but can minimise the impact of customers affected during a fault.

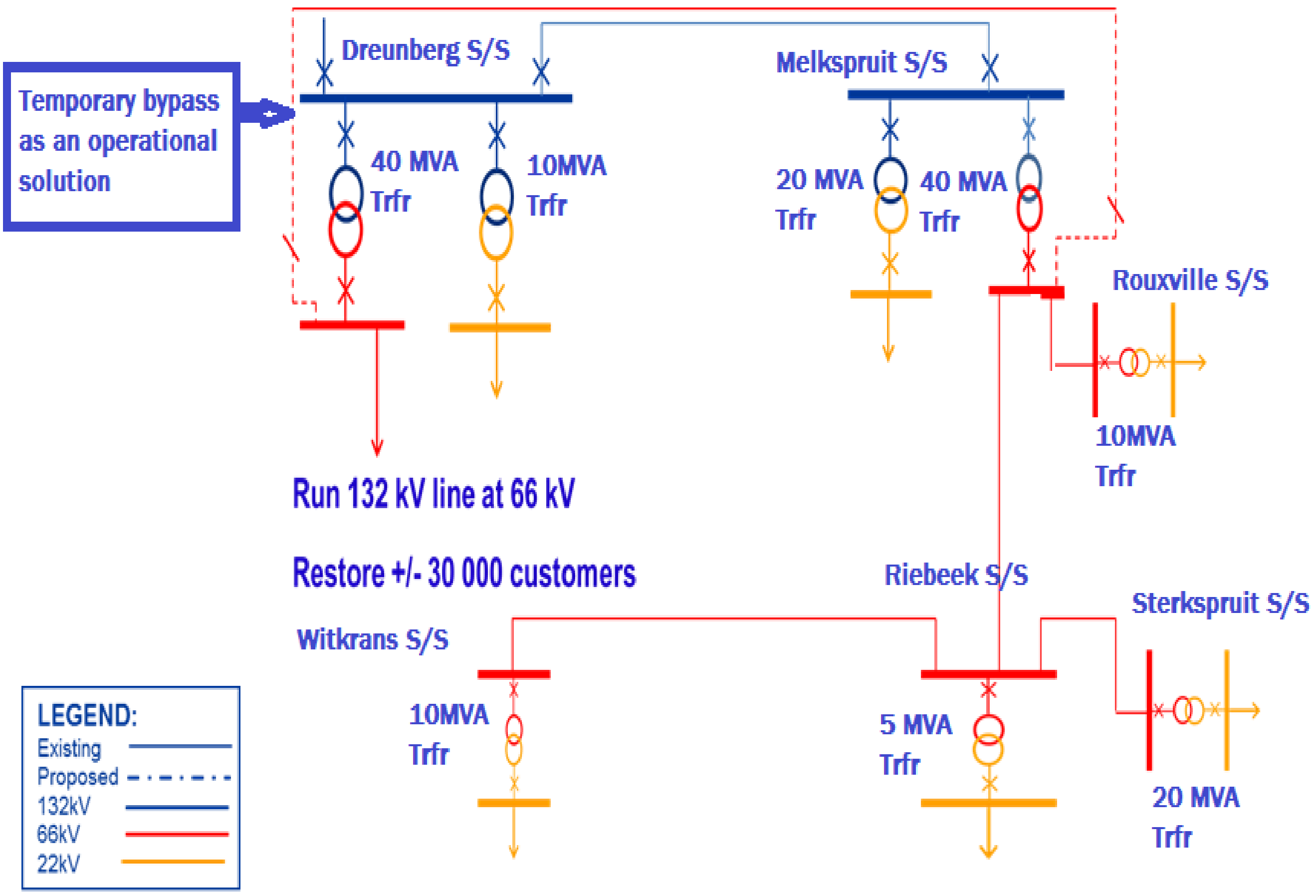


Figure 2: Operational Solution run 132 kV at 66 kV

1.5.3 Solution 3

To carry out a predictive reliability analysis and compute its indices by using present fault rates and durations of outages on the 132/66/22 kV Aliwal North Sector Network and thus propose new 132 kV line from a different source of supply, making use of the already started construction of the 132 kV line of Melkspruit-Riebeek 132 kV line. This alternative will require a comprehensive analysis on the benefit to cost and cost of unserved energy (COUE). Thus thereafter draw up a conclusion on which solution is the best. See figure 3 below the proposed 132 kV line will be assembled from Elliot Substation which is 132/66 kV substation. This configuration will formulate the ring that will make ECOU power system distribution network to be firm and less vulnerable from reoccurring faults. This will also improve maintenance schedule with the outages that will affect customers. Area highlighted in green shows the alternative source of supply from Elliot Substation.

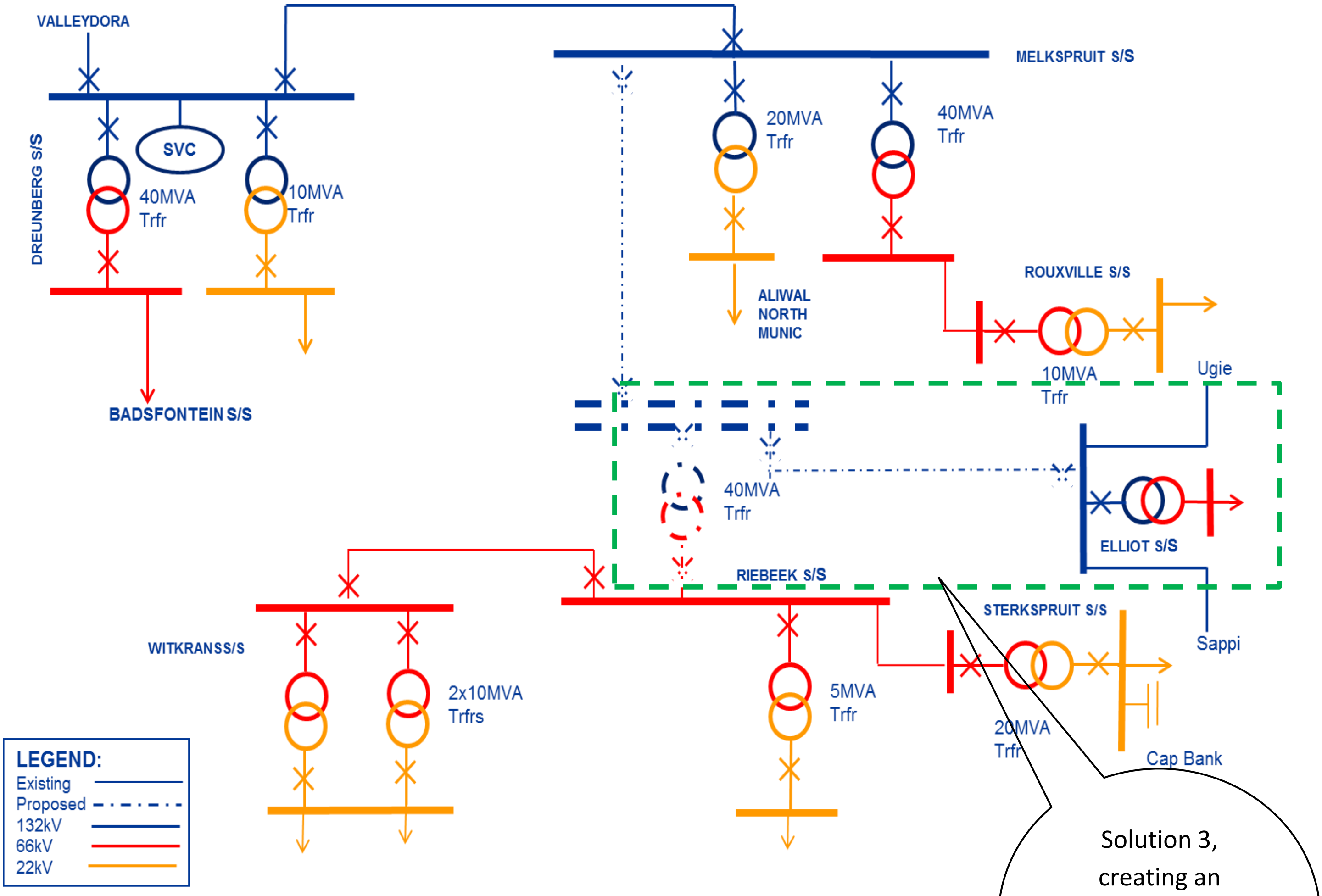


Figure 3: Introduction of alternative source of supply for reliability improvement

1.6 Hypothesis

Customer satisfaction in terms of electricity supply is an important issue in the new regulated environment faced with electric power utilities. The distribution system load flow analysis, reliability assessment, value based reliability planning are carried out in order to optimise the reliability of the network and to minimise customer interruption. Further comparison will be carried out between the simulation and analytical technique. At the moment most of the probability techniques available for reliability evaluation are in the area of adequacy assessment because the ability to assess the security is very limited.

1.7 Delimitation of the Research

This research project will focus on the evaluation of DigSilent and utilised within it the embedded reliability assessment module. The case study will be sculpted within DigSilent and the results will be compared against failure mode and effect Analysis (FMEA) to determine the load and system indices. The real case study will be utilised to find out whether the load and system indices are compared against the evaluation techniques (DigSilent and FMEA).

1.8 Research outline

Figure 4 shows the outline of the dissertation.

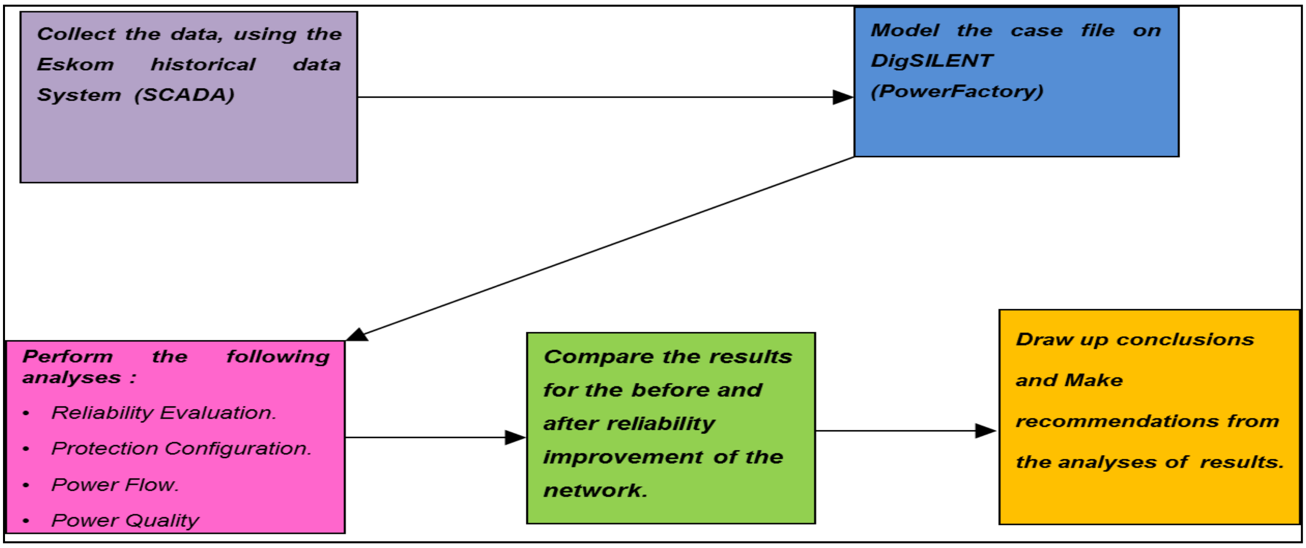


Figure 4: Research outline

1.9 Assumptions

It must be assumed that the DigSilent and Retic Master simulation tools that will be used to conduct the analysis for this project are the best simulation tools that can be used to perform these studies based on the fact that the both case files are scaled using data from SCADA system. It must also be assumed that the FMEA excel spreadsheet is best approach used to compare the results with those obtained using DigSilent. The case study used must also be assumed to be the best for this evaluation.

1.10 Significance of the Research

The outcome of the project will assist in determining the degree to which the electric power systems meet the customer load requirements and many uncertainties that exist in the real world. The study will enlighten the short term planning required for the utility in order to address operational related network constrains. To achieve a reliable network scheme that reduces the number of frequently occurring faults, improves the continuity of supply and customer satisfaction. This study applies reliability analysis after the strengthening of Eskom Aliwal North Sector power system network to help answer questions such as:

- Is the system reliable enough;
- Which scheme is more reliable and fails less and;
- Where can the next rand be spent in order to improve the reliability for distribution network?

1.11 Methodology used to Approach Research

- Perform literature review on reliability evaluation of Distribution networks.
- Evaluate the effects of the strengthening already done in Aliwal North Sector distribution network.
- Use PowerFactory to quantify the reliability of operational and maintenance activities.
- Evaluate the impact of new protection system on the reliability.
- Motivate benefit to cost analyses for reliability improvement programme.
- Draw conclusions and make recommendations from the literature review and results obtained

1.12 Dissertation Outline

The dissertation is divided into 6 Chapters:

Chapter 2 is a literature review of what is known about the topic, its significance and the need for research to be conducted in this field.

Chapter 3 is the data collection from various sources including Scada system from Eskom ECOU, outages, fault statistics, power quality issues.

Chapter 4 is the analysis of results obtained from various case studies conducted and findings are made.

Chapter 5 Conclusions on the power system reliability analysis of the Aliwal North Sector Eastern Cape Operating Unit have been made.

Chapter 6 recommendations on the main contribution of the thesis are made and directions for future research are offered.

1.13 summary

This chapter began with an introduction to power systems reliability as it causes electricity inconvenience. The problem statement together with sub-problems and alternative solutions were reviewed and were briefly explained as to how they bring about solution to the thesis. The shortcomings were pointed out leading to the formulation of the objective for this investigation. The layout of how the dissertation is organised is also included in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

A power system is designed in such a way that it is capable of supplying customers with electrical energy at an economically reasonable degree of continuity and quality of supply, taking into account the load growth [1]. What constitutes a 'reasonable' level can be examined in terms of the costs and the worth to the consumer of providing an adequate supply. Nowadays, modern society expectance has come to a stage that electrical energy supply should be continuously available on demand. This is sometimes not possible due to a wide range of events, which are generally outside the control of electrical power system regulations [2].

Customer satisfaction in terms of electricity supply is an important issue in the new regulated environment faced by electric power utilities. Reliability has been and still is a major concern with electric power companies and their associated regulatory agencies. This has increased the need to carefully monitor the current levels of customer service reliability and the provision of consistent and comprehensive frame work upon which customer service reliability should be measured in the future.

The term "Reliability" constitutes a very wide range of meanings and cannot be associated with a particular specific definition. It is necessary to recognize its generality as well as to use the term to indicate, in a general manner rather than a specific sense. Therefore reliability can be termed as a probability of a piece of equipment or system performing its purpose effectively for the period of time intended under the operating conditions encountered. Moreover, systems reliability can be improved by reducing the frequency of occurrence of faults and by reducing the repair time or down time of equipment or systems [3].

2.2 Reliability Evaluation

2.2.1 The term reliability

The significance of reliability analysis is to help the utility sector to answer questions like "Is the power system reliable enough?" "Which part of the system fails less?" and "Can the next rand be spent in order to improve the system?" Reliability in power systems can be divided into two basic facets; system adequacy and system security [1]. Adequacy relates to power system ability to generate sufficient electrical energy and transport it to the consumer. Security on the other side relates to the response of the power system to any disturbances.

2.2.2 Reliability Indices

Thorough reliability evaluation of the power system can be divided into two basic segments; measuring of the past performance and predicting the future performance following are the basic indices that have used to assess the past performance [2] [3]:

- System Average Interruption Duration Index (SAIDI) indicates the average duration of a sustained interruption the customer would experience per year.

$$SAIDI = \frac{sum\ of\ duration\ of\ all\ customer\ \ interruptions}{total\ customers\ in\ the\ system} = \frac{\Sigma\, U_i\, N_i}{\Sigma\, N_i}$$

- System Average Interruption Frequency Index (SAIFI) indicates how often on average (frequency) the customer connected would experience a sustained interruption per annum.

$$SAIFI = \frac{total\ number\ of\ customers\ interuptions}{total\ number\ of\ customers\ served} = \frac{\Sigma \lambda_i N_i}{\Sigma N_i}$$

- Customer Average Interruption Duration Index (CAIDI) indicates the average duration of a sustained interruption that the only customer affected would experience per year.

$$CAIDI = \frac{sum\ of\ durations\ of\ customer\ \ interruptions}{total\ number\ of\ customers\ interruptions} = \frac{\Sigma\, U_i\, N_i}{\Sigma\, \lambda_i\, N_i}$$

- The Average Service Availability Index {Unavailable} (ASAI/ASUI) represents the fraction of time (often expressed as a percentage) that a customer has received supply during one year.

$$ASAI = \frac{Customer\ hours\ of\ available\ service}{Customers\ hours\ demanded} = \frac{\Sigma \mathrm{N_i} \times 8760\ - \Sigma\ U_i\, N_i}{\Sigma\, N_i\ \times 8760}$$

$$ASUI = 1 - ASAI = \frac{Customer\ hours\ of\ available\ service}{Customers\ hours\ demanded}$$

- Energy Not Supplied (ENS);

$$ENS = total\ energy\ not\ supplied\ by\ the\ system = \Sigma L_{a(i)}\, U_i$$

- The Retic Supply Loss Index is the measure of the MV supply unavailability (MV/LV transformers and bulk loads) caused by sustained interruptions.

$$RSLI = \frac{\Sigma\ MVA.Hours.Lost\ per\ month}{Installed\ MV\ MVA\ transformer\ base + Bulk\ Load\ MVA\ base}$$

- The Distribution Supply Loss Index (DSLI) of a network is the measure of the HV Supply unavailability (HV/MV transformers and bulk loads) caused by sustained interruptions.

$$DSLI = \frac{\Sigma\ MVA.Hours.Lost\ per\ month}{Installed\ HV\ Transformer\ MVA\ base + Bulk\ Load\ MVA\ base}$$

Past performance statistics provide valuable reliability profile of the existing system. However, power system planning entails the analysis of the future systems and evaluation of system reliability when there are changes in; configuration, operation condition or in protection schemes [4]. This provides necessary support in estimating the future performance of the system based on the power system topology and historical data of the component failure rate. Due to stochastic nature of failure occurrence and outage duration, it is generally based on probabilistic models. The basic indices associated with system load are; failure rate, average outage duration and annual availability [5].

SAIDI indicates the total duration of interruptions an average customer is exposed to for a predefined period; whereas SAIFI signifies how often an average customer is subjected to sustained interruptions over a predefined time interval.

CAIDI indicates the average time required to restore the services. ASAI specifies the fraction of that a customer has received the power during the predetermined interval of time whereas ASUI indicates the exact opposite of ASAI. ENS specifies the average energy the customer has not received in the predefined period of time. Reliability indices form an integral part of this study, as these indices are used to measure power system network performance [5].

2.2.3 Reliability Cost and Worth

The concept of reliability is described as an inherent characteristic and specific measure that describes the ability of any system to perform its intended function. The primary technical function of a power system is to supply electrical energy to its end customers. This has always been a significant system issue and power system personnel have always strive to ensure that customers receive adequate and secure supplies within reasonable economic constraints[6]. The system adequacy basically means the availability of enough generation, transmission and distribution capacities to meet the customer demands. While on the hand system security is considered as the ability of the system to respond to disturbances arising within the system. Therefore, adequacy assessment represents that static condition, whereas the security assessment pertains to the dynamic conditions of the power system [6].

Utilities, in a venture to supply power at an economic price with an adequate level of reliability, often faces challenges to balance the high level of reliability at relatively low cost, since these two aspects encounters each other. Direct evaluation of reliability worth is a difficult task, therefore, a practical alternative, which is being widely used to evaluate the impacts and monetary losses incurred by customers due to power failures. When customers experience an interruption, there is an amount of money that a customer is willing to pay to avoid the interruption and this amount is referred to as the customer cost of reliability [7]. These costs include both tangible and intangible cost and also the opportunity cost for reliability improvement as well as the customer cost for poor reliability. Therefore, the optimal level of reliability is said to be achieved when the sum of utility cost and customer cost is at minimum [8].

The basic concept of reliability cost and worth evaluation is relatively simple and is summarised in figure 5 this same thought can also be presented by the cost vs reliability curves of figure 6.

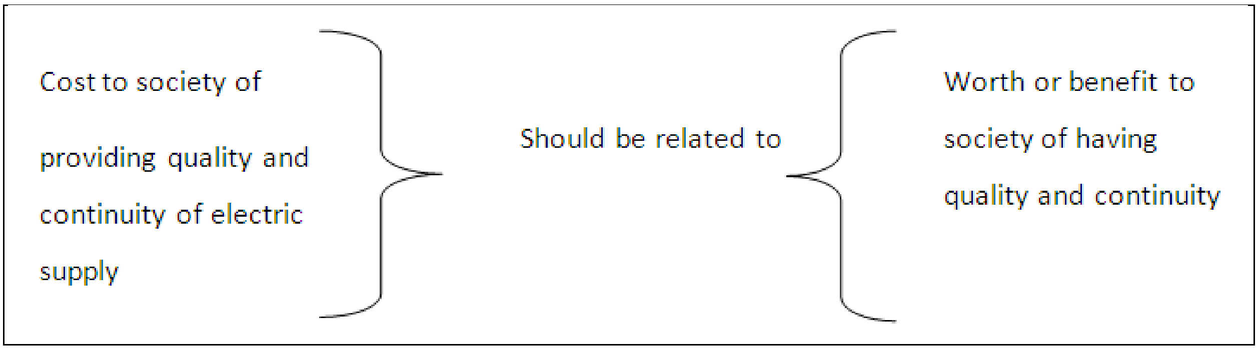


Figure 5: Reliability cost and Reliability worth relationship [9]

As depicted in figure 6, the investment cost increases with higher reliability, whereas on the other hand the customer costs associated with failures decrease as the reliability increases. The total costs can be found by adding the two individual costs. This total cost exhibits a minimum, and so an optimum or target level of the reliability is achieved.

- Calculated indices are usually derived only from adequacy assessments at various hierarchical levels.
- There are enormous problems in assessing consumer perceptions of outage costs.

In Figure 6 [10] the total costs are defined as the sum of initial capital investment plus operating and maintenance cost and the customer cost for the interruption. This enables the reliability benefits to be traded off against the costs. During network development planning (NDP), selecting the preferred alternative is based on quantitative and qualitative analysis to ensure that reliability level is not too high or low.

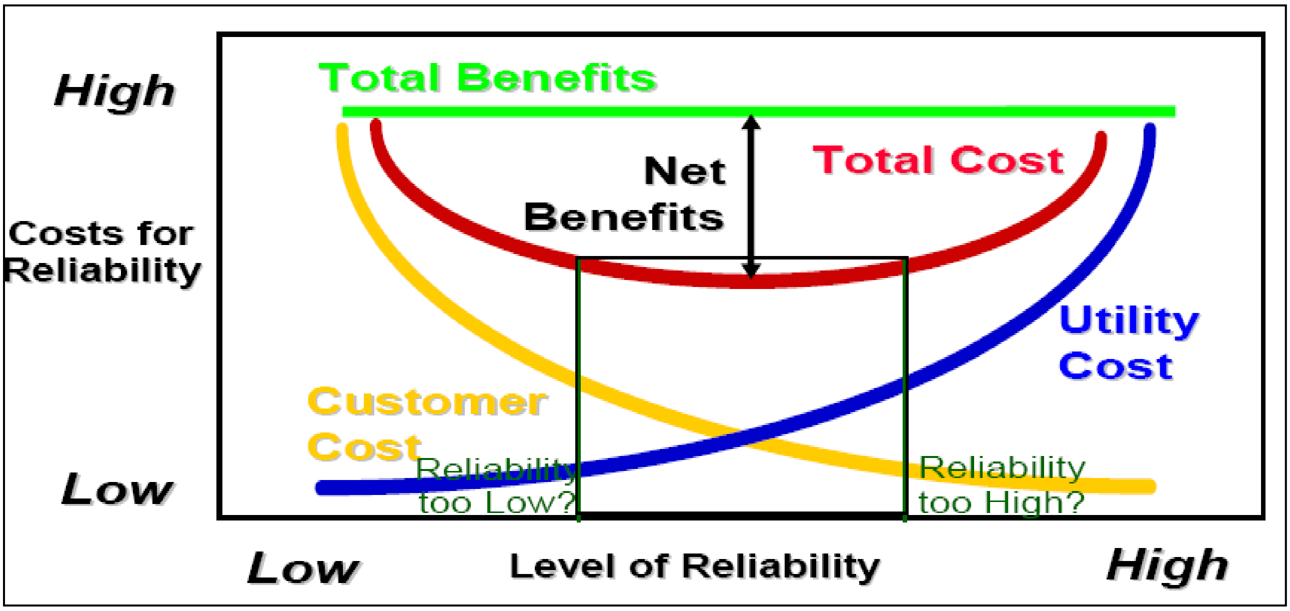


Figure 6: Total reliability cost [10]

2.2.4 The effect of reliability evaluation in the study

Power system reliability evaluation has become the most important aspect of power utilities around the world as it is a measure of the system performance under normal and abnormal conditions. It has the influence on the selection of the preferred alternative. However, it is a tool for decision making when comparing the alternatives.

Power system reliability evaluation is divided into two categories that is system adequacy and system security.

- System adequacy relates to the existence of sufficient facilities within the system to satisfy the customer demand.
- System security relates to the ability of the system to respond to disturbances arising within the system.

Reliability indices such as SAIDI, SAIFI, CAIDI, RSLI, CAIFI and ASI/ASUI form a significant part of the system as they provide information about the network performance by measuring the rate of interruptions that the customers experience.

Most of all, the benefit to cost analysis indicates that the best alternative is based on the initial capital outlay and benefit achieved with the configuration alternatives.

2.3 TYPES OF OUTAGES

Outages taking place on the electrical networks are the main cause of power system failure states. The first point of departure in power system reliability evaluation is to establish what component outage type are to be included into risk assessment work. Component outages are generally categorised as dependent and independent outages, the former is classified as outages that depends on the occurrence of one or more other outages and poses treat in system reliability whilst the latter refers outages occurring randomly on the power system equipment, out of anyone's control.

2.3.1 Independent Outages

- ***Forced outages***

Forced outages, are classified as the type of outages that are occurring randomly on the power system equipment, out of anyone's control. The state of power system equipment is frequently represented with a simple two state model (up or down). The majority of forced type outages in a power system are repairable outages, with each outage associated with a repair time of the outage equipment. Independent forced outages are the events included in the contingency evaluation for most reliability evaluation techniques [12].

- ***Station outages***

Station outages, are determined as outages caused by the failure of any substation component or apparatus, such Current Transformers, cables, circuit breaker, bus-bars and or transformers. In the previous researches it has been found that station originated outages are not included in most composite system reliability studies. However, any failure occurring within the substation range can contribute significantly to unreliability of bulk load points in the composite system [13].

- ***Aging Outages***

In terms of power system equipment both transmission and distribution system, it is quite obvious that the probability of equipment malfunctions increases with age. This popular philosophy is commonly known as an aging effect of equipment.. Finally in the old equipment or components, the failure rate starts to increase exponentially until that particular component fails [14].

2.3.2 Dependent Outages

Just like independent outages, dependent outages also have a significant impact on the power system reliability [15-16]. According to the historical data, major blackouts and outages have been associated with dependent failure events [18].

- ***Common-Mode outage***

Common-mode outage is described as an outage that affects multiple of pieces of power system equipment at the same time due to a common cause. A typical example of a common-mode outage is an environmental condition, [12] such as lightning striking on transmission line tower, resulting in several other power lines connected to that tower to fail simultaneously. Common-mode outages could have a strong impact on the power system reliability [15].

- ***Component Group outage***

Component group outage is characterised as the failure of any piece of equipment in a group of components resulting to the simultaneous outage of all other components in that group. The difference between the component-group outages and common mode outages is that the components in the former have to suffer outages together, while the components in the latter can have individual outages [15]. A typical example of component-group outage is the failure of a piece of equipment in a power system fragment resulting to all other apparatus in that segment losing power, due to the operation of protection devices to isolate the failed component. Power system segment can be defined as a group of components bounded with the same set of protection devices [16]. Protection devices are important to the correct determination of reliability and system loading.

- ***Cascading outage***

Cascading outage is defined as an outage that occurs when the failure of a first component triggers the failure of a second component [17], and so on. A failure in one transmission line can lead to the overloading of the second transmission line. When the auto-protection mechanism cuts off the second transmission line, this may lead to more serious overloading problems on other lines and low voltage problems at some buses. Previous researches show that cascading effect has not been extensively included in traditional grid planning and operations [12]. However, previous vulnerability assessments for cascading outages and analysis studies together with control of major blackouts events demonstrate the importance of including cascading effects in the reliability analysis of power systems [17].

- ***Weather dependent outages***

Weather dependent outages reflect the phenomenon of the failure bunching effect. That is, the probability of component failure increases dramatically under adverse weather conditions. Unfavourable weather such as high temperature, high speed wind, lightning, ice conditions are not general of long duration, but their impact on the system reliability should not be ignore [14]. However, a vast number of past reliability evaluations only apply constant component failure rates, the value of which is based on historical outage statistics of the system.

2.3.3 The Influence of Outages in the Power System Reliability

Power system outages have a significant a significant impact on the power system reliability, due to the reason that the more the number outages experienced by the consumers whether are due to dependent or independent outages, they cause a major increase on the reliability indices. Hence, it is very important power utility industries are to plan and design the power system in such a way that it will reduce the number of lengthy durations of blackout power outages. However, outages contribute significantly on the risk of loss of supply during N-1 contingency configuration such that system wellbeing deteriorates at all load levels. Moreover, outages of the major components due to both the dependent and independent can also cause a complete isolation of load point from the power system. Following are the major components of outages and their relationship with power system reliability;

2.4 Power Quality

Power quality is one of the significant aspects of the utilities. The main function of an electrical power system network is to provide consumers with electrical energy as economically as possible and with acceptable degree of continuity and quality [18]. Power system is planned to meet specified criteria in an attempt to provide consistently high reliability for utility customers refer to power quality as an electric supply condition that causes malfunction of appliances or prevents their use. However, from the utility perspective a power quality is viewed as non-compliance with various standards such as RMS voltage or harmonics. Perfect power quality is regarded as a perfect sinusoidal with constant frequency and amplitude [19]. The power quality is affected when a voltage waveform is distorted by transient or harmonics. Customers are concerned about the power quality since it can reduce voltage levels up too zero. Power system reliability is primarily concerned with customer interruptions and is therefore a subject of power quality [40]. Power quality mostly affects end users which are represented as loads in figure 7 that represents a typical power system diagram.

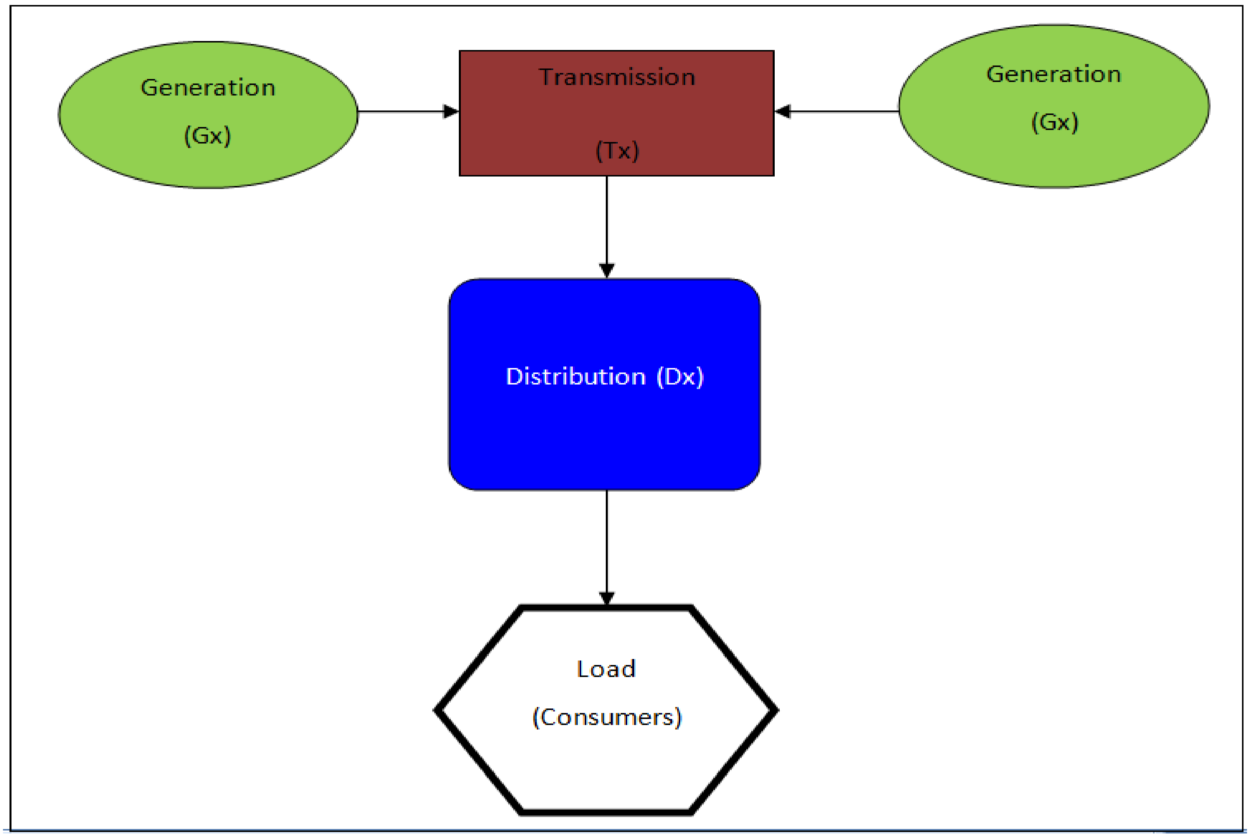


Figure 7: Typical Power System Diagram [20]

To obtain near perfect quality, a utility could spend large amount of money and accommodate equipment with higher power quality needs. On the other hand utility could spend little and oblige customers to compensate for the resulting power quality problems. Power quality concerns are becoming more frequent with the proliferation of sensitive electronic equipment and automated process [21]. Power quality problems are basically classified into many categories such as interruptions, swells, voltage dips, voltage regulation, flicker, harmonics distortions and frequency variations; figure 8 illustrates the hierarchy of power quality.

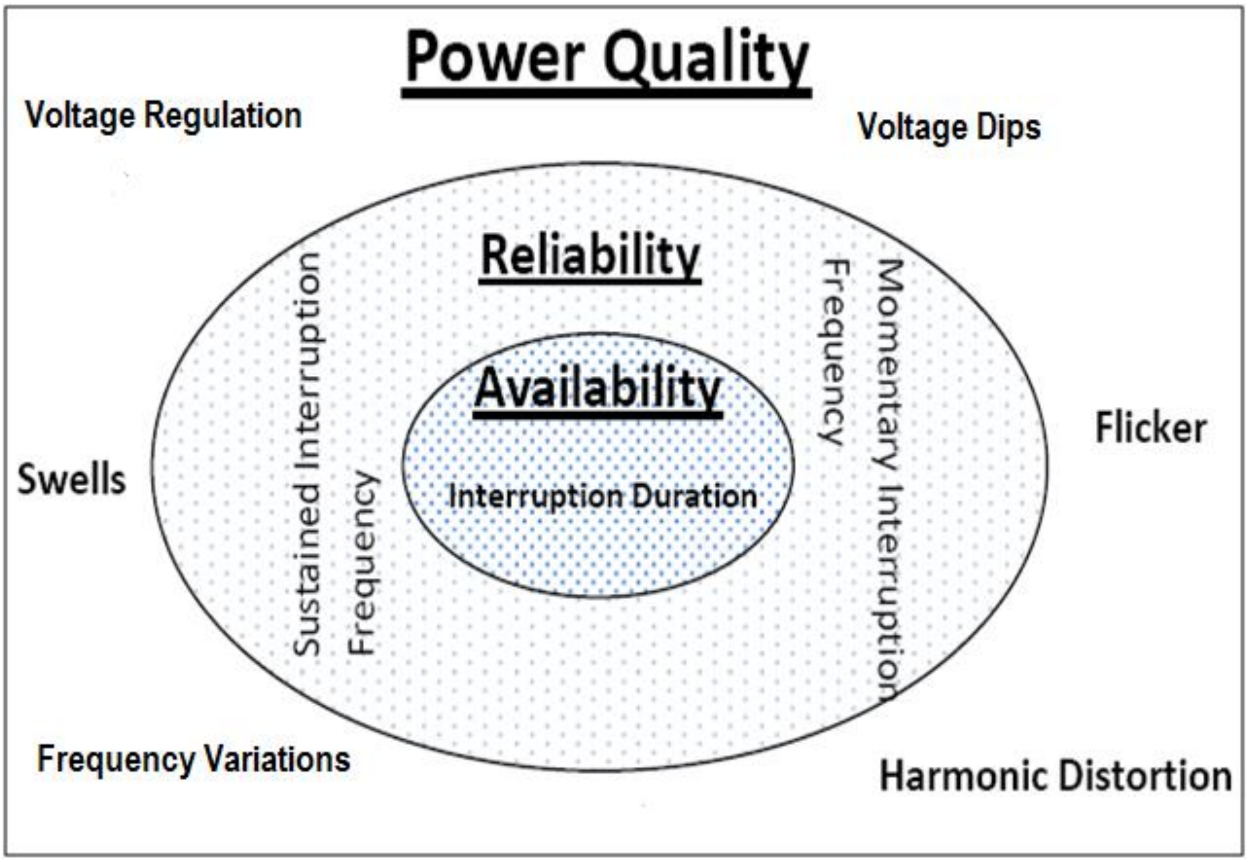


Figure 8: Reliability as a subset of power quality and availability as a subset of reliability [22]

Finally the process of supplying power to consumers embarks from large power stations to transmission system towards smaller units connected at lower voltage levels. Due to this power transportation procedure, power system cannot be regarded as one entity [23, 40], but as an electrical network with customers connected to it as loads, as illustrated in figure 8. This figure shows the responsibility carried out by power system, thus having to maintain a quality and continuity of supply under normal and abnormal conditions [24, 23].

2.4.1 Influence of power quality in the power system reliability

Power quality form an integral part on the power system reliability due to the increased number of sensitive electrical devices in the network such as capacitor banks, svc's and independent power producers (IPP). The configuration of the power system designs (long transmission lines) contribute severely on the power quality challenges, however, commissioning of new plant, animals, birds, adverse weather conditions, vegetation and poor maintenance also contribute in poor quality of supply.

As illustrated in figure 8 following are the main characteristics of power quality;

- Swells

Voltage swells has in impact of on the power system operations as they are linked to the system faults, although they are not common as compared to the voltage dips.

- Flicker

Voltage flickering is actual take very lightly, but the impact it has on the system is quite significant, as per the utility standards any voltage flicker more than duration of 8 seconds is regarded as non-compliance. This result to inadequate supply to the consumers.

- Dips

Voltage dips are the primary cause of power quality abnormalities; hence it influences the power system reliability. Voltage dips are caused by malfunctioning of transformer tap changers, auto-reclosers, arc furnaces and equipment with high starting current (Motors and Rock drillers).

- Frequency

Due to the increase demand of power supply, consumers specific times of the year, month or even a day draw more power from the system. This in frequency drop, which has a major impact on the power system reliability as it result in Under Frequency Load Shedding (UFLS). Furthermore this can also be described as system inadequacy.

- Harmonics

Harmonics becomes a major concern in the power system operations, which could have a severe impact on power system reliability. The network strengthening is required due to rapid demand of power by the consumers, but some of the short-medium term solutions are not favourable in terms of power quality, Capacitor Banks, Static Var Compensators and additional power transformers are all good sources of harmonics. Then on the other hand harmonics result in malfunctioning of protection devices due to high currents flowing into the system.

- Voltage Regulation

The effect of voltage regulation in the power system reliability is realised due to the reduction of the voltage in the customer point. This voltage reduction is caused by the high impedance in the power system – this could be due to long transmission lines and the type of conductors used – therefore the aforementioned power system behaviour causes the system to be unable to transport adequate energy to the consumers within the specified voltage limits.

2.5 Power Flow

In terms of alternating current (AC) power flow analysis is the determination of the bus voltage magnitude and phase angle, [25] generation and load at each bus in megawatts and megavars, flow of real and reactive powers on each transmission line etc. Power flow analysis form an integral part in planning the future development of the power system and satisfactory (reliable) operating the system [26].

Power flow analysis is performed to determine the steady state operation of an electrical power system network; this ensures the system reliability. It calculates the voltage drop on each feeder, the voltage at each bus and the power flow in all branches and feeders in a system [28]. At a given load situation, usually peak load, electrical quantities are evaluated, such as voltage, thermal loading, active and reactive losses. Active losses make the most important contribution to the operating cost. Voltage drop and thermal loading indicate if the system solutions satisfy the given limitations. Losses at each branch and total power losses are calculated [27].

2.5.1 Power System Hierarchical Levels

Due to the complexity of the power system, it is broken down into three functional operating zones which include generation, transmission and distribution. The concept of hierarchical levels (HL) has been developed in the order to establish a consistence means of identifying and grouping those functional operating zones. Figure 9 the hierarchical levels and figure 10 illustrates a typical power system hierarchy showing components that represent generation, transmission and distribution [32].

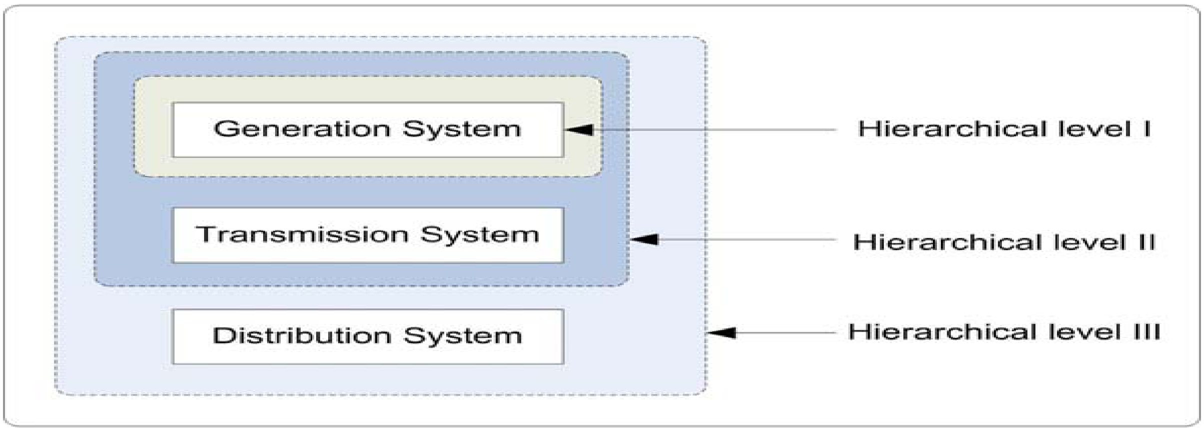


Figure 9: Hierarchical levels of Power System for Reliability Analysis [32]

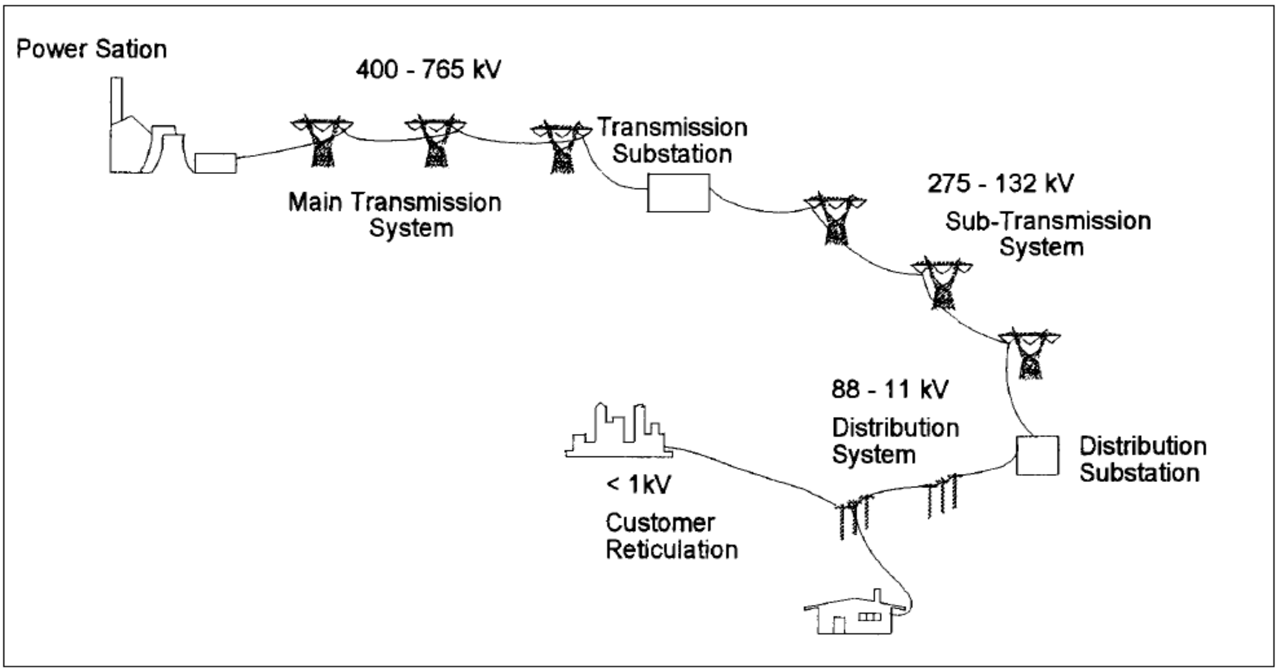


Figure 10: Typical power system representation [30]

As illustrated in figure 10, level one (HLI) refers to generating stations and their capability on a collective basis to satisfy collective system demand, second level, that is HLII refers to combination of both generation and transmission power system and its ability to deliver electrical energy to the bulk supply points and finally the third level (HLIII) refers to the entire system including distribution network and its ability to satisfy the capacity and energy demands of individual consumers, as shown in the power system network diagram in figure 2.7 [29].

As per [30] HLI and HLII studies can be performed but a complete HLIII study is usually impractical due to the scale of the problem. Since distribution facilities are the most vulnerable part of the power system network, the reliability of the distribution network is evaluated by considering the ability of the network fed from bulk supply points. And bus indices evaluated in HLII assessments can be used as inputs to the distribution functional zones [30].

2.5.2 Bus Classifications

Each bus in the system has four variables such as voltage magnitude, voltage angle, real power and reactive power. During the operation of the power system, each bus has two known variables and two unknowns. Generally, the bus must be classified as one of the following bus types [31].

- ***Slack or Swing Bus***

This bus is well-known as the reference bus. It must be connected to a generator of a high rating relative to the other generators. During the operation, the voltage of this bus is always specified and remains constant in magnitude and angle. In addition to the generation assigned to it according to economic operation, this bus is responsible for supplying the loses of the system [31].

- ***Generator or Voltage Bus***

This is a voltage controlled bus which keeps the voltage and magnitude constant during the operation. Also, the active power supplied is kept constant at the value that satisfies the economic operation of the system. In most times, this bus is always connected to a generator where the voltage is controlled using the prime mover control. However, sometimes it is connected to device that exporting VARs to the system such as Static Var Compensator (SVC) whereby the voltage can be controlled by varying the value of the injected VAR to the bus [35, 38].

- ***Load Bus***

This bus is connected to a generator so that neither its voltage nor its reactive power can be controlled. On the other side, the load connected to the load bus will change the active power and reactive power at the bus in a random manner. In order to solve the load flow problem in this bus the value of the complex power (real and reactive) has to be assumed at this bus [32, 37].

2.5.3 Variables of Power Flow

At each bus two out of the four quantities δ, $|V|$, P and Q are specified and the remaining two are to be calculated. Table 1 below shows the bus type with known and unknown variable [30, 36, 37].

Table 1: Bus Types and its Quantities

BUS TYPE	KNOWN VARIABLES	UNKNOWN VARIABLES
Swing / Slack / Reference Bus	V, δ	P, Q
PV / Generator / Voltage Control Bus	P, V	Q, δ
P Q / Load Bus	P, Q	V, δ

2.5.4 Techniques of Solutions

Because of the non-linearity and difficulty involved in the analytical expression for the power flow equations, numerical iterative techniques must be used such as:

- Gauss-Sidel Method (G-S)
- Newton-Raphson Method (N-R)

The first method (G-S) is much simpler than the second one, but the second method (N-R) is reported to have better convergence characteristics and is faster than (G-S) method. But due to the fast moving technology in the world, new software is capable of performing both methods, for an example DigSilent. This provides a quicker and reliable load flow analysis to power system engineers [33, 34, 35]. Figure 11 show the typical IEEE bus system.

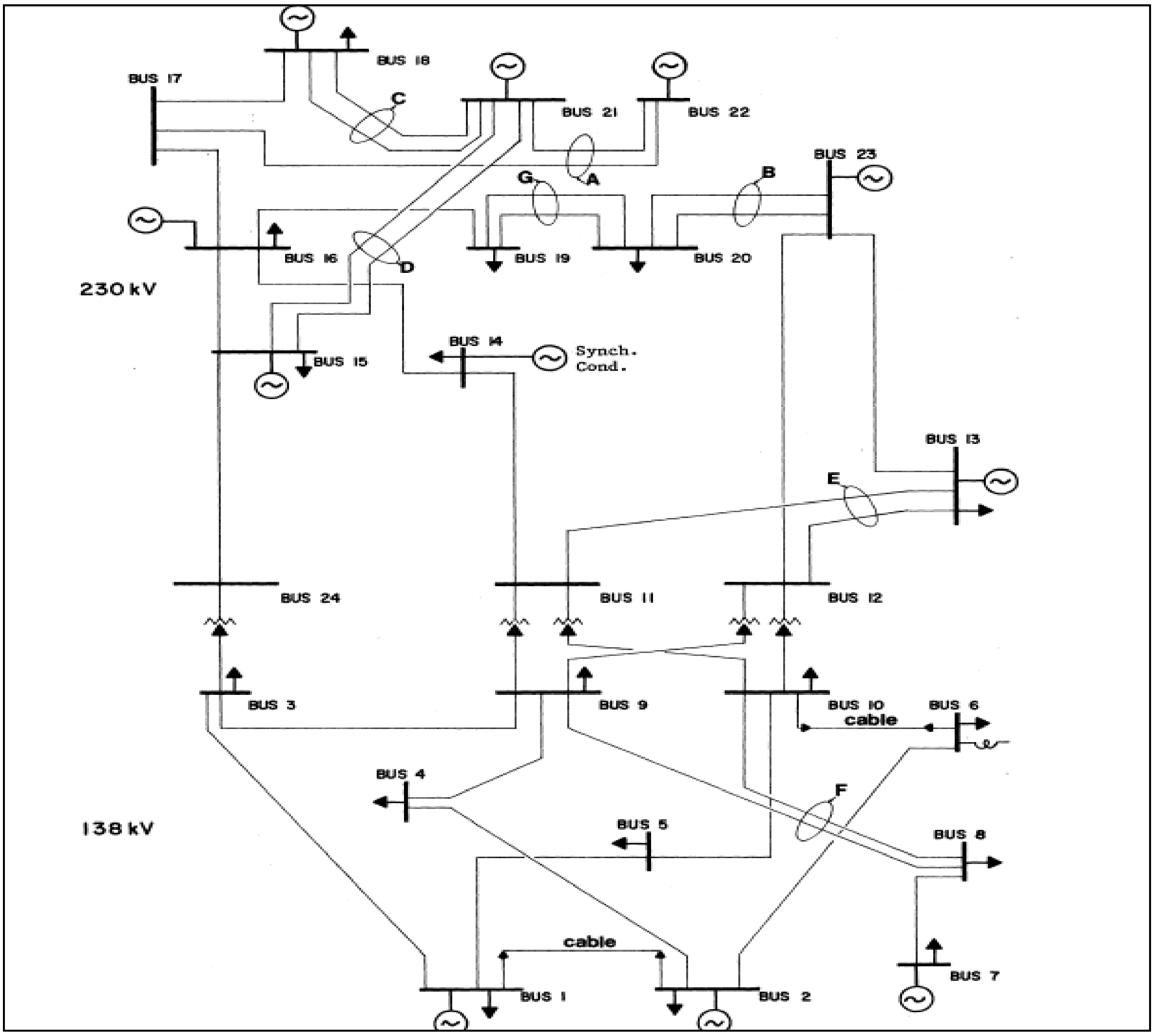


Figure 11: IEEE Reliability test system [33]

2.5.5 Influence of the power flow in power system reliability

Power flow analysis is the determination of the bus voltage magnitude and phase angle generation, and load at each bus in megawatts and megavars, flow of real power and reactive power on each transmission and distribution lines. Power flow analysis is essential in planning the future development of the system and satisfactorily operation of the system. Power flow analysis is first primed over the studied system, and then the reliability evaluation (indices) is computed based on the power flow analysis.

2.6 Protection

2.6.1 Background information about protection system

It is a general requirement of any power system network that it has to be designed well and maintained properly in order to accomplish an acceptable level of reliability [40], quality and economic price of the electricity supplies as well as to limit the number of faults that might occur during operation. A number of ancillary systems are available in the distribution network to assist in achieving these system requirements. The most important of these ancillaries are the protection system devices, which are installed to clear faults during network operation and avoid any damages to the distribution network equipment. Automatic operation of protection system is necessary to isolate faults on the system as fast as possible in order to reduce damages. The economic costs and benefits of a protection system must be considered in order to present a suitable balance between the requirements of the protective scheme and the available financial resources. The requirements set to the implemented protection system may be summarised as follows [61]:

- Reliability: the ability of the protection system to operate correctly. It has two elements: dependability – a certainty of correct operation when a fault occurs, and security – an ability to avoid incorrect operations;
- Speed: minimum operating time to clear a fault in order to limit damage.
- Selectivity: maintaining continuity of supply by disconnecting the smallest possible section of the network necessary to isolate the fault.
- Cost: maximum protection capabilities at the lowest price as possible.

It requires a higher degree of concession in order to achieve the optimum protection system. Protection system that is properly coordinated is essential to ensure that an electrical network operates within the requirements to safeguard equipment, staff, public, animals, birds and the entire power system network.

2.6.2 Principle of Over-Current Protection

Over-current protection is one of the commonly used protection principles implemented as a protection of: power lines, cables, transformers and motors. This type of protection can be used as a primary as well as a backup protection Figure 13. When it is used as a primary protection, the over-current protection has the task of sending an immediate tripping command when the fault is inside the protective zone, and as a backup protection to send the command after a set graded time (if the primary protection for the fault hasn't reacted). For implementation of this protection philosophy in a network with multiple infeeds, a direction criterion is required [64].

There are two principles of over-current protection: definite-current and inverse time principle (Figure 14). The definite-current protection device operates instantaneously when the current reaches a predetermined value (I>, I>>) and the set time has passed (T_I>, T_I>>). The setting is chosen so that, at the substation furthest away from the source, the protection device will operate for a low current value and the protection device operating currents are progressively increased at each substation, moving towards the source. Thus, the protection device with the lowest settings operates first and disconnects load at the point nearest to the fault. This protection is not very selective at high values of short circuit current [65].

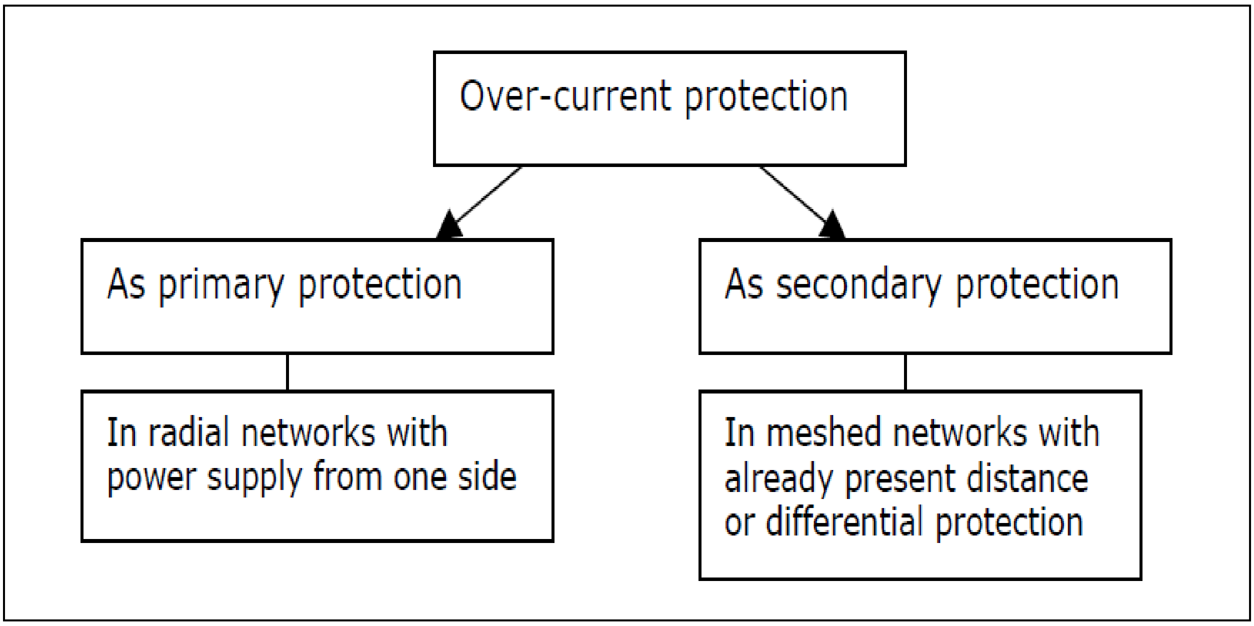


Figure 13: Implementation of over-current protection

The fundamental property of the inverse time protection devices is that they operate in a time which is inversely proportional to the fault current. Their advantage over definite time and definite current protection devices is that, for very high currents, much shorter tripping times can be achieved without a risk to the protection selectivity. They are also divided into inverse, very inverse and extremely inverse [64].

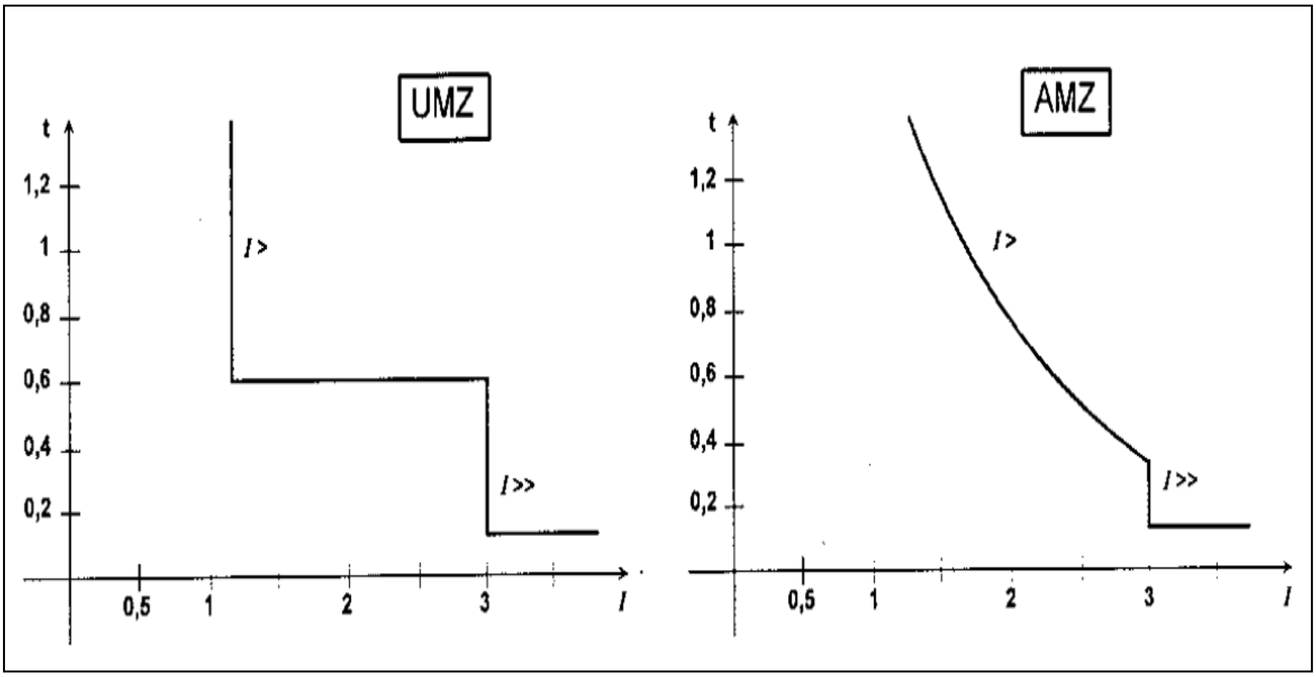


Figure 14: Types of over-current protection

2.6.4 Principle of Distance Protection

Distance protection is regarded as one of the most important types of power system network protection philosophies, concerning protecting a line. The distance protection device is connected generally via voltage and current transformers to the protected line [62]. The distance protection device monitors this line, if a fault on the line occurs it should send an immediate tripping command to the circuit breaker on the line to trip. The system philosophy of distance protection is presented in Figure 15. It is necessary that all of the system components must be available in the scheme to fulfil the protection task [66].

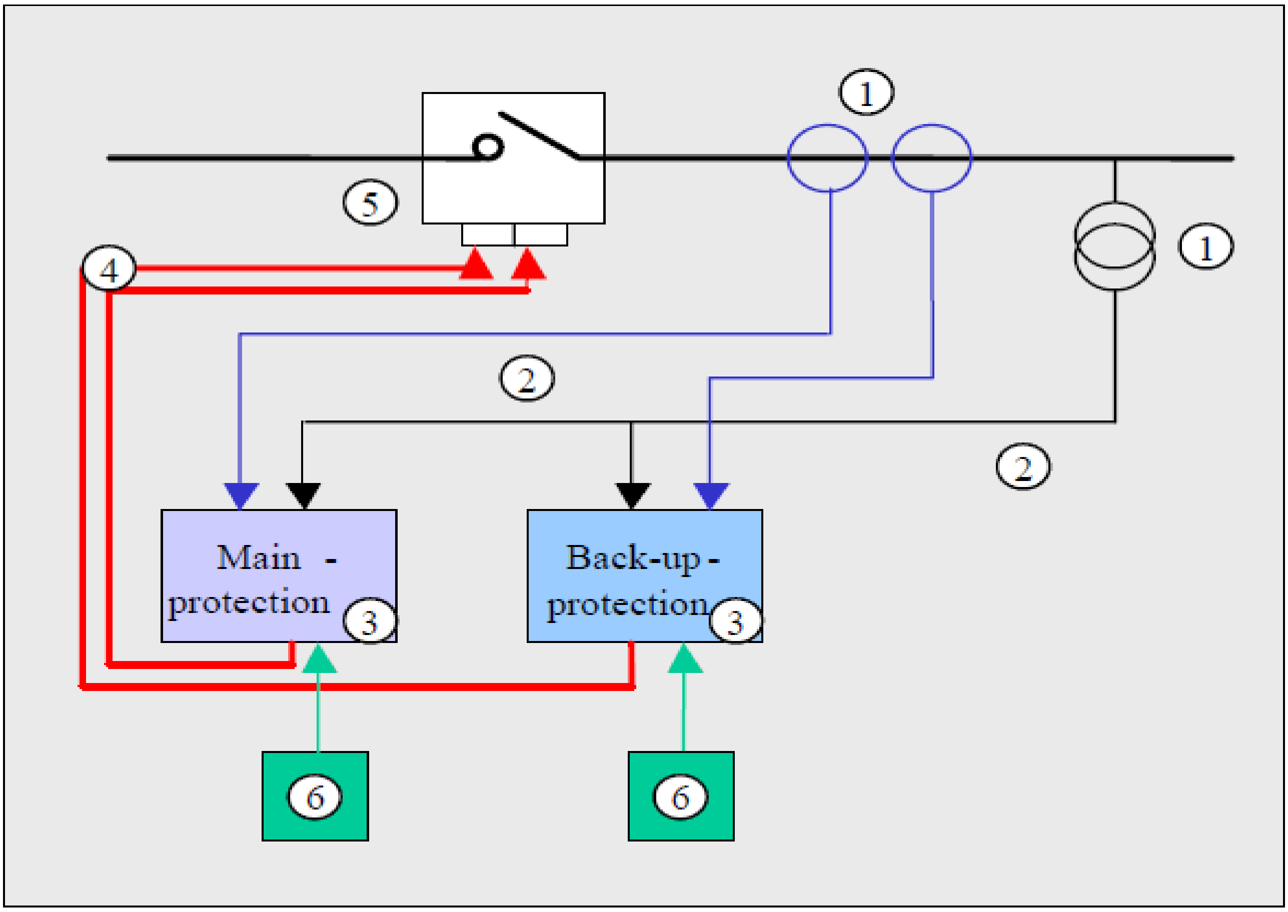


Figure 15: System components of the distance protection device

1) Adaptation of measured data (CT and VT)

2) Transportation of measured data

3) Data acquisition main & back-up protection

4) Control system

5) Circuit breaker

6) Auxiliary system (Battery)

The selectivity of disconnection is achieved by calculating the distance from the placing point of the protection device to the fault. Using time grading the distance protection can be used as a backup protection for further line parts or other upcoming lines [68]. The distance protection device can also be set in two directions: forward (as shown in Figure 17 and Figure 18), and reverse, for example as a backup protection for a generator, or transformer [66].

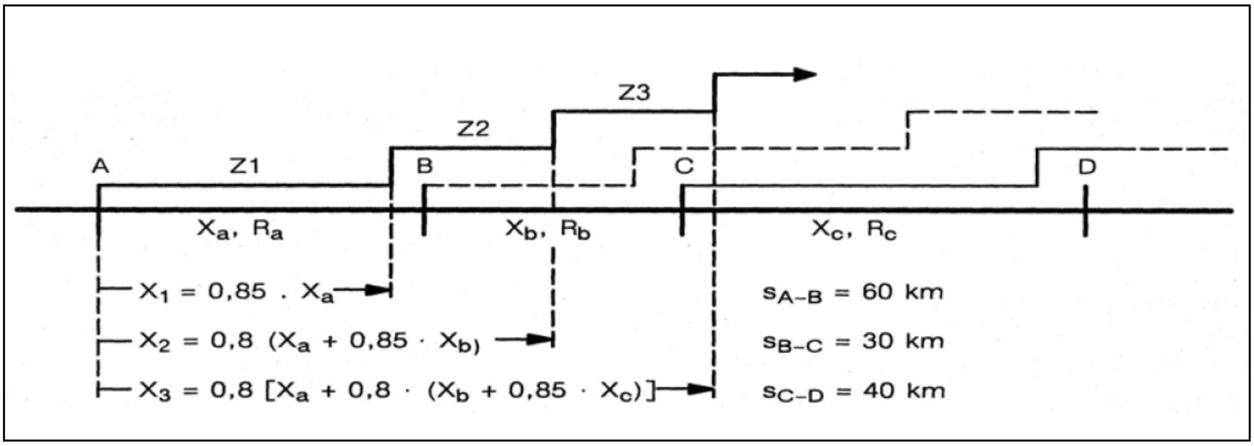


Figure 16: Protection zones of the distance protection at bus bar A

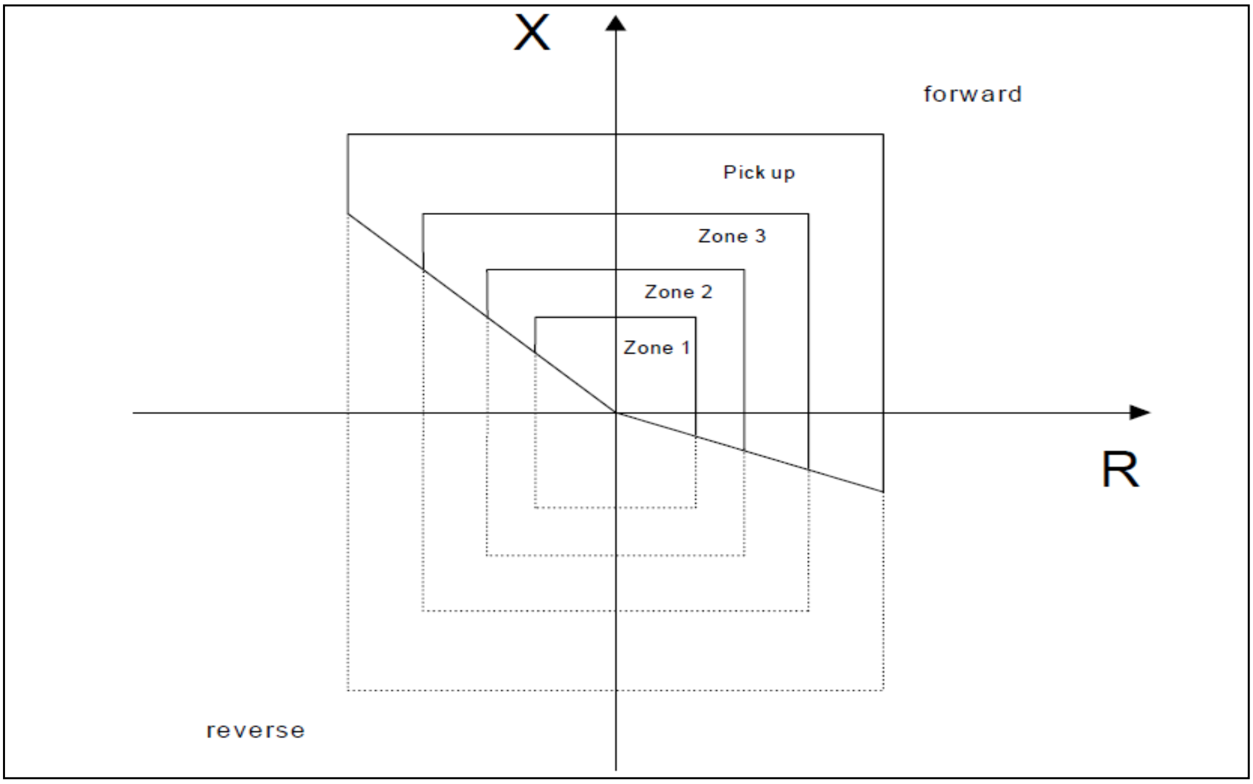


Figure 17: Tripping characteristics of a distance protection device

For calculating the distance to fault (impedance) the distance protection device needs the input values of the three-phase voltage and current, which can be measured at the placing point of the protection device. A total of 6 voltages and 6 currents values are measured (phase to phase and phase to neutral values).

With the calculation of the impedance, the distance to fault can also be calculated. The tripping command is sent when the calculated value of the impedance is within the specially designed and parameterised tripping characteristic (Figure. 2.16). In Figure 2.16 a polygonal characteristic is presented. Some distance protection relays also use MHO (inverse Ohm) characteristics, cycle characteristics, etc.

2.6.5 Principle of Differential Protection

Differential protection device is connected on both terminals of the protected component via the current transformers as shown in figure 18, thus the tripping characteristics (operation) of differential protection is shown in figure 19. The primary function of differential protection philosophy is to send immediate tripping command to both circuit breakers only when a fault is within the protected zone [63]. This protection should not operate for external faults (no back up protection function is possible).

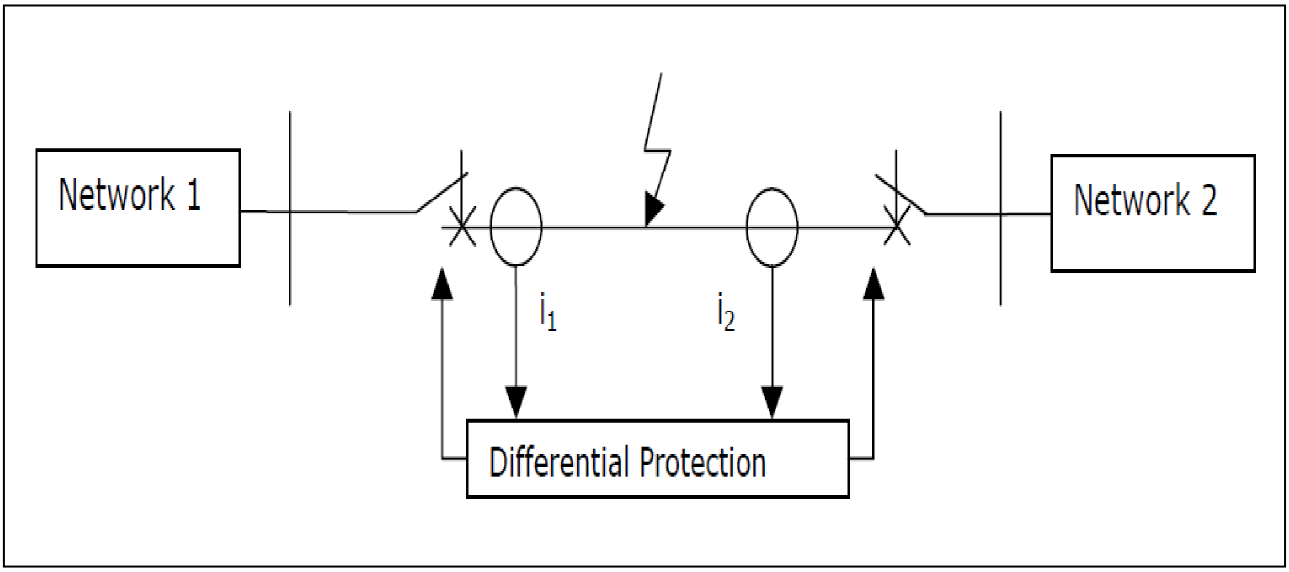


Figure 18: Functional principle of differential protection

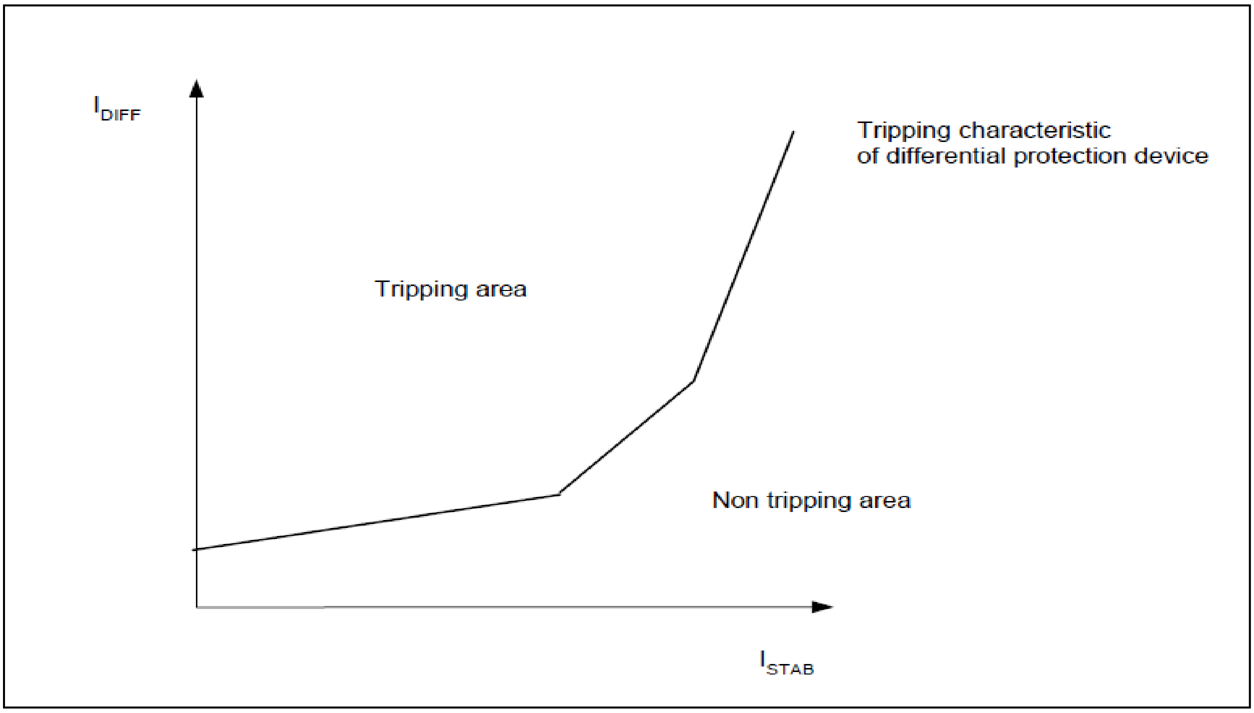


Figure 19: Tripping of differential protection

The function principle of the differential protection is based on the electromechanical principle of balancing. Two parameters are defined: differential current of equation 1 and stabilising 2, defined as follows:

Differential Current: $I_{DIFF} = | I_1 + I_2|$ ________________________ 1

Stabilising Current: $I_{STAB} = |I_1| + |I_2|$ ________________________ *2*

The tripping characteristic is represented in the equation (3)

$I_{DIFF,\ PICKUP} = F_{(ISTAB)}$ ________________________________ 3

This type of protection philosophy has a very high selectivity, high speed and mostly used for protecting transformers, generators, and short line (distance protection is not easy to realise). The differential protection can be realised either as a comparison between moment values of the two measured signals or as a comparison of the phases of the two measured signals. The disadvantage of using the differential protection is the need of pilot wires for communication between both protection devices forming the differential protection principle [64].

2.6.6 Influence of Numerical Protection in Power System Reliability

The use of numerical protection philosophy in the power system provides automated protection devices; this increases the power system reliability. Numerical protection has handy advantages compared to the old protection method. Following are the key characteristics of numerical protection;

- High reliability
- Self-diagnosis
- Events and interruption records
- Integration of other digital systems'
- Adaptive protection

Numerical protection is available in various protection philosophies, following are those protection technics;

- Over-current protection

It can be used as backup or primary protection, when used as a backup it sends a tripping command after a set graded time. Then when it is used as a primary protection, it sends an immediate tripping command as soon as the fault is within the protected zone.

- Distance protection

It is regarded as the best protection method to protect the high or medium voltage lines; it uses the current and voltage transformers to protect the line. The primary function for distance protection is to monitor fault on the line and send immediate tripping command when a fault occurs.

- Differential protection

Another common form of protection for apparatus such as transformers, generators, busses and power lines is current differential. This type of protection works on the basic theory of Kirchhoff's current law, which states that the sum of the currents entering and exiting a node will equal zero. Differential protection requires a set of current transformers at each end of the power line, or each side of the transformer. The current protection relay then compares the currents and calculates the difference between the two.

2.7 International and South African (Eskom) Standards of Reliability

Power system reliability standard (guide) means a requirement to provide a reliable operation of the bulk power energy [49], without limiting the foregoing requirements for the operation of the existing bulk power system facilities, including computer-generated protection and design of planned additions or modifications to such facilities.

A stable flow of electricity is critical for health and well-being of personnel throughout the world who rely on the power system grid for the delivery of electric energy. Since electricity is entwined with every aspect of day-to-day life, the issue of reliability is paramount. In addition to the inconvenience experienced by the consumers during prolonged periods without electricity service [40], a power outage can literally mean the difference between life and death. From specialised care equipment such as dialysis machines to every day heating and cooling devices like air-conditioners or furnaces, the impact of a power interruption on consumers can be significant. Power interruptions have enormous potential of resulting in fatalities, injuries, days of lost productivity and millions of rands in production losses and equipment repairs [48].

Furthermore, the electric industry around the world has recently been promoting the smart grid as way to improve reliability and efficiency. While this may be the case, many smart grid programs lack specific safety and power quality performance goals. Hence, it is a challenge for the average customer to know if the innovation of smart grid will dramatically improve the reliability and quality of power they receive.

Finally, the effects of power outages go beyond the annoyance from the outage itself. Despite being responsible for deaths and injuries they also pose a real public safety. When an area of city loses power, police and firefighters must be diverted from protecting neighbourhoods to recovery operations and make sure citizens are safe. When the power fails, many residents turn to candles for light and generators for power – both of which introduce an inherent danger. Similarly, the transportation infrastructure is compromised as traffic lights go dark and police are diverted to direct traffic. In addition to the safety of personnel, the overhead lines present a significant safety hazard when live powerlines are downed, threatening anyone who comes in contact with them. Hence, there is a need for power system reliability standards that the utilities are bound to comply with [42, 43].

It is mandatory globally that the utilities must be regulated as per the approved international or local standard to ensure and maintain a considerable consistence in terms of power system design, planning, operation and maintainability. This section review power system reliability standards, i.e. Eskom and National Energy Regulator of South Africa (NERSA) and North American Electric Reliability Corporation (NERC) in order to make a comparison with NERSA and Eskom reliability power system reliability standards or policies [42].

2.7.1 National Energy Regulator of South Africa

NERSA is a regulatory authority that was established as a juristic person in terms of section 3 of the National Energy Regulator Act, 2004 (Act No. 4 of 2004).

NERSA's mandate is to ensure that the three industries in the energy sector are regulated, these industries includes Electricity, Piped gas and Petroleum pipeline industries, in term of Electricity Regulation Act, 2006 (Act No. 4 of 2006), Gas Act, 2001 (Act No. 48 of 2001) and Petroleum Pipelines Act, 2003 (Act No. 60 of 2003). NERSA's mandate for this section will be focused in the electricity industry [42], where the regulatory functions are as follows [48]:

- Issuing licences for operation of electricity generation, transmission and distribution facilities;
- Issuing licences for import and export of electricity;
- Setting up prices and tariffs;
- Implementing compliance monitoring in the electricity industry;
- Establishing national information system in the electricity industry.

From the aforementioned functions from the regulatory body (NERSA) to the utility (Eskom), the author has picked up the one with the word 'compliance' which relates very well with the power system reliability.

2.7.1.1 NERSA on Eskom's Power System Reliability (Compliance)

Eskom is mandated as per NRS 048-2 standard from the regulatory body to ensure that all the network interruption events to be categorised according to the nature of the event. Power interruption events are classified into five categories:

- Unplanned interruptions;
- Planned interruptions;
- Voluntary customer load reduction events;
- Involuntary customer load reduction;
- National Control load shedding initiated events

Unplanned interruptions on the networks

Unplanned interruptions as defined by NEARSA are considered as the disconnection of one or more phases of the network supplying the customers for a period of more than 3 seconds, this time period NERSA based it in terms of QOS measurement guide.

The definition of an interruption in [43] is not defined in terms of measurement but rather in terms of the disconnection of the supply point, since measurements may provide erroneous indications whether an interruption occurred or not on the network. Approved instruments by [44] may be used to assist in the interruption performance assessment of a network failing which an interruption threshold of 10% and duration threshold of 3 seconds is recommended. Unplanned interruptions are typically caused by:

- Failure of components such as jumpers, joints, conductors, circuit breakers and transformers.
- A fault that does not result in reconnection of the circuit on all phases to the customers within 3 seconds.
- A circuit breaker trip on one or more phases due to events such as an operator error or protection operation (e.g. overload protection).
- A circuit breaker trip on one or more phases due to emergency action by the utility.

Planned interruptions on the networks

As per NRS048-4 standard planned interruptions are interruptions that are due to network maintenance.

Voluntary load reduction

The customer voluntary load reduction event are characterised by the curtailment, partial curtailment, or reduction of customer load, where all of the following provisions are met:

- These arrangements are required by the utility to protect the security of the supply system in its general customer base to avoid possible problems such as under frequency load shedding, load reduction to manage voltage stability problems or power system overload problems.
- That the customer has voluntary agreed to such reduction prior to the event, and has been able to determine the load magnitude to be reduced. This agreement may be u in terms of a contract and may be executed by the automatic relays designed to trip the load as agreed by the customer in such a contract.
- That the customer voluntary load reduction event shall not be classified as a planned interruption, but assessed separately.

Involuntary customer load reduction events

In situations where a customer load reduction event is not classified as voluntary load reduction event, it shall be classified as an involuntary event. Body, licensed by the National Energy Regulator of South Africa (NERSA) that generates, transmits or distributes electricity is known as licensee. Such events include customer notification, by the licensee just before requiring that the customer reduce load.

National Control load shedding events

Any load shedding required due to the shortage in generation in one form or another, by the transmission licensee is an intake supply related event. This kind of event refers to network interruptions where National Control Centre requests the Regional Control Centres to reduce load as a direct result of national utility generation capacity shortfall.

2.8 DigSilent, Retic Master, Data Management System (DMS) Failure Mode & Effect Analysis

2.8.1 DigSilent and Retic Master

PowerFactory software was developed by the Germany based consulting and Software Company commonly known DigSilent. This Company provide highly specialised services within the field of electricity power system which includes generation, transmission, distribution, and industrial plant and factories. PowerFactory software package comes with so many embedded system tools and simulations, but for this Dissertation PowerFactory will be used for protection, quality of supply, load flow and reliability. The tool that is not so familiar is the reliability tool [67]. This tool comprises of the following features:

- Standard reliability assessment features with sophisticated a modelling technique that enables all forms of reliability assessment to be carried out.
- The reliability analysis complements the non-stochastic contingency analysis or N-1 analysis to allow ranking outage events in terms of frequency or duration.
- The failure model includes annual frequency of failures and repair time. For lines, this is entered in per length terms.
- Loads are represented by load forecast and growth curves. Thus each can be assigned an interruption cost in one of three forms (this will require a cost function to be defined first) such as:
    - Currency/Customer/interruption;
    - Currency/kW/interruption;
    - Currency/interruption.

All reliability assessment functions in DigSilent (PowerFactory) software tool are therefore based on the Weibull-Markov model (WM-model) [69]. There are many utilities that are using DigSilent (PowerFactory) universally and in South African, for example biggest municipalities such as Nelson Mandela Metropolitan Municipality, City of Cape Town, eThekwini Municipality, City Power (Johannesburg), eKurhuleni (Johannesburg), including the largest power utility in Southern African (Eskom) is uses this software to run power flows, protection settings, n-1 contingency plans, fault levels analysis both on the High Voltage (HV) and Medium Voltage (MV) line. The advantage of PowerFactory compared to other power system simulation tools such power world, power system simulator for engineering (PSS/E) is that PowerFactory consist of different versions which cater in different in different stages and licences standards.

Retic Master tool is the tool that enables efficient analysis of Medium Voltage (MV) network such as 22 kV and 11 kV. Since the study of the dissertation entails 22 kV reliability analysis. This software will be useful in the analysis, especial in the installation of voltage regulators, capacitor banks and variation of transformer tap changers to improve MV voltages.

2.8.2 Failure Mode and Effect Analysis

The failure modes and effects analysis method is an alternative method to the network reduction technique [70]. This method is one of the simplest ways of estimating reliability. It is based on an inductive or based on analysis that is used to identify the failure mode of components in a distribution system affected by changes in power or loss of power to a specified load caused by the states of breakers, circuit breakers, loads and subsequent control actions to restore the system. The failure modes are directly related to the minimal cut sets of the system [71].

The failure modes analysis is based on approximate equations. System indices can therefore be evaluated by applying these equations for series components in order to combine all overlapping outages. Three basic reliability parameters used to constitute these equations are the average load point failure rate, the average annual load point time or unavailability and the average load point outage duration.

The equations are as follows:

- The average load point failure rate $\lambda s = \lambda ii$ 4
- The average annual load point unavailability $Us = \lambda irii$ 5
- The average load point outage duration $rs = Us\lambda s$ 6

The main advantage of this method is that it provides a more detailed description of the failure behaviour of the distribution system while evaluating the consequences of all failure modes of all components. The disadvantage of FMEA is that it is repetitive, and it is difficult to examine multiple failures in an efficient manner. FMEA method is capable of producing information that can be vital in assessing critical areas and deducing those areas in which investment will give the greatest reliability improvement [72] believe that this information is not readily deducible from the network reduction method, particularly when the system increases in size.

2.8.3 Overview of DMS

The Network Manager Data Management System) DMS client-server architecture and distributed design makes it possible to divide the software system into parts that can be distributed between different servers connected to a common local area network. With this approach, the main system database can be physically distributed among different servers in the system, while it still constitutes and operates as one logical entity. This means that programs are fully transparent to the physical location of single data items and can be moved freely and easily between the servers without impact on the code or the need for reprogramming [2]. The major advantages of the distributed Network Manager concept are:

- The system is easy to scale, in case the network and control system need to expand.
- Parallel processing provides high performance and allows better computational workload distribution and higher safety.
- Distributed software modules enable the realization of customized systems based on a standard product.
- Distributed software modules enable also customizable redundancy allowing balancing of different application performance and hardware requirements.

The Network Manager architecture conforms to all major industry open-design standards for real-time database management services and inter-task communication. Most of all, Network Manager DMS provides display and analysis capabilities for the “as-built”, the “as operated” (or current state), and proposed state of the electrical network [3]. Network Manager provides the operator with a powerful tool to perform his duties by combining the ability to analyse these three conditions of the electrical network, along with the various network safety and security check functions. Network Manager also maintains a database of customers, service personnel and field crews. This provides valuable information and allows for the storage of historical information related to customer service quality and crew performance.

2.9 Conclusion

The relevance of reliability indices (SAIDI, SAIFI etc.) in this dissertation is for one or both of two reasons that includes; assessment of the past performance and or predicting the future performance of the system. These will be achieved by collecting the historical data of the system performance to model reliability indices, using FMEA and DigSilent. The data should then reflect and respond to the factors that affect systems reliability and enable it to be modelled and analysed. This implies that it should relate to the two main processes involved in component behaviour, i.e. the failure process and the restoration process conditions

Power system outages have a significant impact on the power system reliability, the more the number outages experienced by the consumers whether are due to dependent or independent outages worsens the network reliability performance. The relevance of power system outages in the dissertation is to assist in determining their impact on the poor performance of power system reliability. Moreover, it will further assist in proving whether the system will still be vulnerable to planned outages after reliability improvement.

Power quality analysis is important parameter of this dissertation as it will demonstrate whether the reliability improvement on the Aliwal North power system will have a positive impact on the quality of supply on the area i.e. no adjustment will be required in terms of the power quality such installation of voltage regulator, capacitor banks, voltage balancing, adjustment transformer tap changers etc.

Power flow analysis is the determination of the bus voltage magnitude and phase angle generation, and load at each bus in megawatts and megavars, flow of real power and reactive power on each transmission and distribution lines. Power flow analysis is relevant in this dissertation as it will provide an indication whether reliability improvement will result in over voltages or change in the phase angle in the network, which may require a creation of a Normal Open Point in the system to avoid voltage exceedance. Moreover, it will also give guidance in planning the future development of the system and satisfactorily operation of the system.

Protection coordination forms part of power system operations in such a way that the system is able to supply power to the consumer under normal and abnormal conditions; this is done by separating the unhealthy piece of the network from the rest of the system and is achieved by good protection coordination. Moreover, proper coordination of relays is possible if the relay stings are set as per the required operation. Therefore, the relevance of the protection coordination in this dissertation is to determine whether the relay coordination will still be operating appropriately after the reliability improvement in the power system network by evaluating single phase to ground, phase to phase and three phase fault analysis.

Reliability standard is method at which the utility power system performance is measured against and some regulatory bodies implement penalties if minimum standards are not met. Therefore the role of reliability standard is very important aspect in dissertation. Its relevance comes at a point where it will provide evidence that the Aliwal North power system interruption will conform to NERSA reliability standards requirements after the reliability improvement have been implemented. Moreover, all interruptions will be able to be classified as per the event according to NRS048-2 reliability standards.

DigSilent and FMEA are the two software simulation tools that are going to be used for the analysis of reliability for both the current performance and predictive performance. Their relevance to the dissertation is to provide the detailed analysis of reliability indices, measuring their current performance and predicting the future performance. Furthermore, compute a comparison between the reliability performance before and after reliability improvement implemented on the Aliwal North power system network.

CHAPTER 3: DATA COLLECTION

3.1 Introduction

The aim of this chapter is to define the method followed for collecting data for the reliability analysis. Close attention is paid to the method chosen for gathering the data from the Distribution Management System. The data required for the reliability analysis study was collected by means of real time software, fault statistics, type of protection scheme used, voltage levels, maximum demand, outages and power quality problems. For the purpose of integrity for the real time software used, it was critical to define the real time software and described it how it works.

3.2 Aliwal North Network (Reliability Data Collection).

Aliwal North power system is situated in the northern part of Eastern Cape along the banks of Orange River, which divides the boarder of Free State Province and Eastern Cape Province, see appendix A for Eastern Cape Map. The Aliwal North power system network is considered to be the most vulnerable network to outages and faults. The vulnerability of this network is caused by the fact that five substation entirely depend on a single source (Dreunberg-Melkspruit 132 kV line), see figure 20 below for the configuration of the Aliwal North power system network.

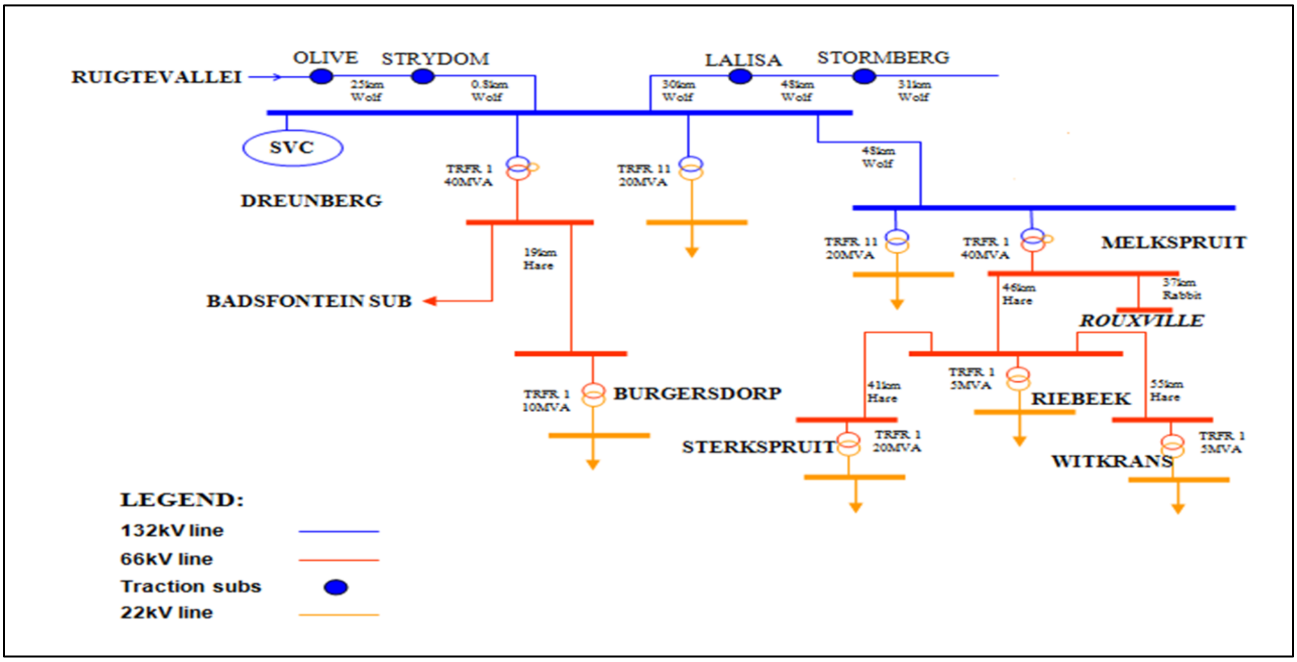


Figure 20: Aliwal North Power System

3.3 Distribution Management System

Distribution Management System (DMS) architecture consists of various distributed application components required by Distribution to manage its electrical distribution networks. It is a SCADA system from which the data used for this dissertation will be obtained. These capabilities include monitoring and control of equipment for power delivery, management processes to ensure system reliability, voltage management, demand-side management, outage management, work management, automated mapping and facilities management [1].

3.3.1 DMS role on the project

DMS is the tool that will be used to collect the following data for this dissertation:

- Maximum demand of Aliwal North power system.
- Linking of the Substations.
- Network events list such as failure rate.
- Real-time busbar voltages.
- Sterkspruit – Lower Telle 22 kV network
- Indication changes

The power system data as collected in the DMS real time software tool add valuable information to this thesis as it will portray the exact behaviour of the network as it stands on the field. Figure 21 below illustrates the busbar loading profile in MVAs on the Dreunberg/Melkspruit 132 kV line, downloaded from the DMS power system downloader tool.

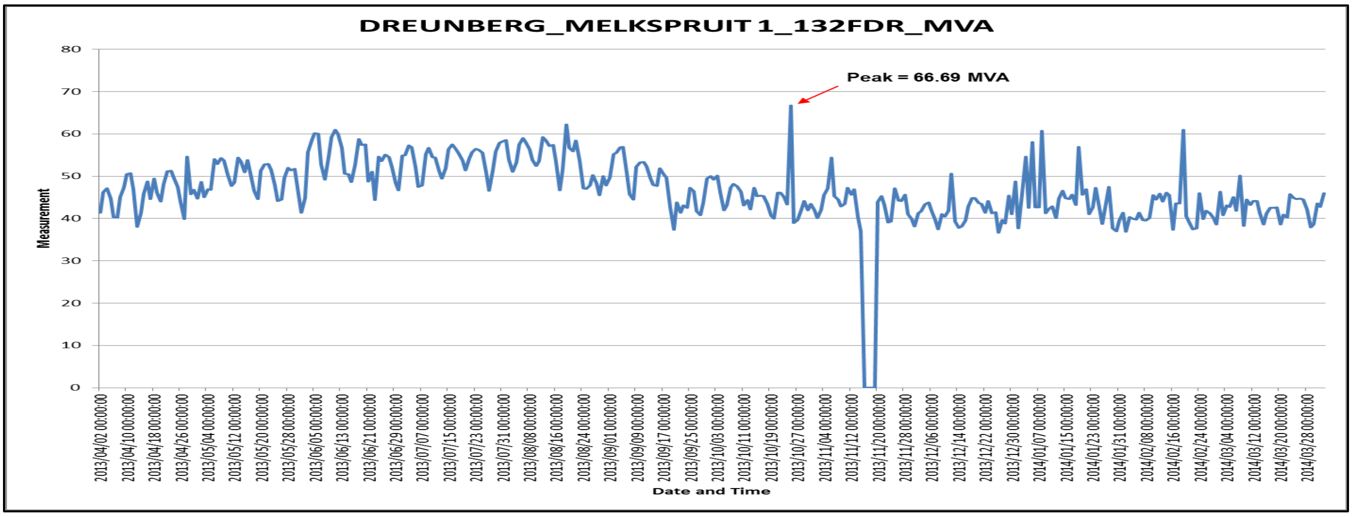


Figure 21: Loading profile measured in MVAs.

3.4 Outage Event

There are various types of outage events that can be carried out on the power system network. Reliability indices will be calculated based on the interruptions, see figure 23 for classification of the event failures and their levels. These types of outage can be classified as notified, live work, emergency, customer and negotiated. See figure 22 for the outage statistics data on the Aliwal North power system network, see appendix B for the contributing events to the emergency outages. Therefore, for this dissertation the negotiated type of an outage was picked up. This outage took place on the Dreunberg/Melkspruit 132 kV line, it affected 5 substation and 43 000 customers were without supply for the duration of 12 hours as per the outage plans, see appendix J for the outage events as downloaded from the (Fault Management System) FMS. The purpose of the outage was to improve the quality and security of supply. The following were the improvements to take place on the system:

- Dreunberg Substation extension with new Melkspruit 132kV feeder bay.
- Melkspruit Substation Extension with new Dreunberg & Riebeek 132kV Feeder Bays.
- Riebeek 132/66/22kV 2X40 MVA substation extensions - primary works, control building and platform extension.
- New Melkspruit - Riebeek 132kV Line
- Re-route of the Rouxville 66kV line
- Sterkspruit SS – 66 & 22kV busbar extensions, second Transformer and additional 22 feeder bays & 22kV link lines
- Sterkspruit SS – The refurbishment of the existing transformer 1 and its associated primary and secondary plant equipment.
- Sterkspruit SS – The splitting of load from the current 4 x 22kV feeders into 8 x 22kV feeders and moving of panels

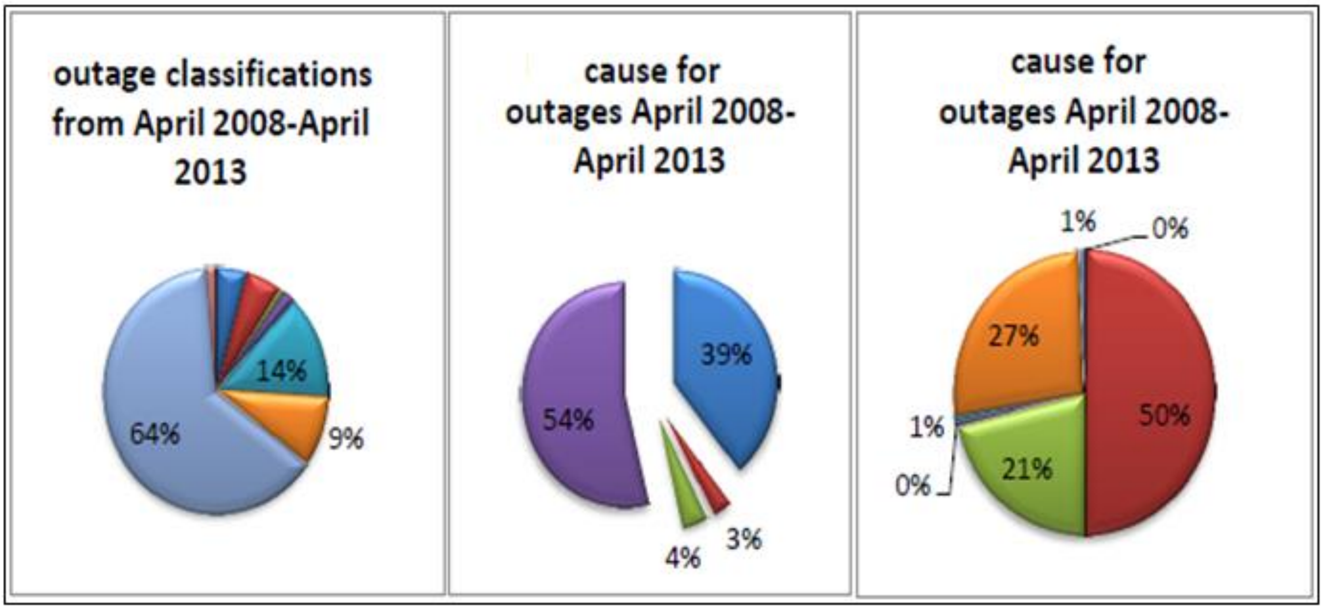


Figure 22: Classification of Outages.

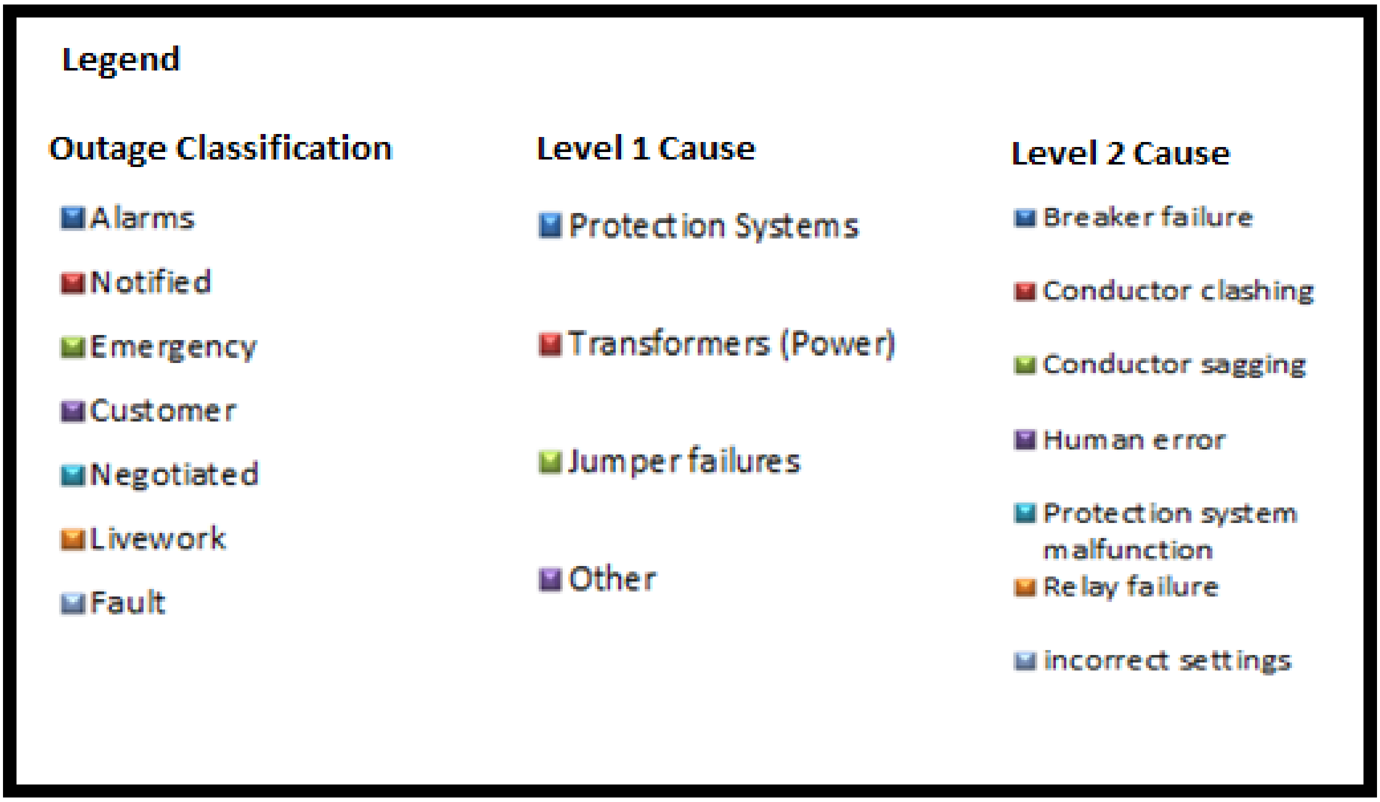


Figure 23: Key index as to what each colour referring to.

3.5 Benefit vs Cost Data Collection

This section shows how the benefit-cost ratio for different scenarios of load at risk, source line lengths, and cost of Energy Unserved (COUE) rates.

It is the information in table 1 that informs decision whether or not to build one or two lines for HV and MV substations respectively. The following information from table one is useful for benefit to cost analysis:

- Load at risk in MVAs.
- Line length in kilometres.
- COUE rate
- The benefit to cost ratio.
  - In table 1, cells with a benefit-cost ratio > 0.8 are marked in green, suggesting that an additional line is economically justified. Cells in red suggest that the second line is not economically justifiable.

During analysis of the benefit to cost it is the benefit to cost ratio that will determine whether or not the additional HV line is necessary to build.

Table A1: Benefit vs Cost ratio of a second Sub-transmission Feeders

Benefit vs cost analysis of a second sub-transmission line (Voltage = 132 kV; COUE = R 40 kWh)										
		Line length [km]								
		1	5	10	15	20	25	30	35	40
Peak load at risk [MVA]	2	0.22	0.16	0.13	0.12	0.12	0.11	0.11	0.11	0.10
	4	0.43	0.32	0.27	0.25	0.23	0.22	0.22	0.21	0.21
	6	0.65	0.48	0.40	0.37	0.35	0.34	0.33	0.32	0.31
	8	0.87	0.64	0.54	0.49	0.47	0.45	0.44	0.43	0.42
	10	1.08	0.80	0.67	0.62	0.58	0.56	0.54	0.53	0.52
	12	1.30	0.96	0.81	0.74	0.70	0.67	0.65	0.64	0.63
	14	1.52	1.12	0.94	0.86	0.82	0.78	0.76	0.75	0.73
	16	1.73	1.28	1.08	0.99	0.93	0.90	0.87	0.85	0.84
	18	1.95	1.44	1.21	1.11	1.05	1.01	0.98	0.96	0.94
	20	2.16	1.60	1.35	1.23	1.16	1.12	1.09	1.07	1.05
	22	2.38	1.76	1.48	1.36	1.28	1.23	1.20	1.17	1.15
	24	2.60	1.92	1.62	1.48	1.40	1.34	1.31	1.28	1.26
	26	2.81	2.08	1.75	1.60	1.51	1.46	1.42	1.39	1.36

3.5 Quality of Supply event data

Figure 24, shows data collection on Sterkspruit substation 22 kV busbar voltages. During the analysis of the data in chapter 4, the voltage profile data will be analysed taking a closer look on the following items:

- Causes of fluctuations.
- Impact of these fluctuations.
- Period in which the normally occurs.
- The percentage exceedances.

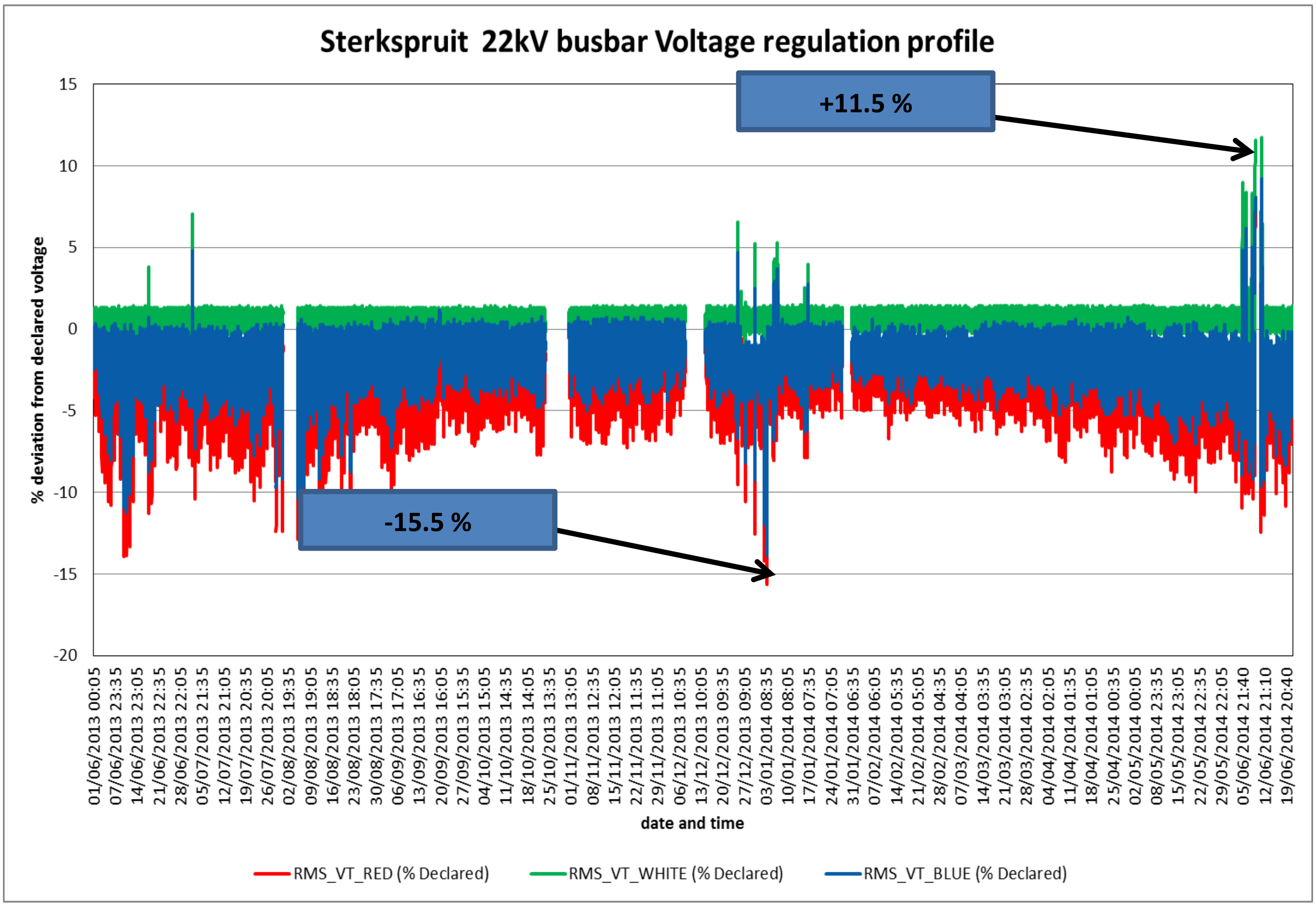


Figure 24: Voltage profile of Sterkspruit 22kV Busbar (Period June 2013 – June 2014)

3.6 Protection and Coordination

Failure of protection systems has an adverse impact on the continuity of supply and therefore improper protection coordination affects network reliability. Table 2 below, illustrates the data collected from the annual fault level report for Aliwal North network produced at network optimisation department. The fault levels were recorded as per substation, at which the busbar is selected. This data will play an important part during data analysis on chapter 4, for calculations of protection settings and grading of relays. Proper protection coordination is influenced by correct protection settings and relay grading.

Table A2: Snap Short of the Aliwal North power system fault level

Station Name	Bus Bar Name	Voltage (L-L)	Ik(3 ø Fault)	Ik,Angle	Sk(3 ø Fault)	R+	X+	Z+
		kV	kA	deg	MVA	Ohm	Ohm	Ohm
Dreunberg	132kV Bus 1	132	21.32	-85.215	188	0.012	0.138	0.138
Dreunberg	132kV Bus 2	132	3.17	-71.293	724	7.716	22.786	24.057
Melkspruit	132kV Bus 1	132	4.99	-77.668	190	0.543	2.485	2.544
Melkspruit	22kV Bus 1	22	4.99	-77.668	190	0.543	2.485	2.544
Melkspruit	22kV Bypass Bus	22	1.87	-73.86	214	5.65	19.524	20.325
Riebeek	132kV Bus 1	132	1.93	-71.407	221	6.289	18.696	19.725
Riebeek	132kV Bus 2	132	1.53	-78.832	58	1.603	8.121	8.278
Riebeek	22kV Bus 1	22	1.53	-78.832	58	1.603	8.121	8.278
Riebeek	22kV Riebeek Trfr	22	1.27	-84.24	48	1.007	9.987	10.037
Riebeek	22kV Riebeek Trfr	22	1.19	-68.469	271	23.558	59.71	64.189
Riebeek	66kV Bus 1	66	1.19	-68.469	271	23.558	59.71	64.189
Sterkspruit	22kV Bus 1	22	2.32	-67.103	88	2.133	5.05	5.482
Sterkspruit	22kV Bypass Bus	22	2.32	-67.103	88	2.133	5.05	5.482
Sterkspruit	66kV Bus 1	66	0.94	-62.638	107	18.696	36.128	40.679
Steynsburg	11kV Bus 1	11	1.05	-65.464	20	2.504	5.486	6.03
Steynsburg	22kV Trfr HV	22	0.66	-60.969	25	9.27	16.703	19.103
Witkrans	22kV Bus 1	22	1.83	-67.924	70	2.612	6.439	6.949
Witkrans	66kV Bus 1	66	0.8	-61.471	92	22.692	41.742	47.511

3.7 Load flow Data from Load Test Report

Table 3 below provides measured values compared to the nominal voltages, thus computing the actual operating p.u. values for the power flow of the Aliwal North sector power system, focusing strongly on the voltage levels of the high voltage busbar side at each of substations, this data is extracted from annual load test report for more info on this refer to Appendix D. This data will be used for DigSilent load flow simulation in chapter 4.

Table A3: Summary of the ECOU power flow.

ZONE	Station	Bus-Bar	Nominal Voltage (kV)	Measured Voltage (kV)	Measured Voltage (p.u.)
QUEENSTOWN	Witkraans	66kV Bus1	66	60.95	0.94
ALIWAL NORTH	Riebeek	66kV Bus1	66	62.51	0.95
ALIWAL NORTH	Sterkspruit	66kV Bus1	66	59.25	0.92
ALIWAL NORTH	Rouxville	66kV Bus1	66	61.32	0.90
ALIWAL NORTH	Melkspruit	132kV Bus1	132	126.23	0.92

CHAPTER 4: DATA ANALYSIS

4.1 Introduction

This chapter discusses the results using the appropriate tools and methods of manual calculations using the data obtained in chapter 3, as it is the main objective of the thesis to prove in both simulation technics and calculations. The 132/66/22 kV distribution network analysed is that of Aliwal North power system. Most of the data used in this chapter can also be found in Appendices B-K. The expectation of this chapter is to provide adequate reliability analysis of the Aliwal North power system.

The reliability of power system has been and continues to be of major concern in terms of continuity and quality of supply in power system operation. The ideal approach to study the reliability phenomena in a power system is by simulating the power system using suitable reliability tool in DigSilent software. The DigSilent program currently available on the market represents the power system components with genuine realistic models.

These models generally match and represent the characteristics of the components while keeping the complexity of the models to a minimum. Beside presenting a convenient way to generate the required signals and parameters to analyse power systems feature (in this case the reliability schemes), DigSilent also allows the users to study the worst case scenarios that are unlikely to occur in real life, making it possible to cater for unreliable situation that are rare based on the parameters that the software uses. In order to validate the concept of reliability discussed in the previous chapters, the simulations are carried out using DigSilent and the models are based on the real networks. As with the FMEA method, the overhead lines, cables and transformers outages are considered since they are the components that are exposed to the failures.

4.2 Reliability Evaluation of 132 kV network.

As it is outlined on the topic of the dissertation, this section evaluates reliability of the 132/66/22 kV network for the Aliwal North power system Network current performance using the historical data of fault statistics from DMS software and plant performance data. The performance of the reliability indices will be evaluated and modelled using the network in DigSilent in conjunction with Failure Mode and Effect Analysis.

4.2.1 Failure Mode and Effect Analysis Results

As mentioned in chapter 2, FMEA is used to evaluate the contingencies of the components failing and to see how this affects the load points. The failure mode is identified in such a way that component outages overlap to cause system outage. These events are called as overlapping outages and the associated outage time are called overlapping outage time. At this point only components failures are considered. Each overlapping outage that effectively causes system failure as a set of series or parallel elements can be evaluated using equations for series or parallel components; the following analysis is that of the FMEA, data used in the following analysis was taken from network events failures, see appendix B for the duration and type or causes of events.

$$SAIFI = \frac{3.14\times160+3.438\times600+5.95\times160+5.964\times760+5.95\times100+5.95\times160+5.95\times100}{2040}$$

$$+\frac{7.753\times160+10.689\times160+10.11\times160+10.11\times160+10.11\times100+10.11\times200+10.11\times680}{1620}$$

$$SAIFI = \frac{10{,}291.84+16{,}093.72}{2040+1620} = 7.20916\ interuption/customer.yr$$

$$SAIDI = \frac{25.12\times160+27.5\times600+47.6\times160+47.71\times760+47.6\times100+47.6\times160+47.6\times100}{2040}$$

$$+\frac{62.02\times160+85.51\times160+80.87\times100+180.87\times160+80.87\times680+80.87\times200+80.87\times160}{1620}$$

$$SAIDI = \frac{81530.8 + 128{,}735.8}{2040 + 1620} = 57.45\ hours/customer.yr$$

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{57.45}{7.20916} = 7.969\ hours/customer\ interuption$$

$$ASAI = \frac{3660 \times 8760 - (81530.8 + 128{,}735.8)}{3660 \times 8760} = 0.9934417$$

$$ASUI = 1 - ASAI = 0.006553$$

$$\begin{aligned} ENS = {} & 25.12 \times 160 + 27.5 \times 600 + 47.6 \times 160 + 47.71 \times 760 + 47.6 \times 100 + 47.6 \times 160 + 47.6 \times 100 \\ & \times 62.02 \times 160 + 85.51 \times 160 + 80.87 \times 100 + 180.87 \times 160 + 80.87 \times 680 + 80.87 \times 200 \\ & + 80.87 \times 160 \\ = {} & 210{,}266.6KWhr/yr\ \ OR\ 210.266MWhr/yr \end{aligned}$$

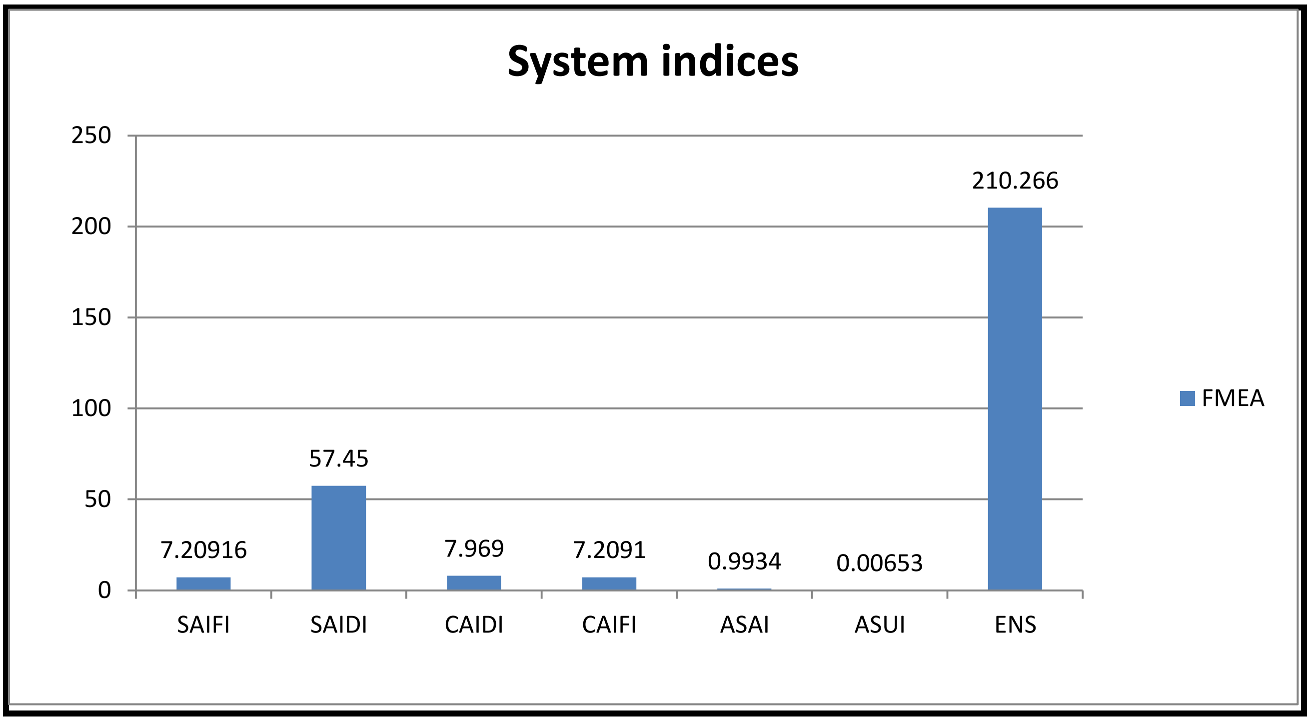


Figure 25: FMEA reliability indices assessment results

4.2.2 DigSilent Simulation Results

Reliability analysis can be defined as an automation and probabilistic extension of contingency evaluation. In DigSilent the author is not required to pre-define outage events, but can optionally select that all possible outages are measured for analysis. The significance of each outage is considered using historical data about the expected duration and frequency of outages according to component type.

Figure 26 and 27 shows DigSilent results as obtained from the 132 kV network case study, the former is the screen short from DigSilent and the latter is the excel format of the DigSilent results. These results illustrate the impact of the fault or an outage that takes place on the Dreunberg/Melkspruit 132 kV network towards the system reliability of the Aliwal North network and it customers.

```
|                |                                                       |   DIgSILENT    | Project:
|                |                                                       | PowerFactory   |-----------------------------
|                |                                                       |    14.0.511    | Date:  09/19/2014
-----------------------------------------------------------------------------------------------------------------
| Reliability Assessment
| -
| - Network, connectivity analysis
-----------------------------------------------------------------------------------------------------------------
| Selection    = Whole System
| No    = Common mode                             | No    = Independent second failures
| Yes   = Busbars / terminals                     | No    = Double earth faults
| Yes   = Lines / cables                          | Yes   = Generators/external grids
| Yes   = Transformers                            | No    = Maintenance
-----------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                          | Annex:               / 1
-----------------------------------------------------------------------------------------------------------------
| System Summary
-----------------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index       :  SAIFI: =     7.687860 1/Ca
| Customer Average Interruption Frequency Index     :  CAIFI: =     7.687860 1/Ca
| System Average Interruption Duration Index        :  SAIDI: =    61.503    h/Ca
| Customer Average Interruption Duration Index      :  CAIDI: =     8.000    h
| Average Service Availability Index                :  ASAI:  =     0.9929791236
| Average Service Unavailability Index              :  ASUI:  =     0.0070208764
| Energy Not Supplied                               :  ENS:   =   139.713    MWh/a
| Average Energy Not Supplied                       :  AENS:  =     9.979    MWh/Ca
| Average Customer Curtailment Index                :  ACCI:  =     5.898    MWh/Ca
| Expected Interruption Cost                        :  EIC:   =     0.000    M$/a
| Interrupted Energy Assessment Rate                :  IEAR:  =     0.000    $/kWh
| System energy shed                                :  SES:   =     0.000    MWh/a
-----------------------------------------------------------------------------------------------------------------
```

Figure 26: PowerFactory results from the results window

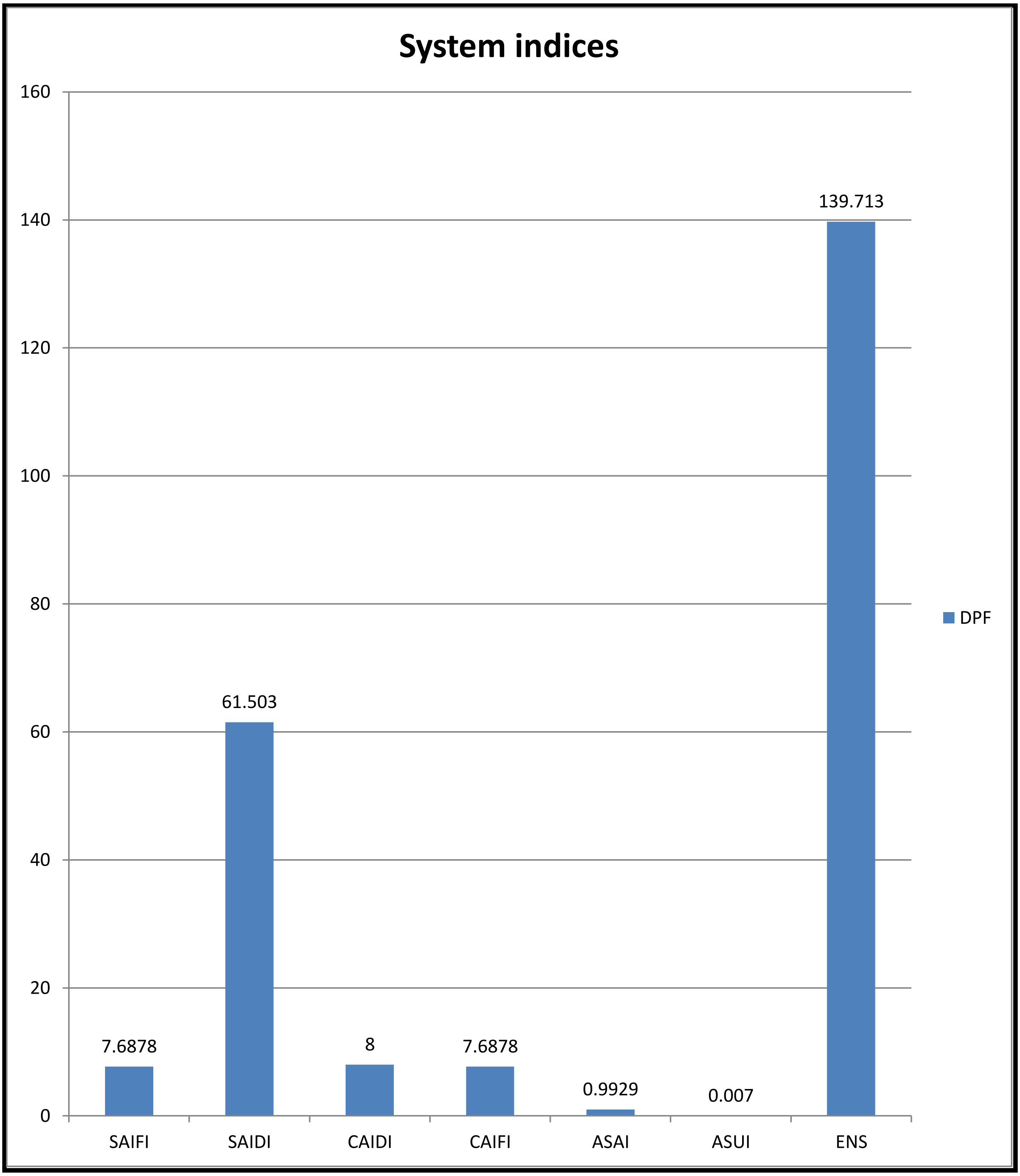


Figure 27: PowerFactory results in tabled form.

4.2.3 Comparison of DigSilent vs FMEA results (132 kV System)

Table A4: Comparison of results from FMEA and DigSilent on 132 kV reliability evaluation

INDICES	FMEA	DPF	%DIFFERENCE of (FMEA in relation to DPF)
SAIFI	7.20916	7.6878	6.22%
SAIDI	57.45	61.503	6.59%
CAIDI	7.969	8	0.39%
CAIFI	7.20916	7.6878	6.22%
ASAI	0.993442	0.992979	0.05%
ASUI	0.006553	0.00702	6.60%
ENS	210.266	139.713	50.50%

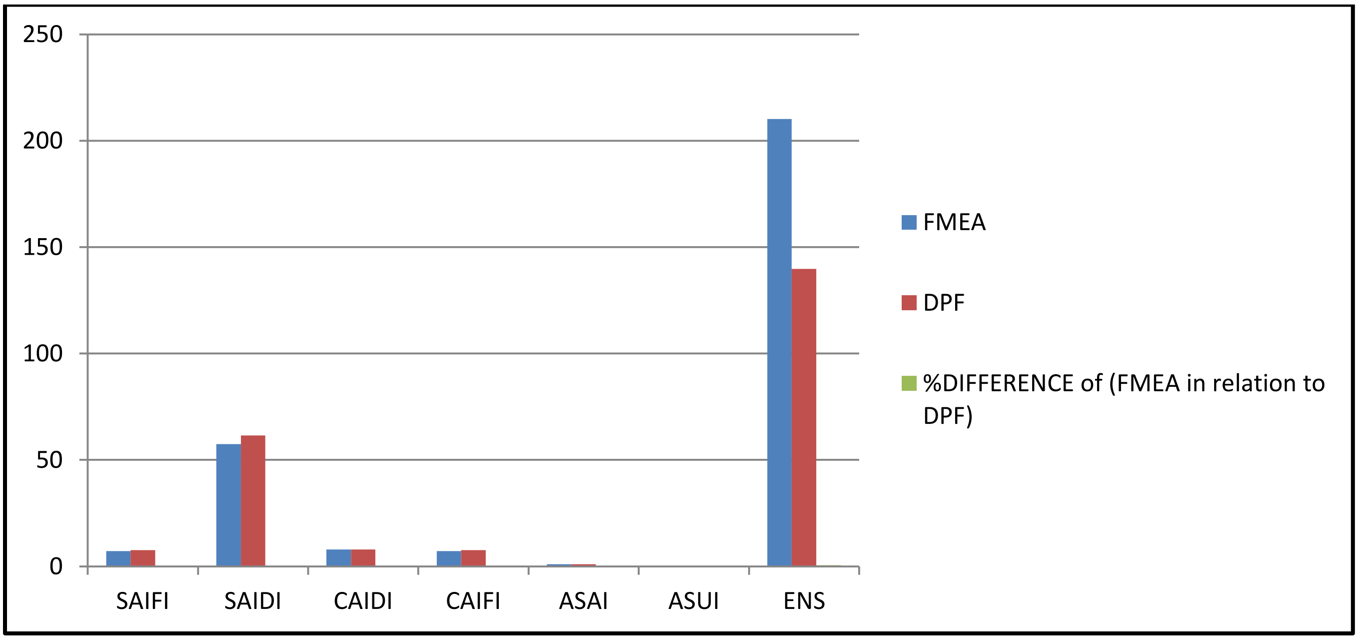


Figure 28: Data Comparison from FMEA and DigSilent (PowerFactory)

From table A4 the two methods have given results that are very close to a degree that the difference shown is minimal. A percentage difference of 50.50 is seen for the ENS results was caused by the lack of sufficient data and therefore alternative formulae's and means were used to obtained results (the kVA is used instead of the number of customer interrupted). Although both methods as provide a high degree of accuracy, DIgSilent is still the preferred choice Based on the fact that the case file is scaled using the real time data from SCADA system and the data measured from the field. This includes the convenience of simulating larger networks, the accuracy of the software (based on data accuracy), the graphical representation of the obtained data etc.

4.2.4 Failure Mode and Effect Analysis and DigSilent results for 66 kV network

Similarly to the analysis of the 132 kV network using the FMEA and DigSilent (PowerFactory), same method and technique will apply in the 66 kV network. The difference is the voltage level and the customer base affected.

$$SAIFI = \frac{8103.72 + 13763.68}{2040 + 1620}$$

$$= 5.9758\ interuption/customer.yr$$

$$SAIDI = \frac{61320.7 + 112685.9}{2040 + 1620}$$

$$= 47.528\ hours/customer.yr$$

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{47.528}{5.9758} = 7.953\ hours/customer\ interuption$$

$$ASAI = \frac{3660 \times 8760 - (61320.7 + 112685.9)}{3660 \times 8760} = 0.995$$

$$ASUI = 1 - 0.995 = 0.0054$$

$$ENS = 61320.7 + 112685.9$$

$$= 174.01\ MWhr/yr$$

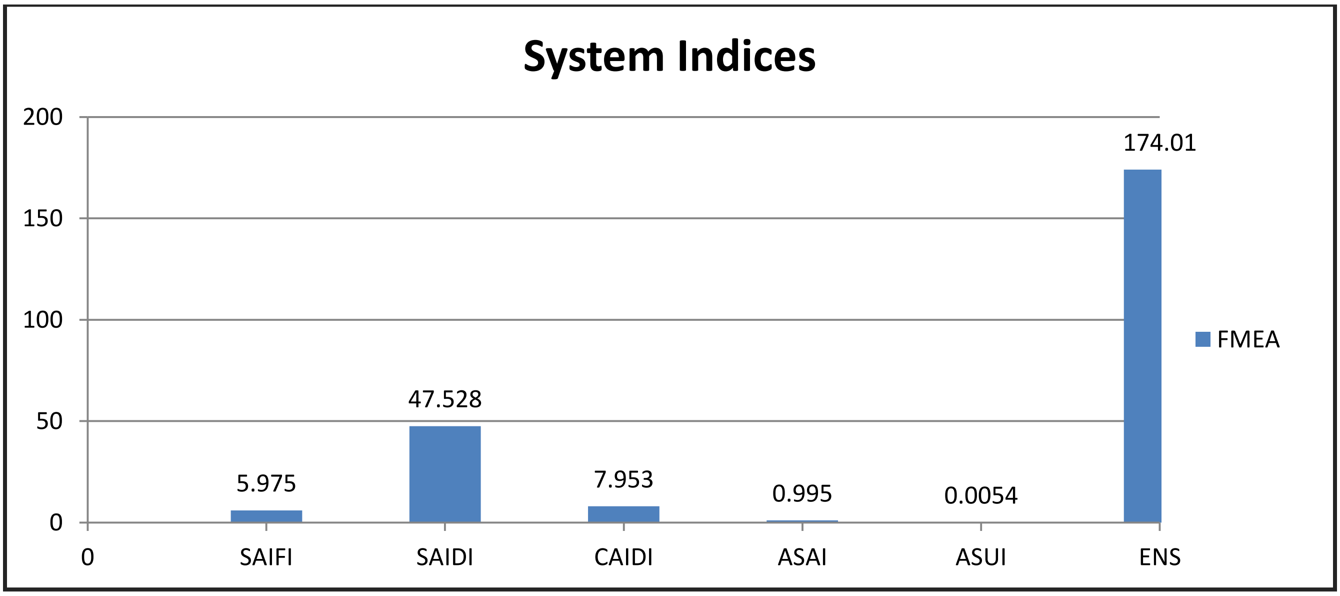
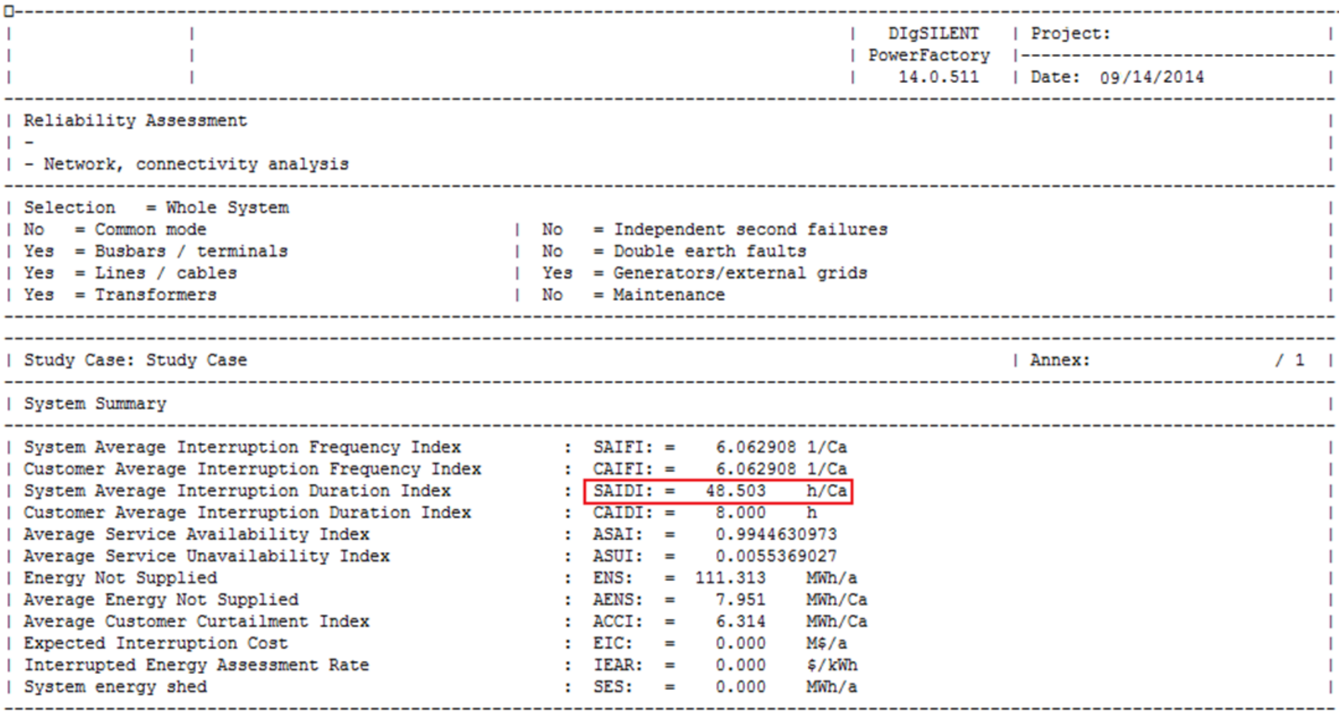


Figure 29: FMEA 66 kV reliability analysis results



```
|                 |                                                             | DIgSILENT   | Project:                      |
|                 |                                                             | PowerFactory |------------------------------
|                 |                                                             | 14.0.511    | Date:  09/14/2014             |
------------------------------------------------------------------------------------------------------------------------------------
| Reliability Assessment                                                                                                           |
| -                                                                                                                                |
| - Network, connectivity analysis                                                                                                 |
------------------------------------------------------------------------------------------------------------------------------------
| Selection   = Whole System                                                                                                       |
| No    = Common mode                                 | No    = Independent second failures                                        |
| Yes   = Busbars / terminals                         | No    = Double earth faults                                                |
| Yes   = Lines / cables                              | Yes   = Generators/external grids                                          |
| Yes   = Transformers                                | No    = Maintenance                                                        |
------------------------------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                                              | Annex:              / 1   |
------------------------------------------------------------------------------------------------------------------------------------
| System Summary                                                                                                                   |
------------------------------------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index         :  SAIFI: =     6.062908 1/Ca                                              |
| Customer Average Interruption Frequency Index       :  CAIFI: =     6.062908 1/Ca                                              |
| System Average Interruption Duration Index          :  SAIDI: =    48.503     h/Ca                                             |
| Customer Average Interruption Duration Index        :  CAIDI: =     8.000     h                                                |
| Average Service Availability Index                  :  ASAI:  =     0.9944630973                                               |
| Average Service Unavailability Index                :  ASUI:  =     0.0055369027                                               |
| Energy Not Supplied                                 :  ENS:   =   111.313     MWh/a                                            |
| Average Energy Not Supplied                         :  AENS:  =     7.951     MWh/Ca                                           |
| Average Customer Curtailment Index                  :  ACCI:  =     6.314     MWh/Ca                                           |
| Expected Interruption Cost                          :  EIC:   =     0.000     M$/a                                             |
| Interrupted Energy Assessment Rate                  :  IEAR:  =     0.000     $/kWh                                            |
| System energy shed                                  :  SES:   =     0.000     MWh/a                                            |
------------------------------------------------------------------------------------------------------------------------------------
```

Figure 30: DigSilent (PowerFactory) 66 kV reliability simulation results

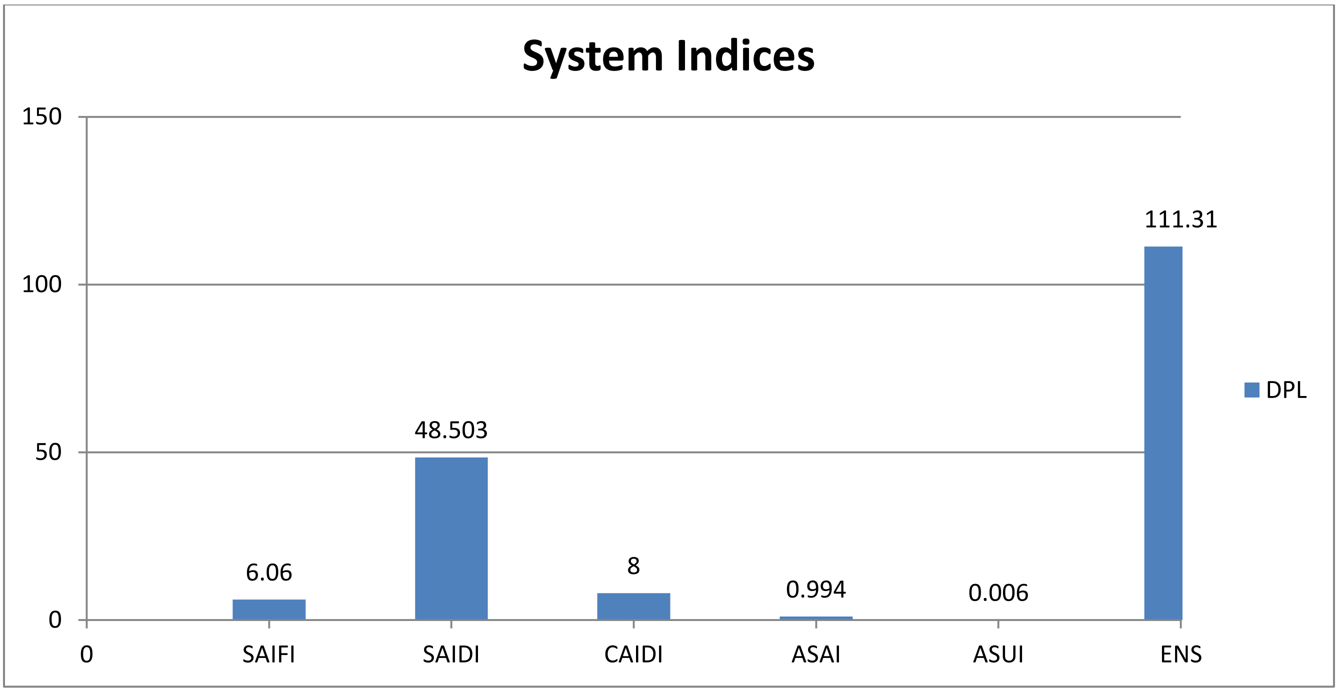


Figure 31: DigSilent (PowerFactory) 66 kV reliability graphical representation results

4.2.5 Comparison of DigSilent vs FMEA results (66 kV System)

Table A5: Comparison of results from FMEA and DigSilent of 66 kV reliability evaluation

INDICES	FMEA	DPF	%DIFFERENCE of (FMEA in relation to DPF)
SAIFI	5.9758	6.0629	1.46%
SAIDI	47.528	48.503	2.05%
CAIDI	7.953	8	0.59%
ASAI	0.995	0.99446	0.05%
ASUI	0.0054	0.00554	2.59%
ENS	174.01	111.313	36.03%

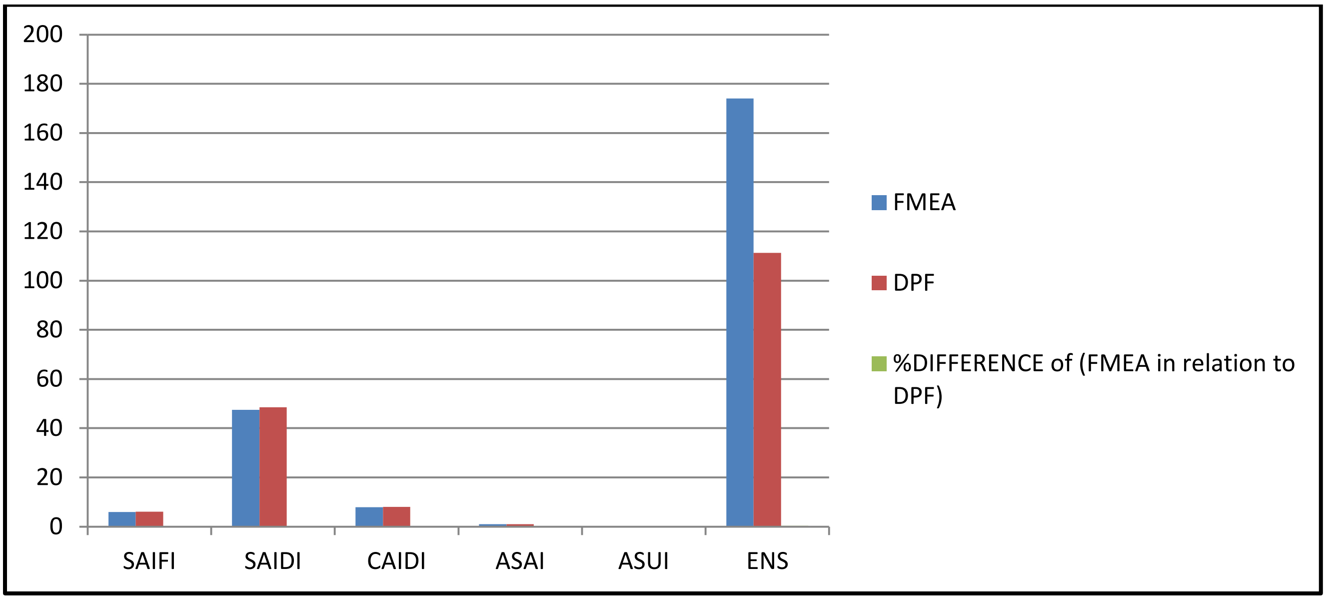


Figure 32: Data Comparison from FMEA and DigSilent in graph format

Similarly to the 132 kV analyses, from table A5 the two methods have given results that are very close to a degree that the difference shown is minimal, almost zero. A percentage difference of 36.03 is seen for the ENS. This is due to the lack of sufficient data and therefore alternative formula and means were used to obtained results (the kVA is used instead of the number of customer interrupted). Although both methods show some degree accuracy, DIgSilent is still the number one choice due to much advantage that is linked with it. This includes the convenience of simulating larger networks, the graphical representation of the obtained data etc.

4.2.7 PowerFactory Simulations for 22 kV network Failure Mode and Effect Analysis

$$SAIFI = \frac{4.236 \times 210 + 4.236 \times 210 + 4.236 \times 1 + 4.2165 \times 240 + 4.2263 \times 1 + 4.2165 \times 240 + 4.236 \times 15}{917}$$

$$= 4.2212\ interuption/customer.yr$$

$$SAIDI = \frac{35.559 \times 210 + 35.559 \times 210 + \ 35.598 \times 1 + 35.50 \times 240 + 35.549 \times 1 + 35.50 \times 240 + 36.37 \times 15}{917}$$

$$= 35.542\ hours/customer.yr$$

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{35.542}{4.2212} = 8.420\ hours/customer\ interuption$$

$$ASAI = \frac{917 \times 8760 - (35.542)}{917 \times 8760} = 0.999999$$

$$ASUI = 1 - 0.999999 = 0.000004$$

$$ENS = \ 3.559 \times 210 + 3.559 \times 210 + \ 3.598 \times 1 + 3.50 \times 240 + 3.549 \times 1 + 3.50 \times 240 + 3.637 \times 15$$

$$= 167.01\ MWhr/yr$$

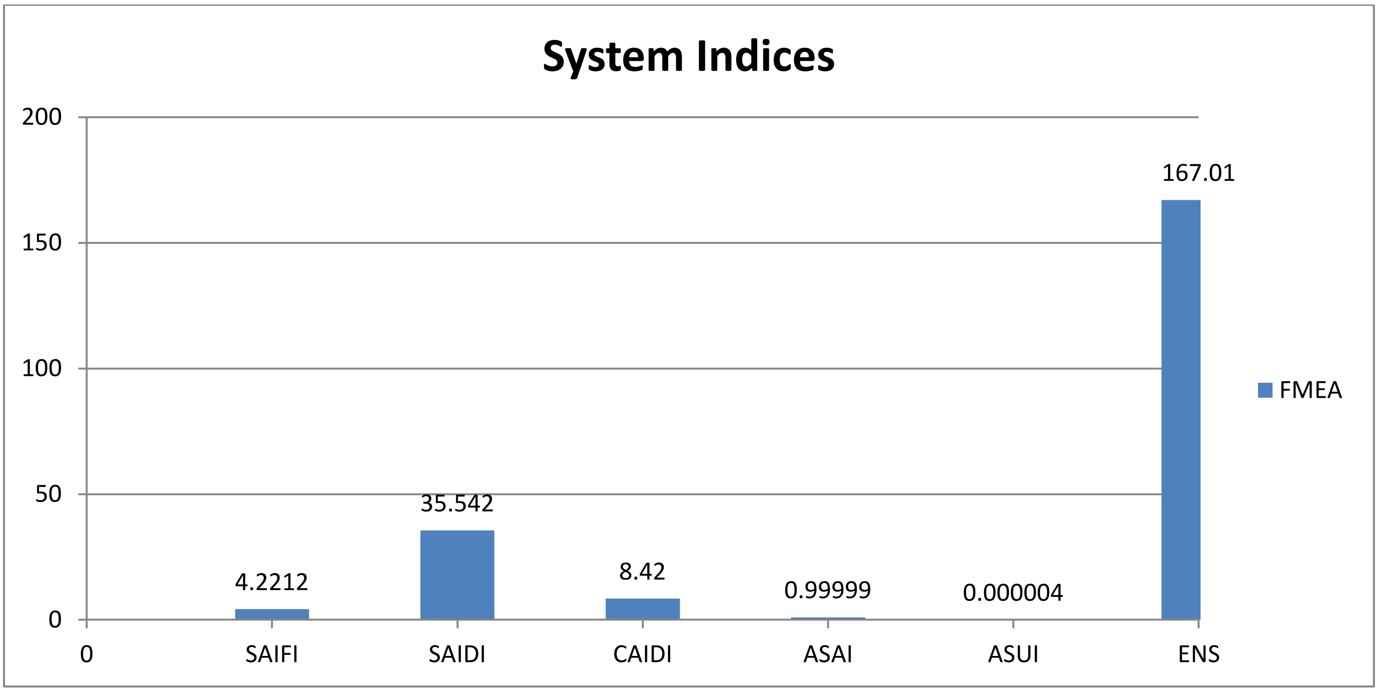


Figure 33: Data Comparison from FMEA and DigSilent (PowerFactory)

4.2.8 PowerFactory Simulations for 22 kV network

```
|                 |                                                      |   DIgSILENT   | Project:                        |
|                 |                                                      | PowerFactory  |---------------------------------|
|                 |                                                      |   14.0.511    | Date:  09/15/2014               |
| Reliability Assessment                                                                                                      |
| -                                                                                                                           |
| - Network, connectivity analysis                                                                                            |
| Selection    = Whole System                                                                                                 |
| No    = Common mode                              |  No    = Independent second failures                                     |
| Yes   = Busbars / terminals                      |  No    = Double earth faults                                             |
| Yes   = Lines / cables                           |  Yes   = Generators/external grids                                       |
| Yes   = Transformers                             |  No    = Maintenance                                                     |
| Study Case: Study Case                                                                                  | Annex:        / 1 |
| System Summary                                                                                                              |
| System Average Interruption Frequency Index            :  SAIFI: =     4.513897 1/Ca                                        |
| Customer Average Interruption Frequency Index          :  CAIFI: =     4.513897 1/Ca                                        |
| System Average Interruption Duration Index             :  SAIDI: =    36.111     h/Ca                                        |
| Customer Average Interruption Duration Index           :  CAIDI: =     8.000     h                                           |
| Average Service Availability Index                     :  ASAI:  =     0.9958777200                                          |
| Average Service Unavailability Index                   :  ASUI:  =     0.0041222800                                          |
| Energy Not Supplied                                    :  ENS:   =   184.373     MWh/a                                       |
| Average Energy Not Supplied                            :  AENS:  =     6.027     MWh/Ca                                      |
| Average Customer Curtailment Index                     :  ACCI:  =     4.563     MWh/Ca                                      |
| Expected Interruption Cost                             :  EIC:   =     0.000     M$/a                                        |
| Interrupted Energy Assessment Rate                     :  IEAR:  =     0.000     $/kWh                                       |
| System energy shed                                     :  SES:   =     0.000     MWh/a                                       |
```

Figure 34: DigSilent (PowerFactory) 22 kV reliability simulation results

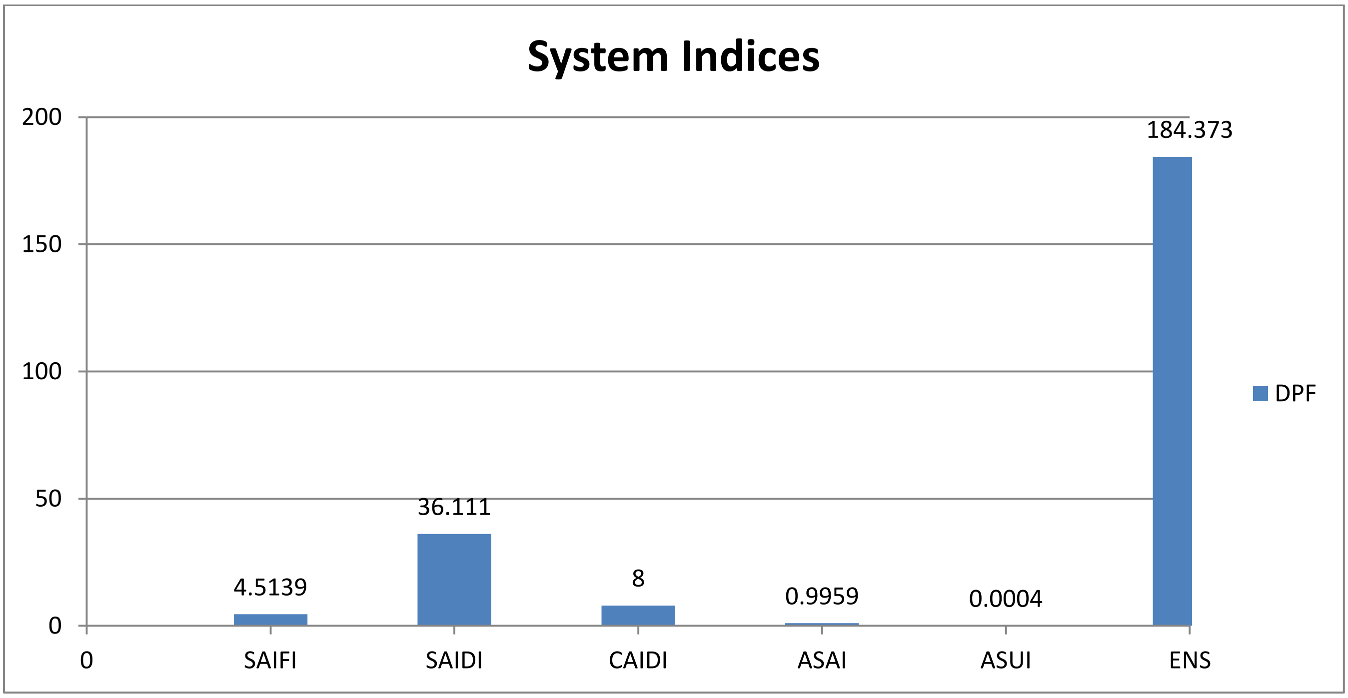


Figure 35: Data Comparison from FMEA and DigSilent (PowerFactory)

4.2.9 Comparison of DigSilent vs FMEA results (22 kV System)

Table A6: Data Comparison from FMEA and DigSilent (PowerFactory)

INDICES	FMEA	DPF	%DIFFERENCE of (FMEA in relation to DPF)
SAIFI	4.2212	4.5139	6.93%
SAIDI	35.542	36.111	1.60%
CAIDI	8.42	8	4.99%
ASAI	0.9999	0.9959	0.40%
ASUI	0.000004	0.000004	0.00%
ENS	167.01	184.373	10.40%

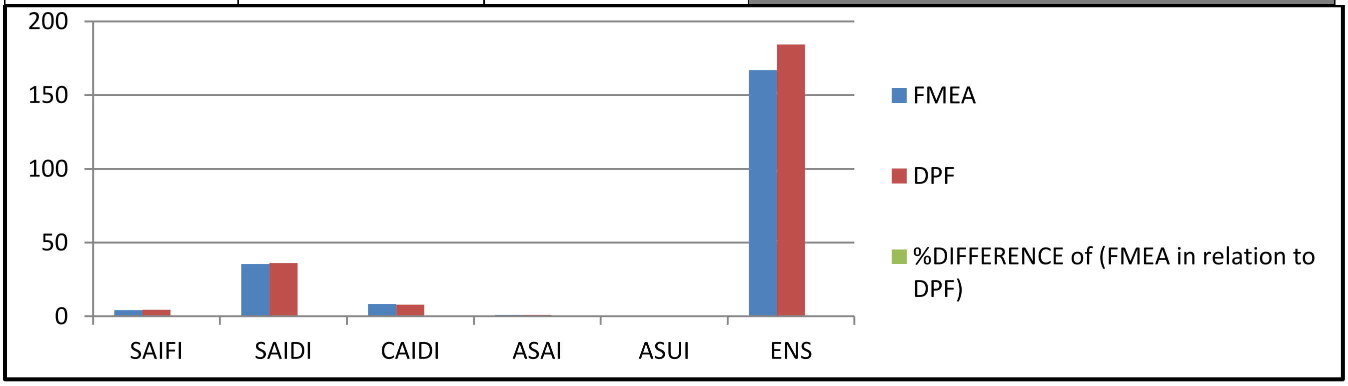


Figure 36: Data Comparison from FMEA and DigSilent

Similarly to scenario 1 and 2 (132 and 66 kV), based on table A6 the two methods have given results that are very close to a degree that the difference shown is negligible (zero). A percentage difference of 10.40 is experience for the ENS. This is due to the lack of sufficient data and therefore alternative formulae's and means were used to obtained results (the kVA is used instead of the number of customer interrupted). Although both method as shown a high degree of accuracy, DigSilent is still the number one choice due to many advantage that are linked with it. This includes the convenience of simulating larger networks, the accuracy of the software, the graphical representation of the obtained data etc.

Due to this significant difference between PowerFactory and FMEA, the solution was that DigSilent results are the most trustworthy, because DigSilent incorporates all embedded conductor parameters that FMEA ignores or assume a certain value to them, based on the input data used to compute the Microsoft Excel script. This was the conclusion that was reached after simulating all three scenarios. This statement is supported by the fact that DigSilent case file is scaled using the SCADA system data and the data from the field and the case file parameters are set in such a way that they represent the real life system as this tool is used to simulate planned and unplanned outage.

4.3 Load Flow Analysis using Digsilent

In Figure 37 below, the snapshot of DigSilent simulation results, thus taking a closer look at the 132 and 66 kV busbar voltages. The case file simulated on DigSilent was scaled using the real time data input from the Data Management System DMS and that of the load test report, to ensure that the results obtained are as accurate as possible. All the parameters on DigSilent are assumed to be correct by applying the correct setting, furthermore based on the fact that the case file has been scaled with the correct input data from the SCADA system and field. These results as show that the Aliwal North power system become very constraint during peak leading season such winter, it is show on figure 37 that 132 kV busbar is operating at 125 kV during peak (0.93 pu), whereas the 66 kV busbar at Riebeek and Sterkspruit substation experiences lower voltages up to 57 kV (0.86 pu) and 53 kV (0.80 pu). These are too low as per NRS048-4 standard, (see table A8). This motivates the alternative source of supply in the area; the benefit will also be addressing the system to operate within acceptable voltage levels as recommended by national energy regulator.

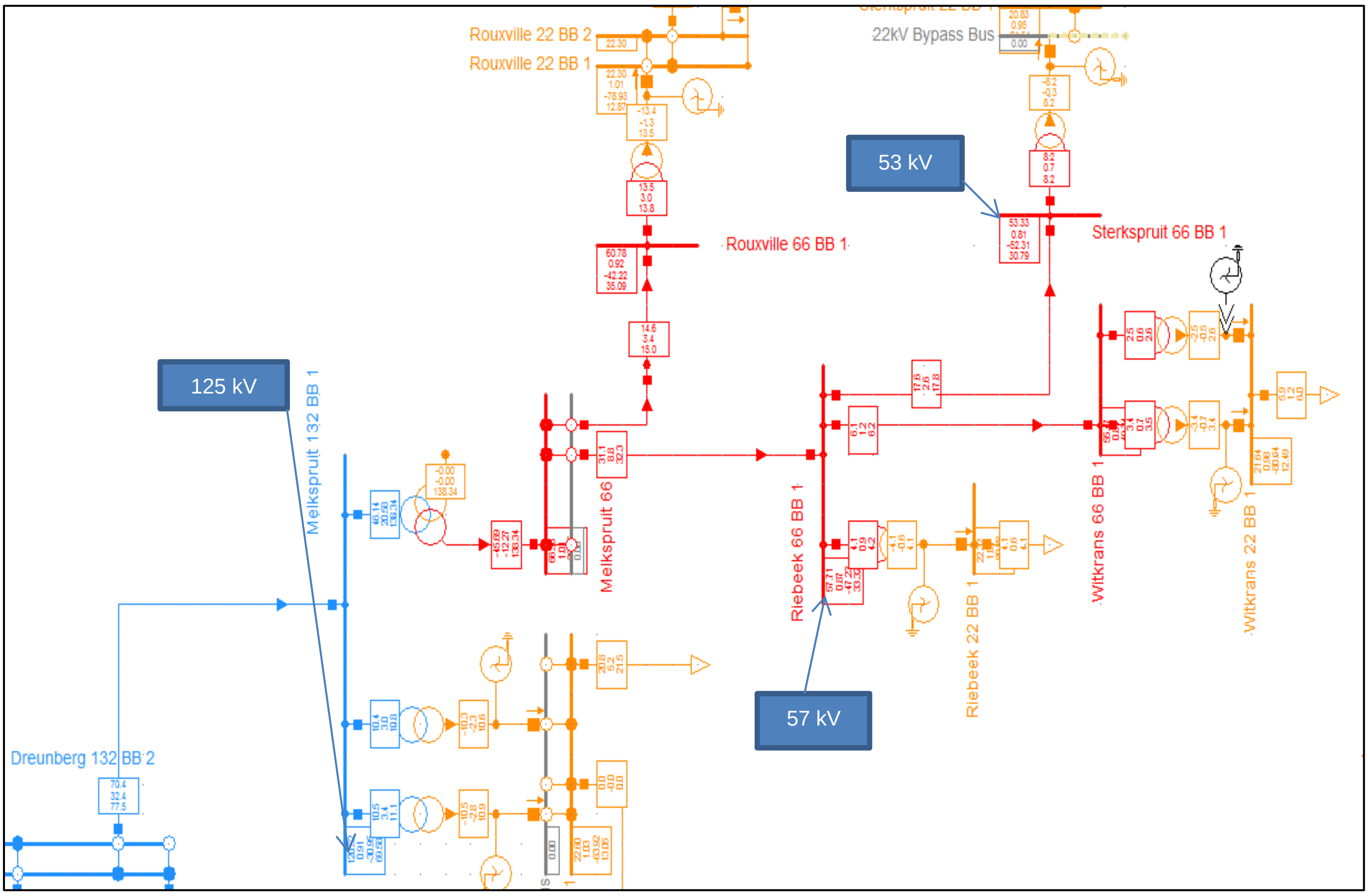


Figure 37: PowerFactory Results for the loading of Aliwal North Sector network

Table A7: Reliability assessment command

LINE NAME	CONDUCTOR TYPE	RATING-MVA	DPF SIMULATION-MVA	UTILISATION-%
Dreunberg/Melkspruit 132 kV	Wolf	101.5	77.5	76.4
Melkspruit/Riebeek 66 kV	Hare	38.8	32.3	83.2
Melkspruit/Rouxville 66 kV	Rabbit	29.2	15	51.4
Riebeek/Sterkspruit 66 kV	Hare	38.3	17.8	46.5
Riebeek/Witkrans 66 kV	Hare	38.3	6.2	16.2
Sterkspruit/LowerTelle 22 kV	Fox	6.6	3.8	57.6
Riebeek/Lady Grey 22 kV	Mink	9.2	3.6	39.1
Witkrans/Barkley East 22 kV	Rabbit	8.8	4.9	55.7
Melkspruit/Goedmoed 22 kV	Rabbit	8.8	7.2	81.8
Rouxville/Zastron 22 kV	Rabbit	8.8	3.5	39.8

Then the table A7 above is the test of the PowerFactory simulation results to check the utilisation factor of the conductor. The colour red symbolises the conductor that used to almost its limits, yellow symbolises that conductor that is in mid-range and the green symbolises the lightly loaded conductor.

The voltages shall not exceed the voltage limits specified in table A8 below, this table is extracted from NRS 048-2 standard.

Table A8: Voltage limits as per NRS048 standard

NORMINAL VOLTAGE (kV)	MAXIMUM VOLTAGE (kV)	MINIMUM VOLTAGE (kV)
400	420	380
275	289	261
220	231	209
132	139	125
88	93	84
66	69	63
44 and Below	**Nominal Voltage +10%**	**Nominal Voltage -10%**

According to the quality of supply standard document NRS048-2, the declared voltages at the substation busbar level must be within ±5% of the nominal voltage. In the Aliwal North case study the declared voltages are those simulated from DigSilent and the voltage results are for the 66 kV busbars are below the 63 kV lower limits according to table A8. At Melkspruit 132 kV busbar simulated voltages are at 125 kV which is exactly at the boundary limits. But not as bad compared to the 66 kV voltages at Riebeek and Sterkspruit Substations which are 57 kV and 53 KV respectively.

4.4 Power Quality

Power Quality (PQ) analysis in relation to the reliability improvement of the Aliwal North power system. PQ components that are going to be dealt with in this analysis are components such as Voltage Swells, Voltage Imbalance, Harmonic Distortion, Voltage Regulation, Voltage Dips and Voltage Flickers.

4.4.2 Voltage Imbalance analysis

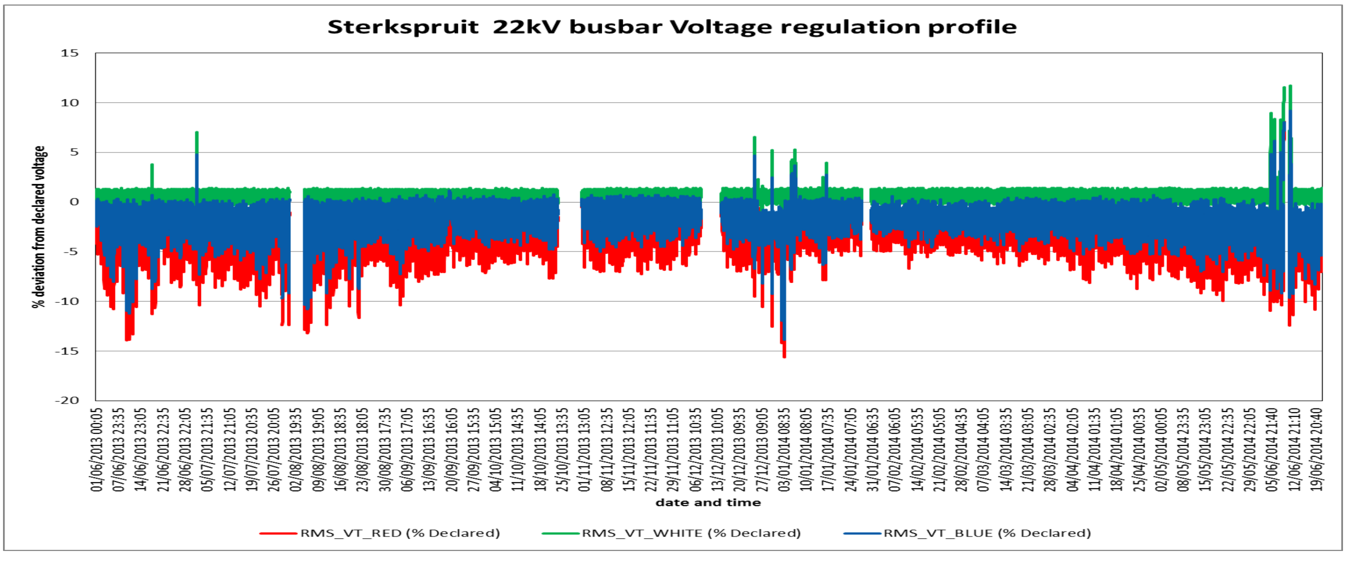


Figure 38: Voltage Profile for unbalanced.

According to the voltage unbalance profile from figure 38 above it is clear that the issue of voltage imbalance on the Sterkspruit Substation 22 kV busbar occurs mainly, during evening and morning peak. This unbalance was noticeably due to the fact that it exceeded the 2% voltage imbalance limit. Moreover the profile also shows that during winter period this voltage unbalance becomes worse in this area. DigSilent (PowerFactory) simulations in figure 39 below show that the phases A and B are the most unbalanced feeders.

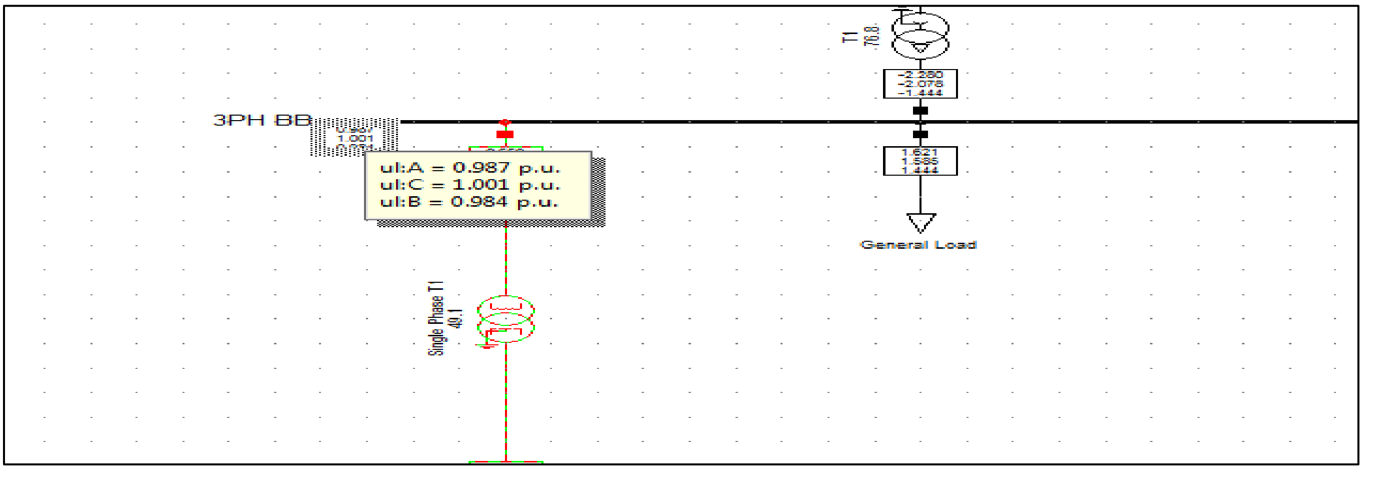


Figure 39: PowerFactory unbalanced results.

Table A9: Voltage or Load Balancing using a spreadsheet

Sterkspruit - LowerTelle 22 kV									
SPUR NAME	**EXISTING PHASING kVA**				**PROPOSED PHASING kVA**				
	ACB	**AC**	**AB**	**CB**	**ACB**	**AC**	**AB**	**CB**	
JMKK003-4			**57**		**64**	**32**	**57**		
JMKK003-10			**16**						
JMKK003-11				**105**	**16**			**105**	
JMKK003-17	**50**		**32**						Move **A**$_{ph}$ to **C**$_{ph}$
JMJL023-5			**64**	**32**		**32**			Move **A**$_{ph}$ to **C**$_{ph}$
JMGK004-112			**50**		**32**				Move **A**$_{ph}$ to **C**$_{ph}$
JMGK004-115		**32**							
JMGK004-118		**25**			**25**				
JMGK004-120			**16**			**16**			Move **B**$_{ph}$ to **C**$_{ph}$
JMGJ001-2			**32**				**32**		
JMGJ001-3			**25**				**25**		
JMGJ001-4	**25**				**25**	**50**			
JMGJ001-8			**32**				**32**		
JMGJ001-10		**32**				**32**			
JMGJ001-11				**64**				**64**	
TOTAL kVA	**75**	**89**	**324**	**201**	**162**	**155**	**146**	**169**	

Table A9 illustrates the simpler approach to solve the voltage unbalance problem, which steered desirable results, it was used to balance the installed loading kVA connected per phase. This analysis was triggered by the voltage unbalanced on the 22 kV busbar at Sterkspruit Substation as shown in figure 38. Out of interest the, one out of four 22 kV feeders fed from the 22 kV busbar was selected to check its load balancing, then Table A9 shows the existing load in kVAs per phase the total highlighted in yellow shows that it is out of balance (phases AC – 89 and phase AB – 324). Then the corrective method was used on the proposed table then the results shows that the voltage unbalanced can be resolved, by balancing the loading per phase. This was carried out considering the electrification plan in the same network in order to balance the phases. The desired results show that feeders are within the acceptable range of voltage balancing as outline by NRS048-4.

4.4.2 Voltage Flicker analysis

During energy and power quality audit of Sterkspruit municipality, it is observed that presently only two induction motors (induction motor1-IM1 and induction motor2-IM2, rated at 450 kW each) are used for one of its water pumping facility and want to connect two additional induction motors (induction motor3-IM3 and induction motor-IM4, rated at 450 kW each) to increase the water pumping capacity. In this case study, simplified assessment methods applied for evaluating the connection of a new IM3 and IM4 induction motor loads to an existing network. Short term voltage flicker level observed during the start-up of the induction motors (IM1 and IM2) at point of common coupling 2 (PCC2), see figure 41. given in Table A10.

Table A10: Short term flicker severity measured for IM_1 and IM_2

INDUCTION MOTORS-IM1&IM2)	Short Time flicker	Short Time flicker levels
When Does not Operate (PST')	0.45	0.9
When Operate (PST')	0.70	0.9

As an induction motor is started up, most of the power drawn by the motor is reactive. This resulted in a large voltage drop across distribution lines. Measured powers of IM1 and IM2 when operates simultaneously is shown in Table A11.

Table A11: Power variations of Induction Motors IM_1 and IM_2

INDUCTION MOTORS-IM1& IM2	Active Power (P) in kW	Reactive Power (kVAr)	Apparent Power (kVA)
When operates with full load	871	445.32	978.24
Difference of Min/Max Power Variations	6.6	4.34	7.8

From Table A11 it is observed that there is a variation in both active and reactive part of the power. Dynamic voltage fluctuations are usually caused by the starting and stopping of motors. Here as per water demand, discharge pipe valve setting of an induction motors keeps on changing. Although a single induction motor alone may not generate flicker complaints, the cumulative effect of several motors starting randomly on a distribution feeder can generate objectionable flicker.

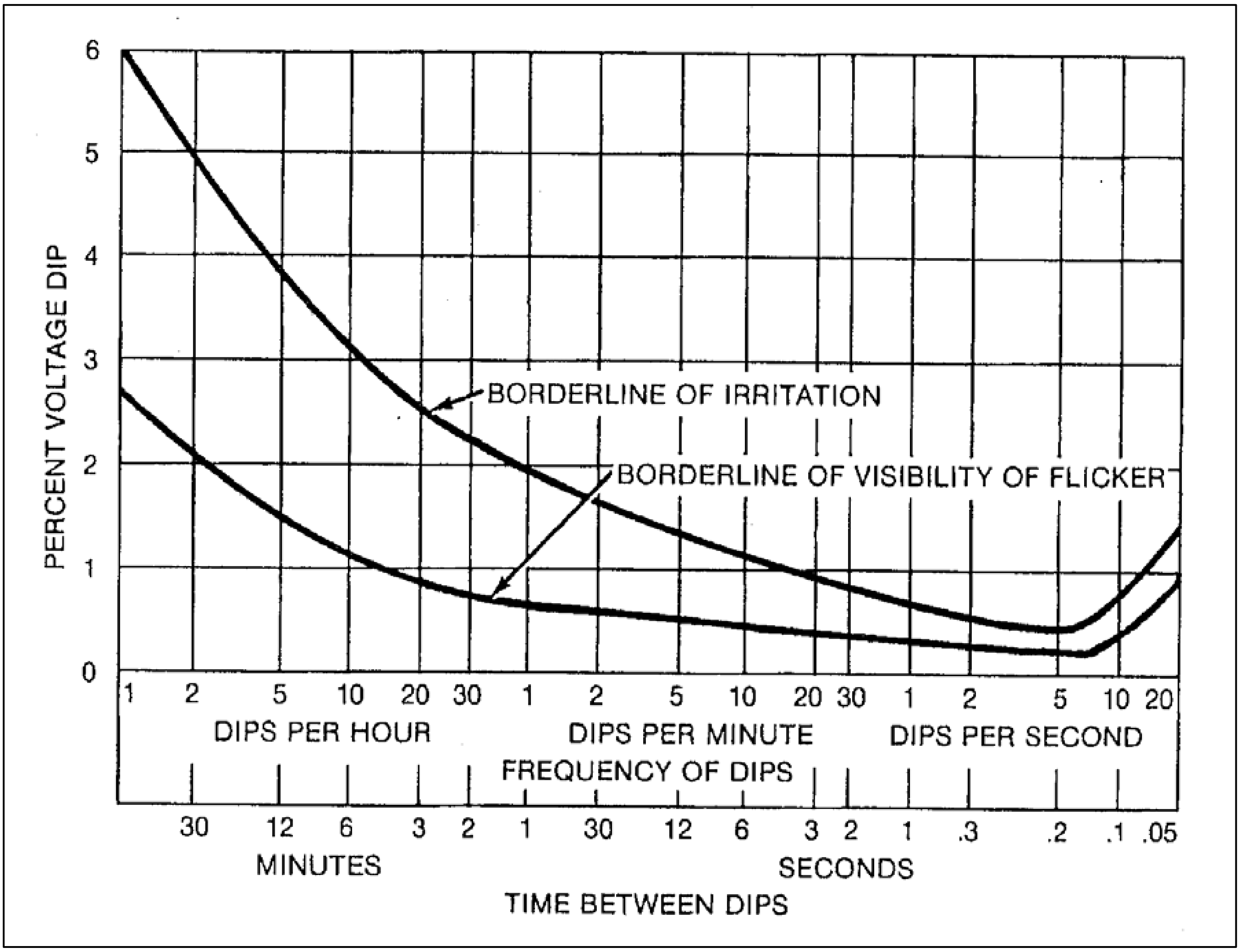


Figure 40: Range of Observable and Objectionable Voltage Flicker versus Time.

Figure 40 gives the key guideline graph developed in DigSilent. For example, if a plant was installing a 900 kW arc furnace, the MVA short circuit at the point of common coupling would need to be greater than 1000 MVA for flicker to be non-objectionable based on Figure 40. If the MVA short circuit was less than 900 MVA, the flicker would be objectionable. If the MVA short circuit was between 900 and 1000 MVA, flicker would be borderline. The short circuit voltage depression at the point of common coupling can be read from the scale along the x-axis. The voltage depression was based on typical arc furnace impedance quantities

A solution to control the severity of voltage flicker is by installing 800 kVar shunt capacitor bank. Capacitor bank can be connected series with induction motor loads in order to compensate voltage variations and to improve power factor of the network. See figure 41 for the corresponding arrangement of the shunt capacitor bank and motor loads.

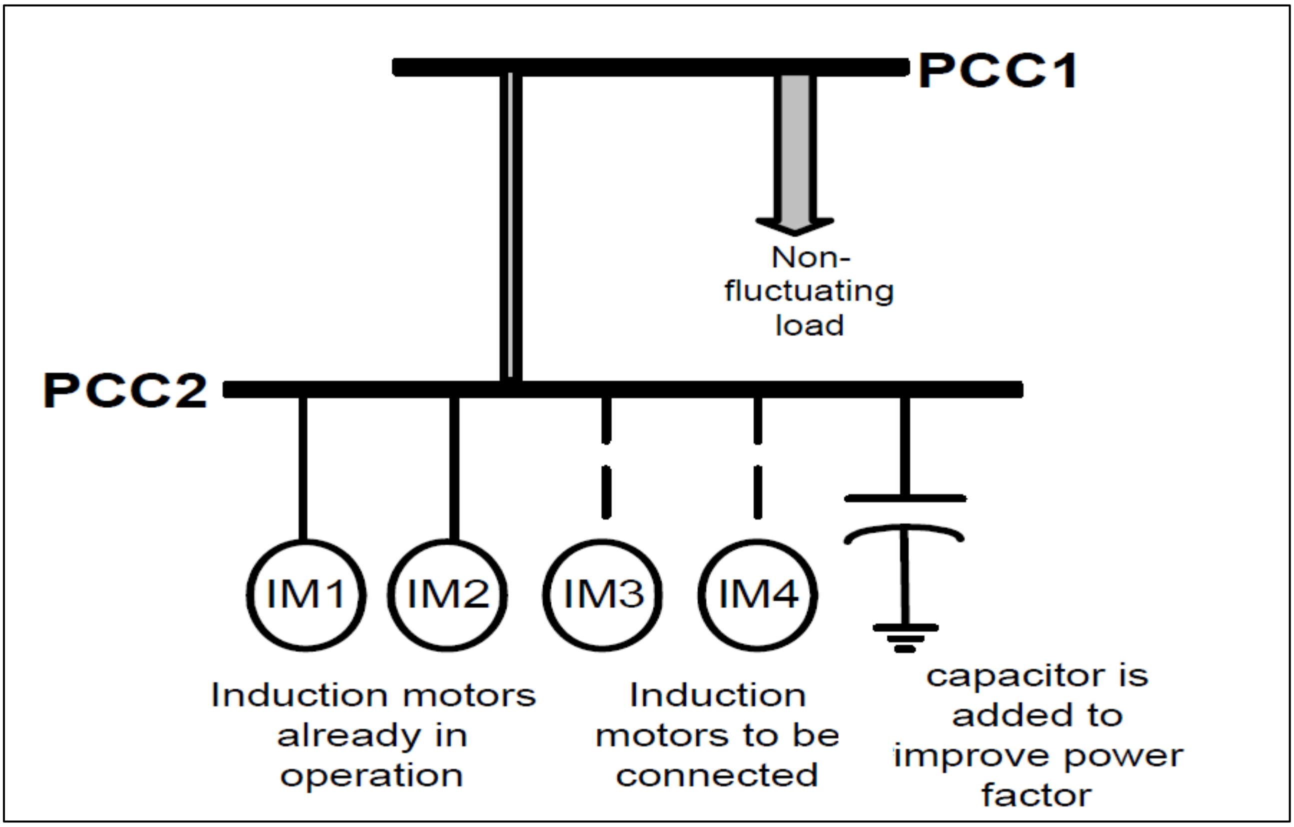
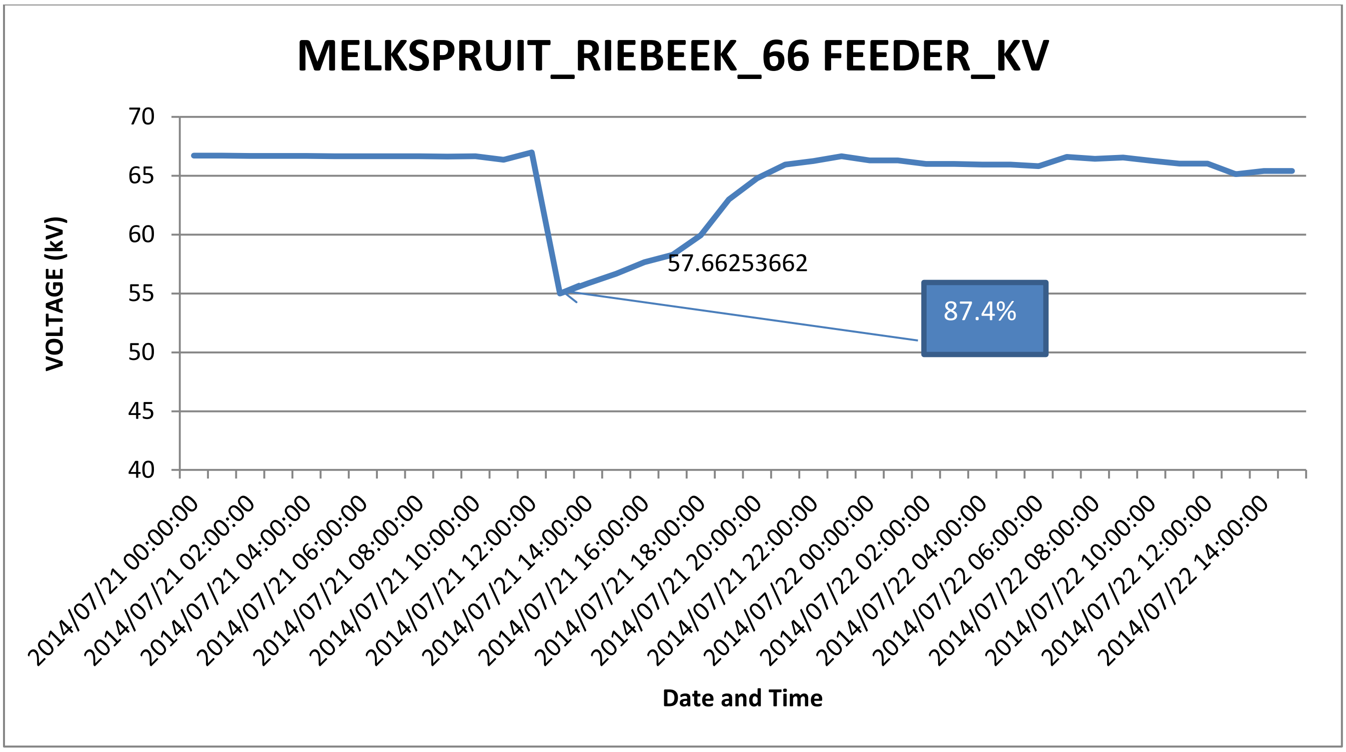


Figure 41: Shunt Capacitor Bank connected series with Motor Loads at PCC2 (Point of Common Coupling)

4.4.3 Voltage Dips Analysis

The duration of a voltage dip is the time measured between the instant at which the r.m.s voltage value falls below 90% of the declared voltage and the instant at which it rises above 90% of the declared value. The amplitude of a voltage dip equals the maximum voltage change during the disturbance, and its duration is the maximum voltage dip duration for the most disturbed phase.

The South African standard (NRS 048 – 2) gives limits for voltage dips in the form of a maximum number of voltage dips per year for defined ranges of voltage dip duration and retained voltage, designated as dip window categories. All voltage dips caused by force on the customer's side (short circuits, large drive starts, etc.) The graph below shows the voltage dip that occurred at Melkspruit/Riebeek 66 kV line. This particular voltage dip was caused by the lightning strike of the 132 kV line between Dreunberg and Melkspruit Substation. The strike resulted in a voltage dip on Dreunberg/Melkspruit 132 kV line. Since this line is a single source to the other 5 substation any significant change in this line can be observed from other lines and substations that it feds, the voltage dip in the graph below was measured on the Melkspruit/Riebeek 66 kV line.

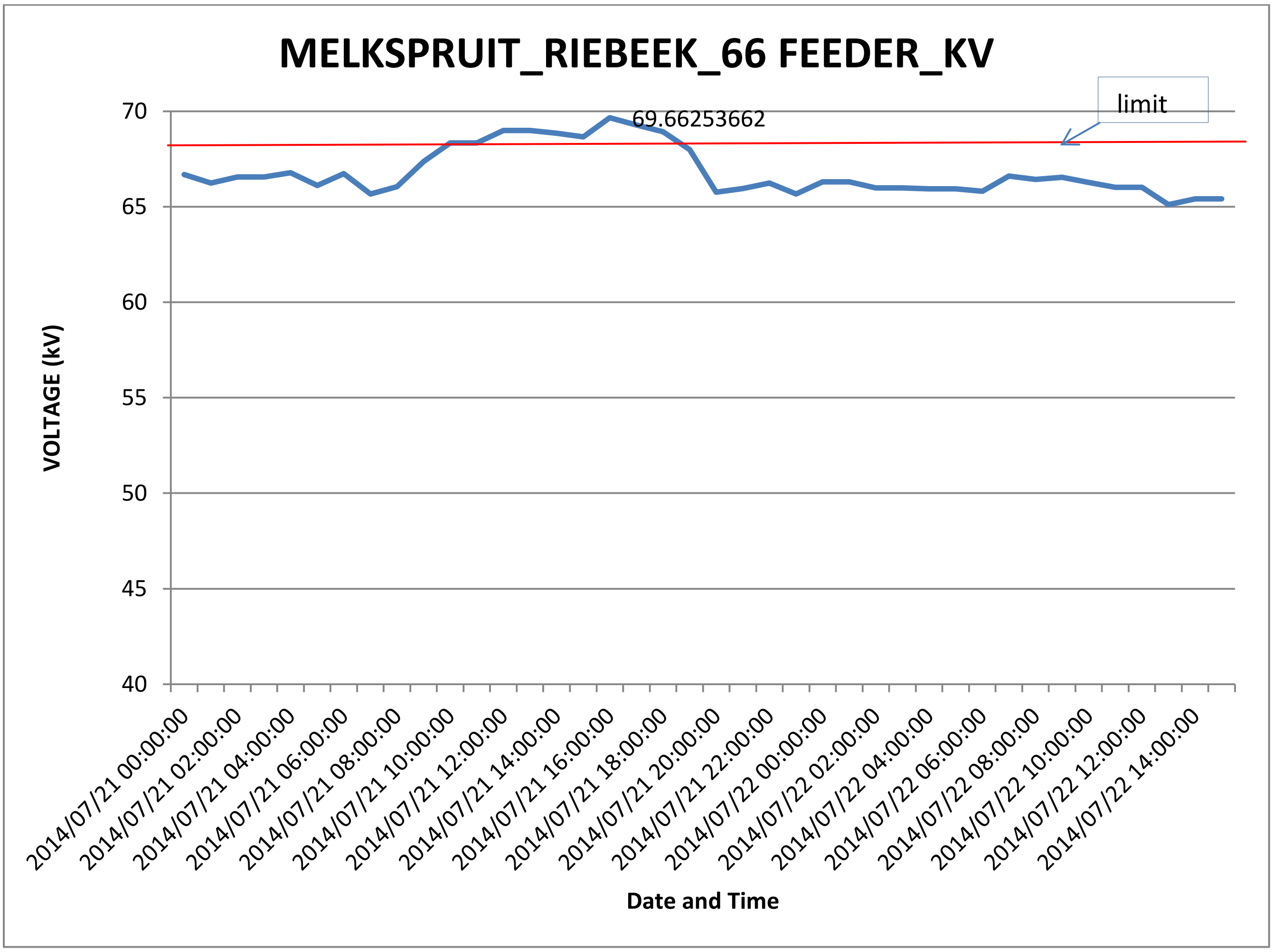


Graph 42: Voltage Profile with Voltage DIPS.

The above scenario is regarded as voltage dip, due to the fact that 87.4% is less than 90% of the declared voltage of 66 kV. It is important to note that a voltage deep has huge impact on the Cost of Unserved Energy (COUE). COUE forms significant aspect of benefit to cost analysis. The voltage dip problems if an alternative source of supply from a different source as outline in solution 3 scenario of the dissertation proposal or chapter one. This further supports the reason of taking up solution 3 as the best investment for improving the performance of the Aliwal North power system network as it become the solution to many underlying problems of this network.

4.4.4 Voltage Swells analysis

Swells can be generated by sudden load decreases. The abrupt interruption of current can generate a large voltage, per the formula: v = L di/dt, where L is the inductance of the line, and di/dt is the change in current flow. Switching on a large capacitor bank can also cause a swell, though it more often causes an oscillatory transient. It is not something popular in the distribution network in particular Eskom ECOU to experience voltage swell, but in the following scenario in the graph below, Melkspruit/Riebeek 66 kV line had a voltage swell on the. This line is feeding three substations, one of the substation is highly loaded i.e. Sterkspruit Substation. When a fault occurs or even an auto-reclose (ARC) on the Riebeek/Sterkspruit 66 kV line it results in voltage swells on the Melkspruit/Riebeek 66 kV line, see graph below.



Graph 43: Voltage Swells incident.

Different types of monitoring equipment are available, depending on the user's knowledge base and requirements. Sags and swells are relatively slow events (as opposed to microsecond duration transients), the wide variety of instruments are generally capable of capturing a sag or swell with reasonable reliability.

The first step in reducing the severity of the system swells is to reduce the number of faults. From the utility side, transmission-line shielding can prevent lightning induced faults. If tower-footing resistance is high, the surge energy from a lightning stroke is not absorbed quickly into the ground. Since high tower-footing resistance is an import factor in causing back-flash from static wire to phase wire, steps to reduce such should be taken. The probability of flashover can be reduced by applying surge arresters to divert current to ground. Tree-trimming programs around distribution lines are becoming more difficult to maintain, with the continual reductions in personnel and financial constraints in the utility companies.

In this analysis it shows that the Aliwal North power system network does not have major problems in voltage swells as they are within NRS 048-2 standard as illustrated in graph above or previous page.

4.4.5 Voltage Regulation analysis

Feeder voltage regulation refers to the management of voltages on a feeder with varying load conditions. Regardless of nominal operating voltage, a utility distribution system is designed to deliver power to consumers within a predefined voltage range. Under normal conditions, the service and utilization voltages must remain within NRS048 standard and limits. During high load conditions, the source voltage at the substation is at the higher end of this range and the service voltages at the end of the feeder are at the lower end of the range, to improve the voltages on the system devices such On-Load Tap Changer, Shunt Capacitor Bank and Voltage Regulators. On the power system network of Aliwal North, it is evident that the most vulnerable network in terms of Voltage Regulation is the 22 kV network in particular Sterkspruit/LowerTelle 22 kV line, (see figure 44 for the voltage profile of this feeder). The profile shows that there is a portion of a network where the voltages are lower than distribution operating units as per NRS048 part 4, the red line in figure 44 indicates the upper limit (1.05 pu) and lower limit (0.90). The most problematic spur line is KNTF006 at 38 km, voltages are at 0.87 pu) which is below the 0.90 pu lower limit.

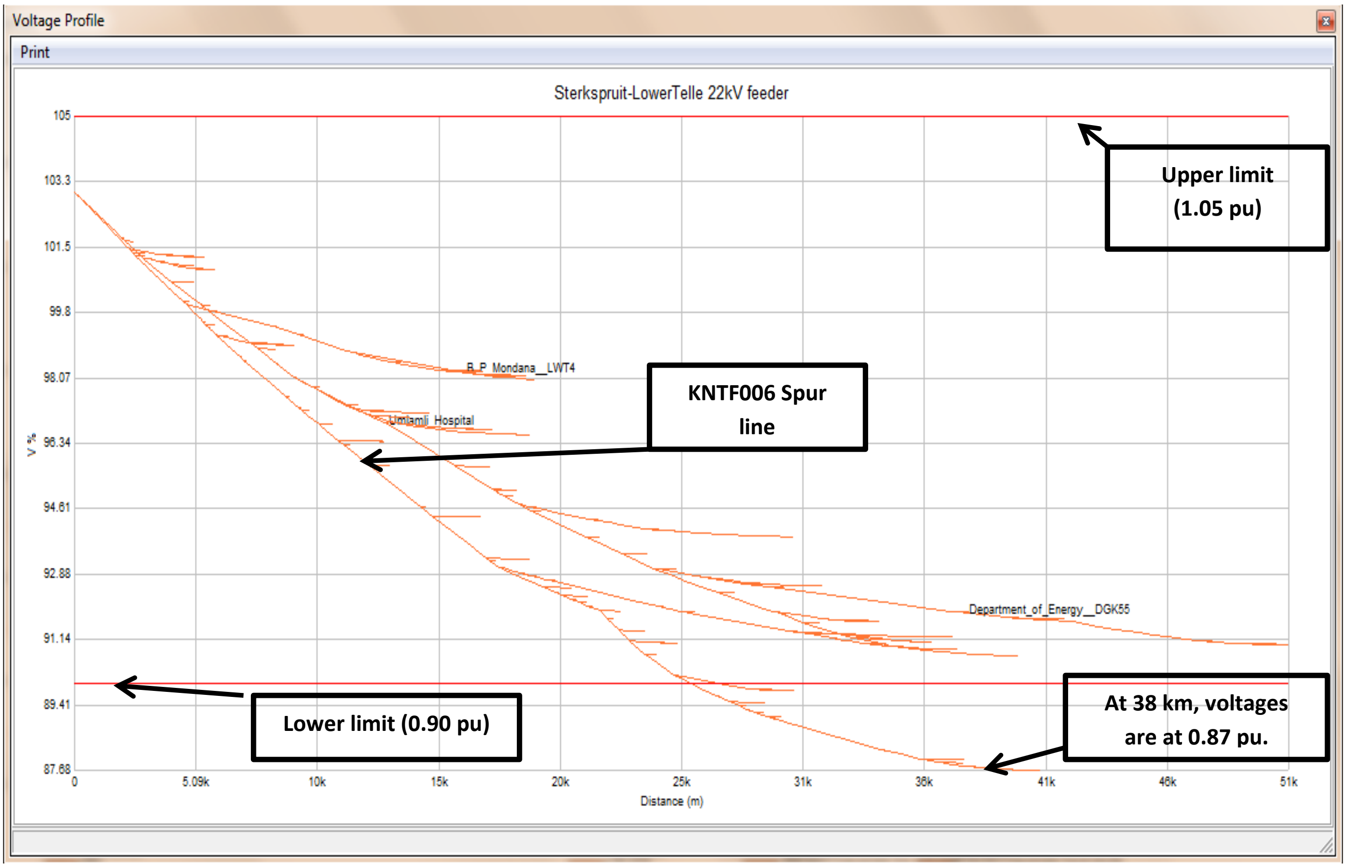


Figure 44: Voltage Profile for LowerTelle 22 kV line simulated from Retic Master under normal conditions.

Figure 45 below illustrates the voltage profile, at which the On-Load tap Changer (OLTC) was the used to improve the voltages. It is a cheaper method to use for the business but it does not make a big difference though. Besides the disadvantage for this method is that the customer closer to the source that were not affected by the low voltages problem experiences high voltages when the tap changers are increased in substation and this might results in damaging the equipment of the customer, therefore the utility will be liable to pay for liability claims from the members of public. There is much improvement as it shown that now the voltages have improved by small margin from 0.87 pu to 0.885 pu which is still below the 0.90 pu limit at 38 km. This shows that the contribution of increasing the number of taps from a transformer to compensate for low voltages is not a permanent solution it can only be a solution of a minimum duration i.e. during peak period which is normally is in a range of ± 2hrs30mins.

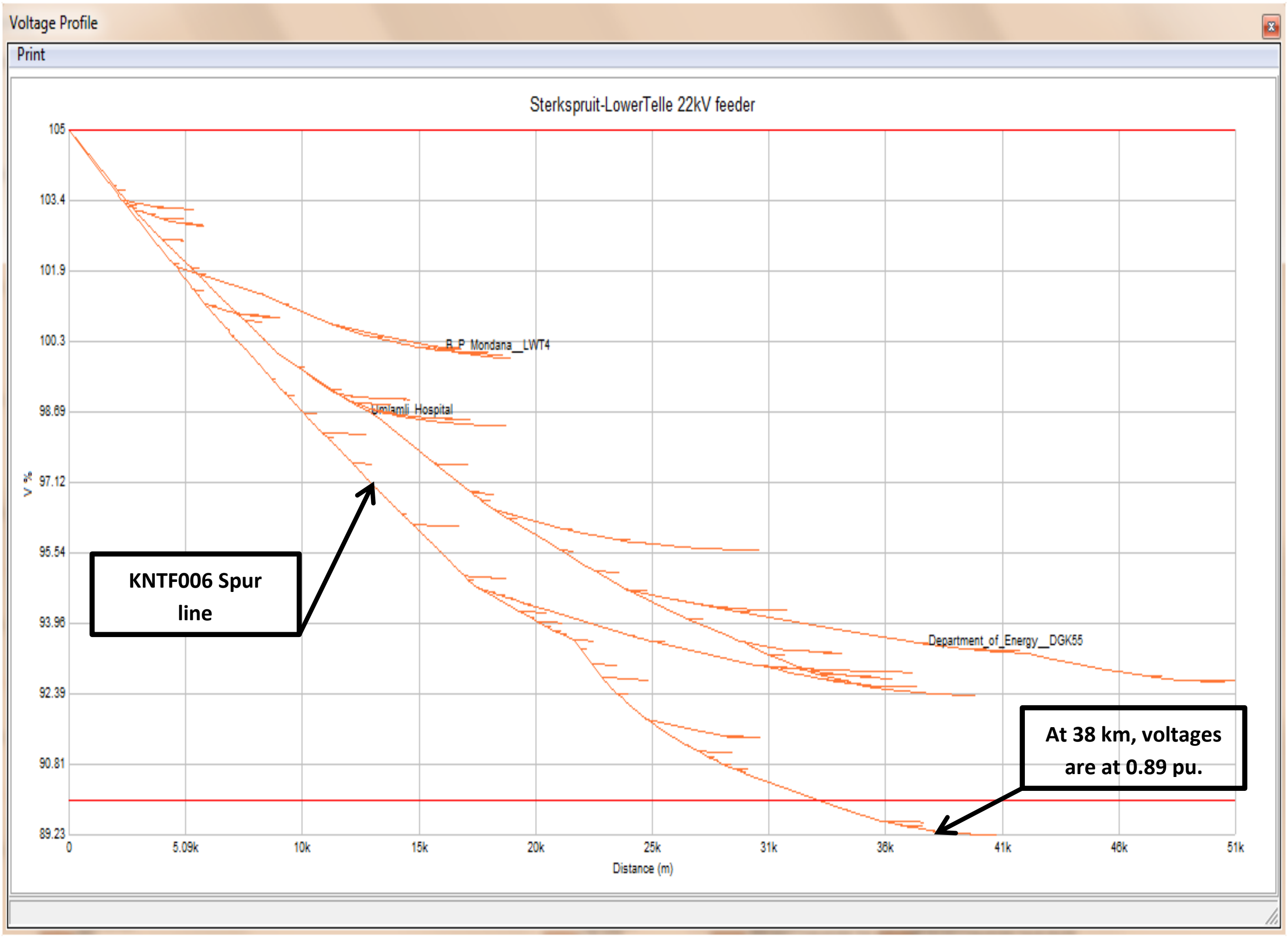


Figure 45: Voltage Profile Improvement using On-Load Tap Changer.

Figure 46 shows the shunt capacitor bank at Sterkspruit/LowerTelle 22 kV network used to improve voltages, when an 800kVAr capacitor is installed. The study also shows installing a capacitor with higher rating do not the give significant difference. This is due to some network lines are more resistive than others, therefore installing capacitor is possibly not the most effective option to improve network voltages for some networks. The contribution of a shunt capacitor bank is not effective at all as it only improved voltages from 0.87 pu to 0.88 pu. The customers at spur line KNTF006 will still experience almost the same impact of low voltages with or without the capacitor bank. The capacitor bank can work in certain networks; the kind of loading supplied by the KNTF006 spur line is not favourable to capacitor banks, no much difference was done by the introduction of the capacitor banks, see figure 46 below.

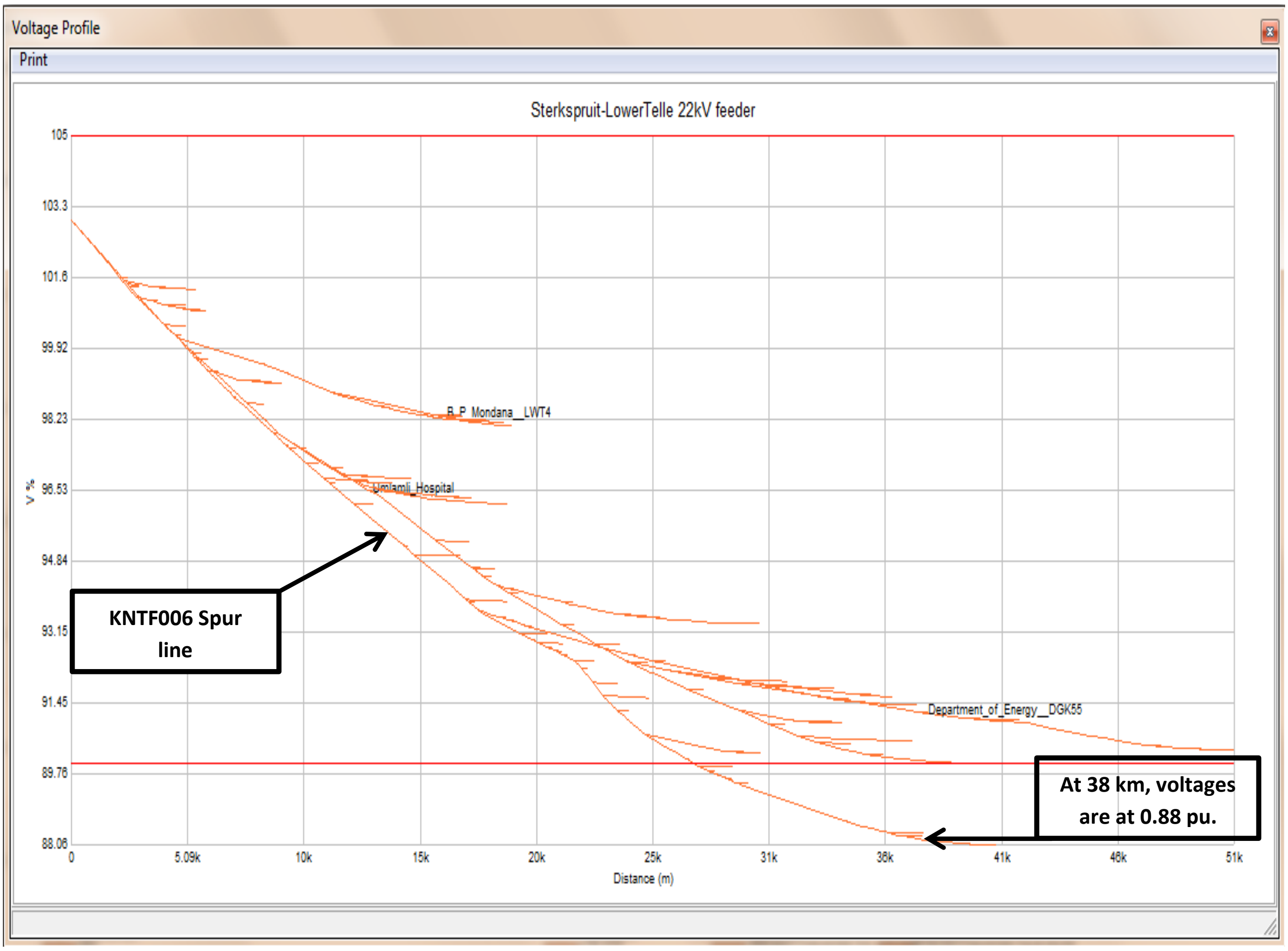


Figure 46: Voltage Profile Improvement using Shunt Capacitor.

Voltage regulators (VR) such as powerPerfector (pP) and MicroPlanet have the advantage of being able to connect further down the feeder to address the voltage regulation issues for any heavy loaded feeder. When the feeder has many customers, this could lead to high voltage levels during the daytime with low demand, and low voltage levels during periods of maximum demand. The voltage regulator would be able to step down the voltage levels during off peak and boost the voltages during peak period.

However unlike other control options such as energy storage, it does not generate additional energy. For this reason voltage regulators become the best solution to achieve voltage regulation in a feeder as it boost voltages up to almost 1.03 p.u, see figure 47 below for voltage profile extracted on Retic Master simulation tool. Now the voltages at the far end customer of the Spur line KNTF006 has been improved from 0.87 pu up to 0.97 pu at the same distance of 38 km.

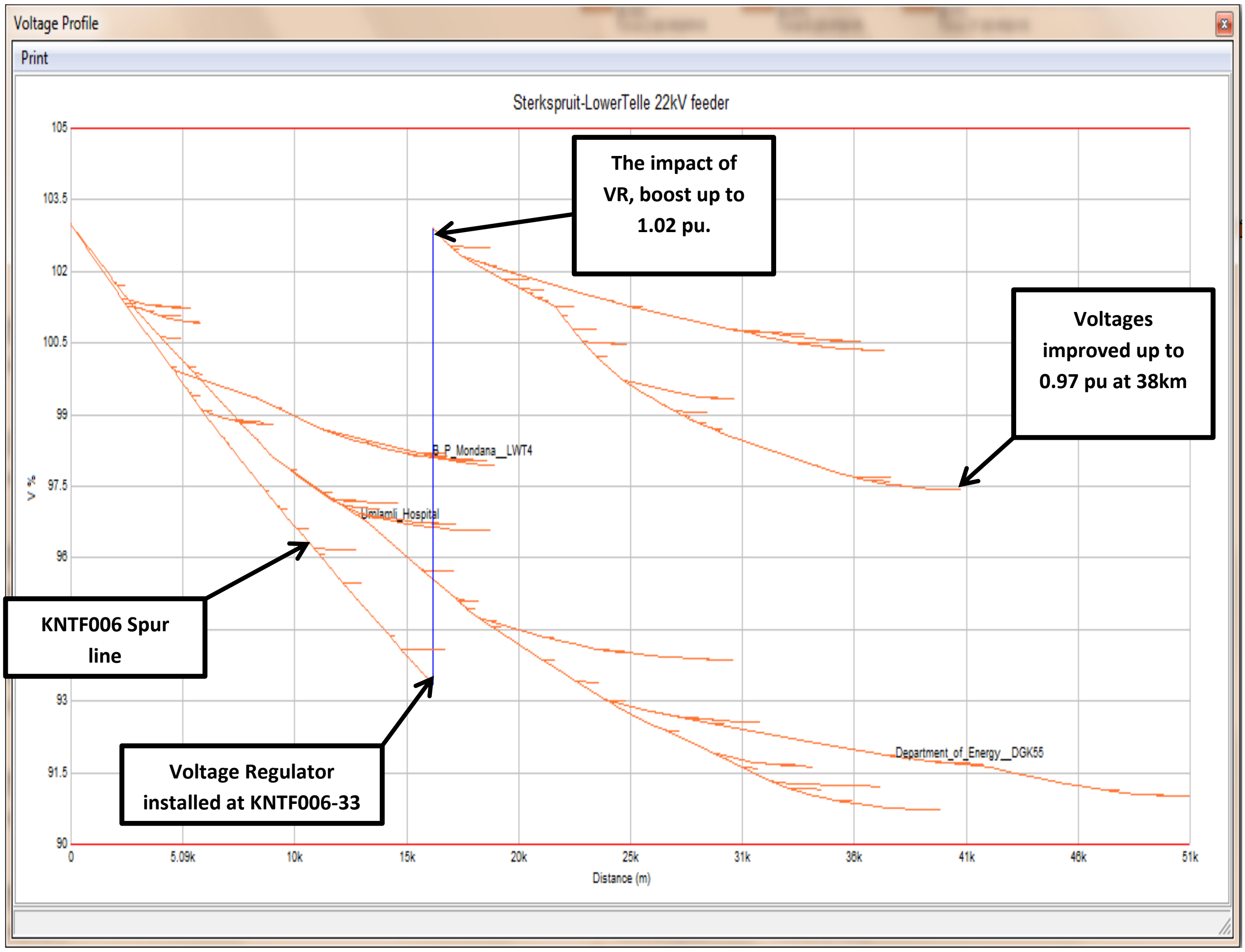


Figure 47: Voltage Profile Improvement using Voltage Regulator.

4.4.6 Harmonics Distortion Analysis (THD)

Harmonic distortion problems are increasing on the Sterkspruit Medium Voltage distribution networks, especially with the application of power factor correction capacitors with resulting resonances close to the 3rd harmonic. Power system analysts typically do not have inductors and Capacitors represented by (L&C) respectively readily available, so they commonly compute the resonant harmonic, h_r, based on fundamental frequency impedances and ratings using the following equation:

$$h_r = \sqrt{\frac{MVA_{SC}}{MVAr_{cap}}}$$

Where, $h_r = resonance\ harmonic$

$MVA_{SC} = system\ short - circuit\ MVA$

$MVAr_{cap} = MVAr\ rating\ of\ capacitor\ bank$

A profile is given here for the 3rd harmonic monitored in both MV (22 kV) buses of a HV/MV (66/22 kV) substation, held between April and June 2014 (three months). The period profile of the three phase magnitudes Total Harmonic Distortion (THD) average values and the permissible limits by the standard are shown in Figure 48 and in Figure 49.

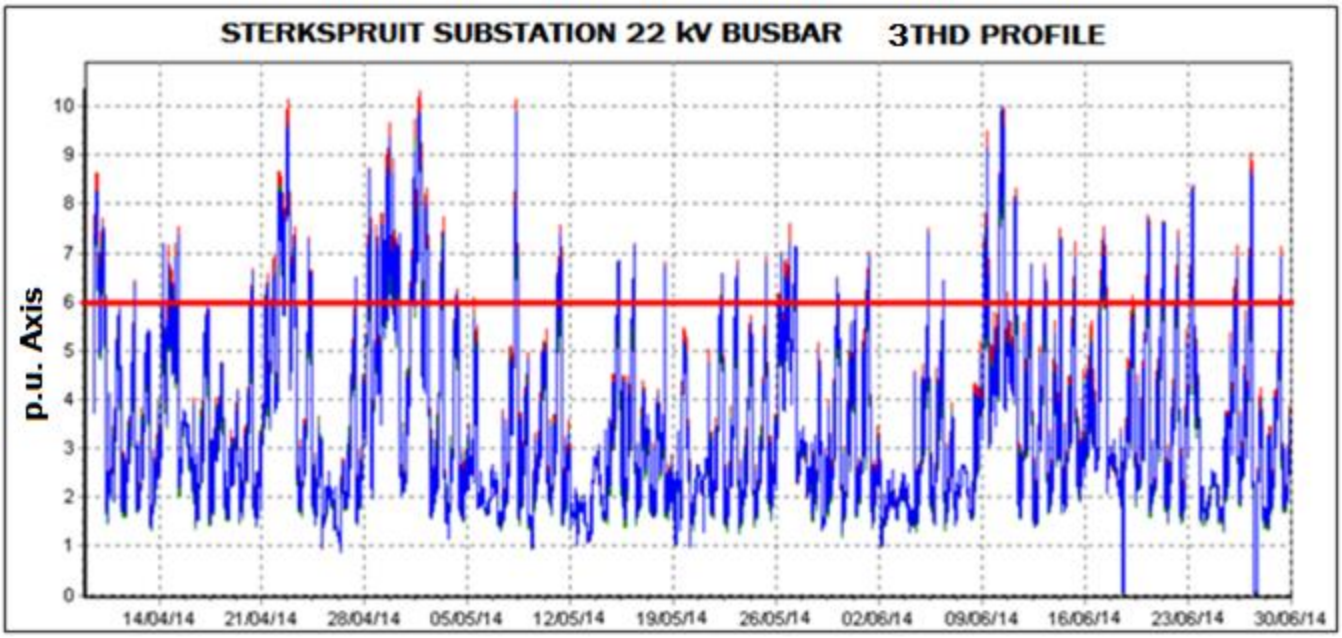


Figure 48: 3rd Harmonic in MV busbar 1.

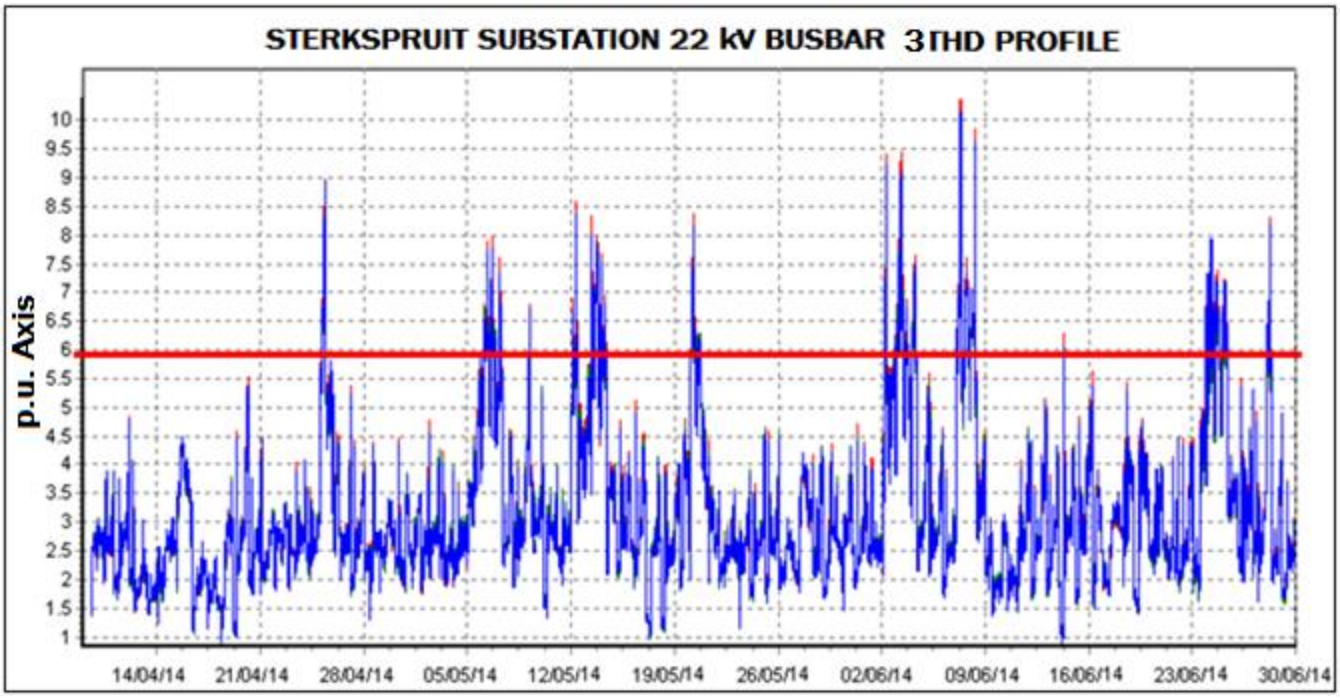


Figure 49: 3rd Harmonic in MV busbar 2.

As shown in the Figures 48 & 49 above, the values of the 3rd harmonics frequently exceeded the limits (6%) defined in standard NRS048. For the first profile, the resonant harmonic is approximately 49%, close to the 3rd harmonic voltage. The HV/MV (66/22 kV) Sterkspruit substation topology is illustrated in figure 50. Two busbars are connected to two transformers and two capacitor banks (CB), one bus for each transformer and capacitor bank. Figure 49 shows that under certain network conditions such as switching in a capacitor bank on the 22 kV busbar at Sterkspruit Substation, the 3rd harmonic is a problem, especially with both capacitors at Sterkspruit are in service, because it causes parallel resonance at that point, as illustrated in the profile in figure 49 the spikes shows the switching of the capacitor bank as a results.

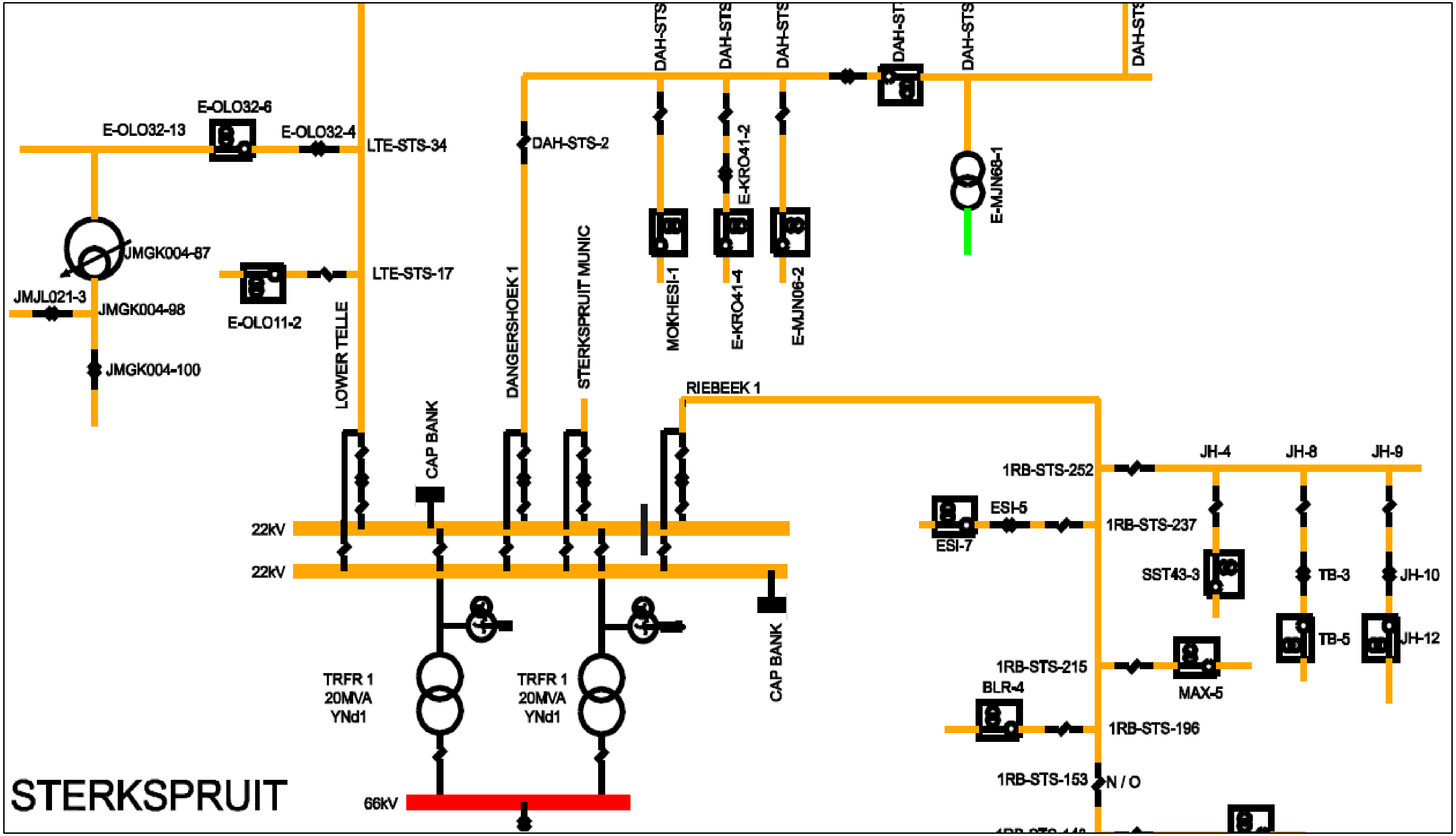


Figure 50: Single Diagram of 66/22 kV Sterkspruit Substation.

The worst week profile for the 3rd harmonic of the three phase magnitudes (average values) and the permissible limits by the standard for both busbars are shown in Figure 51 and in Figure 52. The Capacitor Bank (CB) schedule is represented by two bars. The green colour means the CB is switched on and the red colour means the CB is switched off.

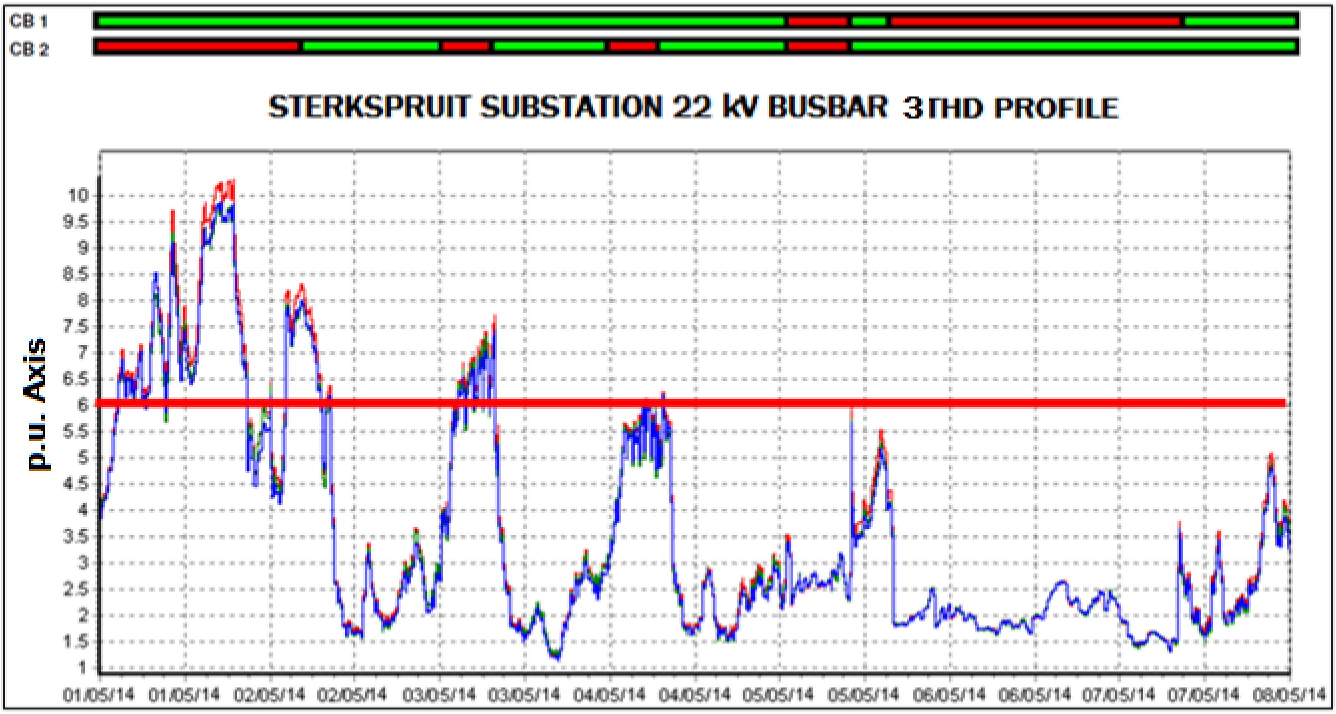


Figure 51: 3rd Harmonic in 22 kV Busbar number 1

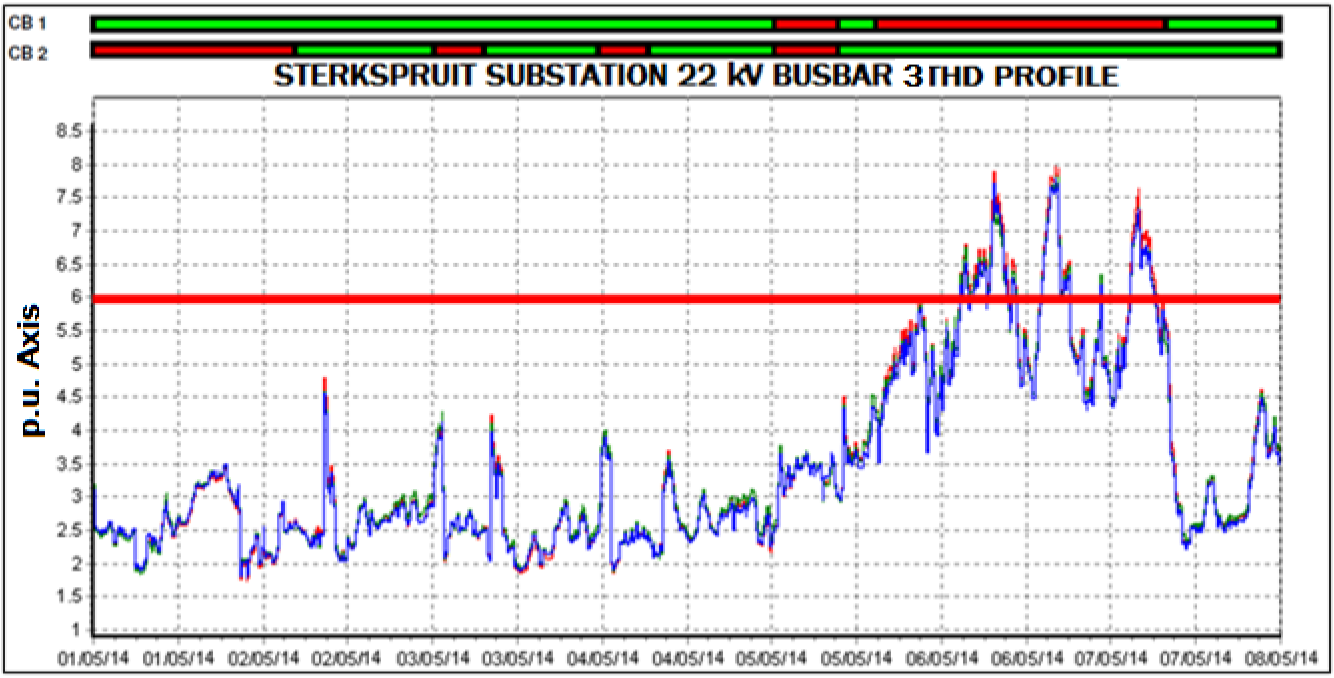


Figure 52: 3rd Harmonic in 22 kV busbar number 2

Harmonic distortion problem is caused by resonance created by the substation capacitor banks in the MV (22 kV) busbar. This resonance was magnifying the 3rd harmonic component in the currents from all the customers on this system, causing high voltage distortion levels after the capacitor bank was switched on to compensate for the low voltages at the 22 kV busbar at Sterkspruit Substation.

In many cases, it may be more economical to control the voltage distortion experienced by all customers by changing the frequency response of the system. This can be accomplished with some changes in capacitor bank on the MV system, particularly by changing the schedule and/or decreasing the power of the capacitor banks.

Procedures to prevent high voltage distortion are presented based on the identification of potential resonance conditions in most probable network configurations. An additional monitoring in an HV/MV substation has validated the procedures in order to prevent harmonic voltage distortion.

The two shunt capacitor banks connected on the MV busbar at Sterkspruit Substation are the primary source of harmonics. Due to this arrangement of the shunt capacitor banks (See figure 50 for their connection on the system) gave the rise to significant amplification of the harmonic voltage, which resulted in 3^{rd} harmonic exceeding the defined standard as per NRS-048 part 4.

This can be rectified by introducing filters that will divert harmonic currents away from the system (using passive filters) or inject phase-shifted harmonic components.

The second is to reduce the system impedance of the Sterkspruit 66 and 22 kV power network, by increasing the system fault levels and avoiding system resonance condition at harmonic frequencies. Eskom ECOU can achieve this by introducing a second 66 kV line between Riebeek and Sterkspruit Substation. This will not only solve harmonics problem as it will be a solution to reliability and improves system voltages. However, also to move one of the shunt capacitor banks to the downstream of the line, thus maintaining the VAR support but alleviating the Total Harmonic Distortion problem at Sterkspruit Substation, as shown in figure 53.

4.5 Protection and Coordination

4.5.1 Short Circuit Analysis Three Phase Faults

For short circuit analysis we consider three phase short circuit as it is the most severe fault amongst all the faults. We are going to assume three phase short circuit on various locations from 66 kV to 22kV level. The impedances of transformers, cables and motors are contributing to the change in fault level at different locations. Formulae used for calculations of short circuit analysis, figure 54, 55 & 56 are the impedance diagrams dawn on DigSilent.

$$Zpu = \%Z\ x\ \frac{Base\ MVA}{Transformer\ Rating}$$

$$Fault\ MVA = \frac{Base\ MVA}{Z_{(pu)T}}$$

$$Fault\ Current = \frac{Fault\ MVA}{\sqrt{3}\ x\ Voltage}$$

Base MVA = 20 MVA

Base Voltage = 22kV

<u>For Sterkspruit Substation 66/22 kV:</u>

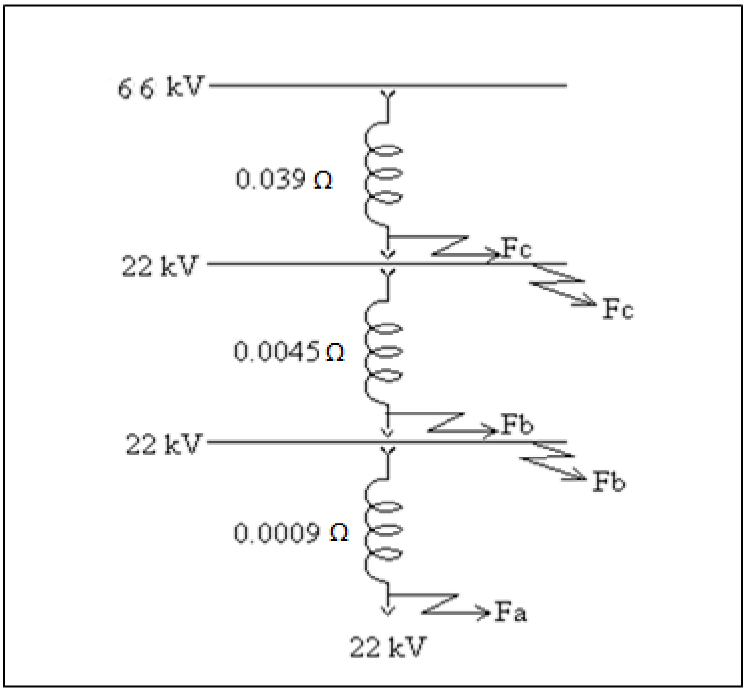


Figure 54: Impedance Diagram for Faults on 22 kV bus on Sterkspruit Substation

For Fault Fa:-

$Z_{(pu)T}$ =0.039+0.0045+0.0009 – 0.1x(0.039+0.0045+0.0009)

=0.0444 – 0.00444

We consider 10% negative tolerance as per IEC Standards (1)

So,

$Z_{(pu)T}$ =0.03996 pu

Fault MVA = 20 / (0.03996)

=500.50 MVA

Fault Current = 500.50x10^6 / (√3 x22000)

=13.13 kA

For Fault Fb:-

$Z_{(pu)T}$ =0.039+0.0045 - 0.1x(0.039+0.0045)

=0.0435 – 0.00435 = 0.03915 pu

Fault MVA = 20 / (0.03915)

= 510.86 MVA

Fault Current = 510.86 / (√3 x 22000)

=13.41 kA

For Fault Fc:-

$Z_{(pu)T}$ =0.039 - 0.0039

=0.0351 pu

Fault MVA = 20 / (0.0351)

=569.80 MVA

Fault Current = 569.80 / (√3 x 22000)

=14.95 kA

For Melkspruit Substation 132/66 kV

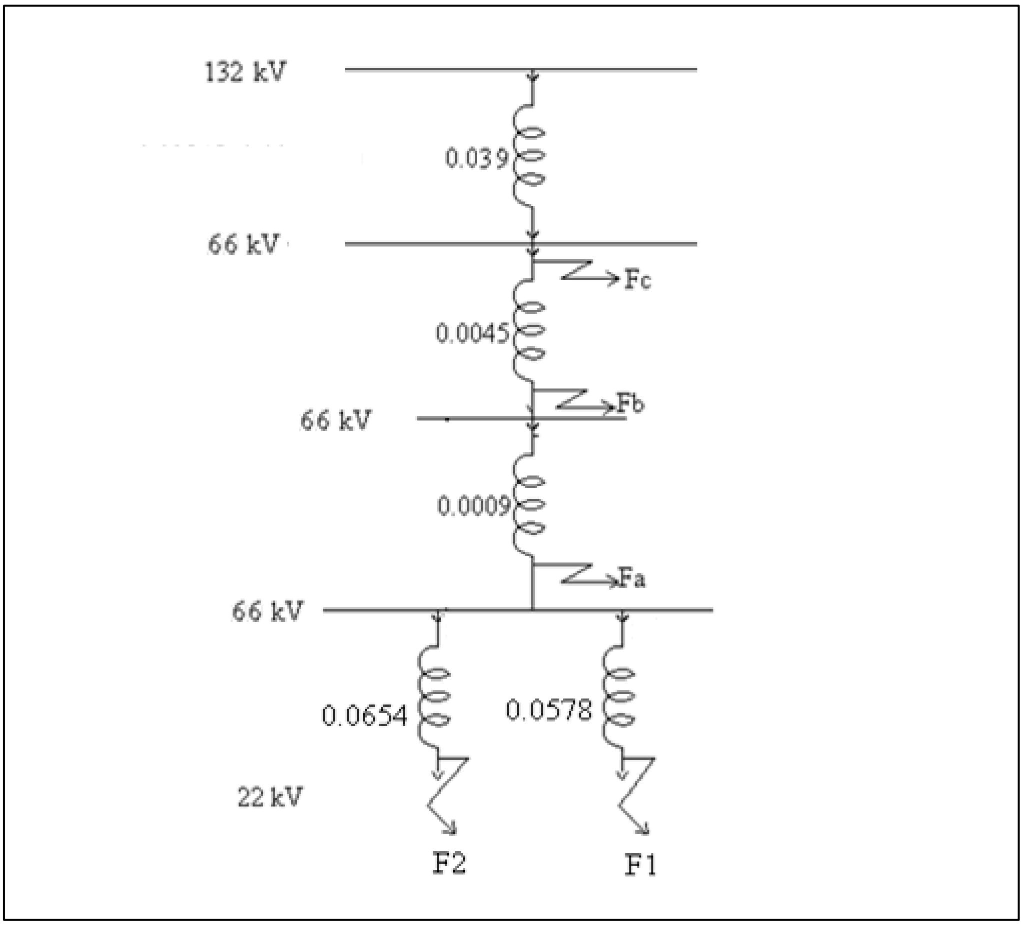


Figure 55: Impedance Diagram of Melkspruit Substation

For Fault $F_{1:-}$

Z_{pu} = 0.0578 x 40/20

=0.1156 pu

$Z_{(pu)T}$ =0.1156+0.039+0.0045+0.0009 – 0.1 x (0.1156+0.039+0.0045+0.0009)

=0.16 – 0.016

=0.144 pu

Fault MVA = 40 / (0.144)

=277.78 MVA

Fault Current =277.78/(√3 x 22000)

=7.29 kA

For Fault $F_{2:-}$

Z_{pu} = 0.0654 x 40/10

=0.2616 pu

$Z_{(pu)T}$ =0.2616+0.039+0.0045+0.0009 – 0.1 (0.2616+0.039+0.0045+0.0009)

=0.306 – 0.0306

=0.275 pu

Fault MVA = 40 / (0.275)

=145.24 MVA

Fault Current =145.24/(√3 x 22000)

=3.81 kA

4.5.2 Relay Co-ordination

Relay co-ordination plays an important role in the protection of power system. For proper protection, proper co-ordination of relays with appropriate relay settings is to be done. Relay settings are done in such a way that proper co-ordination is achieved along various series network. However the review of Co-ordination is always essential since various additions / deletion of feeders and apparatus will occur after the initial commissioning of plants. As power can be received from Main Transmission Substations of captive power plant, the analysis becomes complex. Relay co-ordination can be done by selecting proper plug setting and time multiplication setting of the relay, considering maximum fault current at the relay location.

For a given fault current, the operating time of IDMT relay is jointly determined by its plug and time multiplier settings. Thus this type of relay is most suitable for proper coordination. Operating characteristics of this relay are usually given in the form of a curve with operating current of plug setting multiplier along the X axis and operating time along Y axis. The formula below used is used, for relay operating times:

$$t = \frac{K \; x \, TMS}{(\frac{I}{I} >)^{\alpha} - 1}$$

Where,

t = Operating time in sec

k, α, β = Curve constants

I = Fault Current

I = Set Current

TMS = Time Multiplier Settings

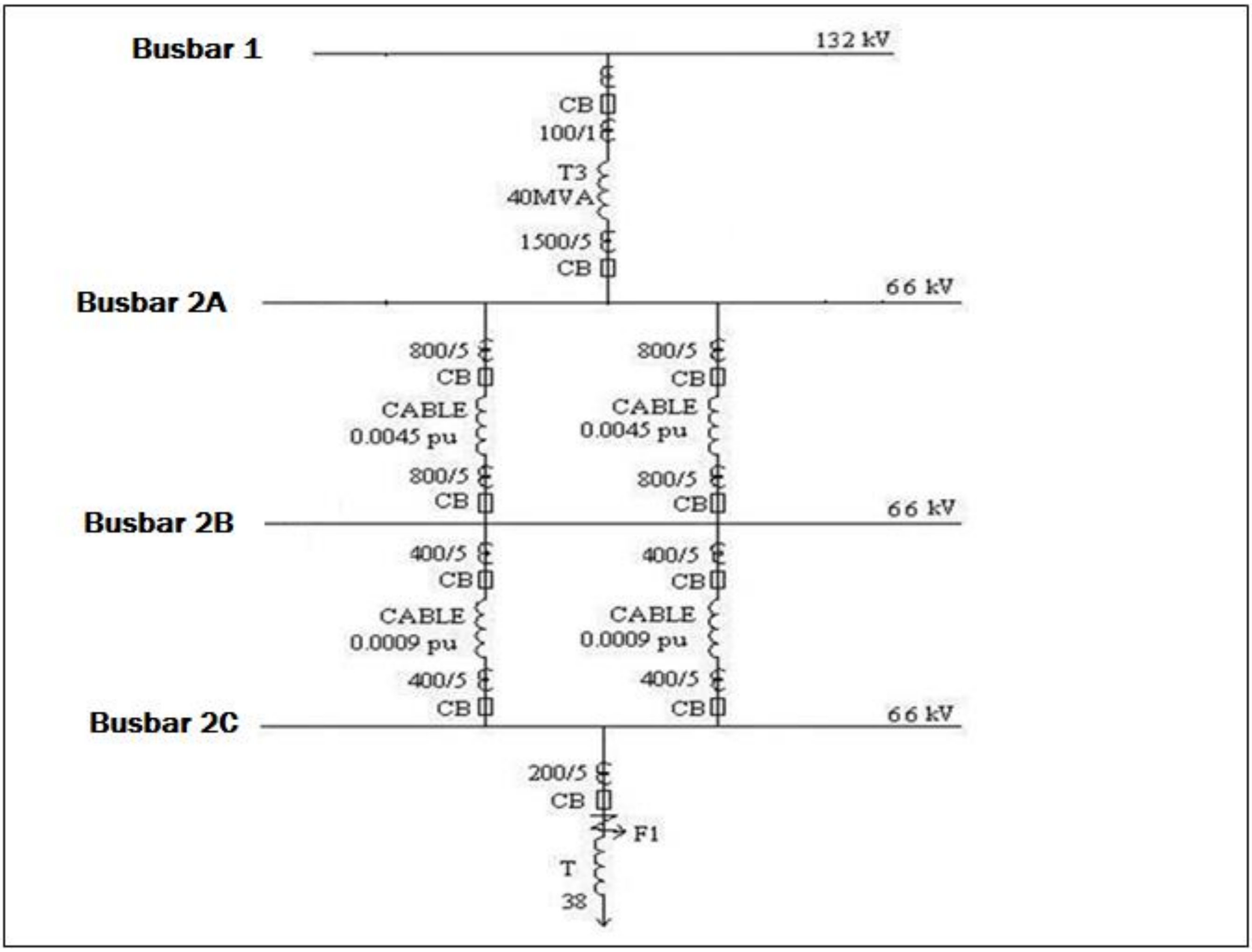


Figure 56: Relay Co-ordination for Melkspruit Substation

When selecting Normal Inverse Curve initially.

k=0.14

α=0.02

β=2.97

Plug Setting=100% i.e. 1

Fault Current I =19.70 kA (132 kV)

Fault Current = 13.50 kA (66 kV)

Fault Current = 8.76 kA (22 kV)

Relay Type used = 7SJ50

Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current

PSM = Fault Current in C.T. Primary / (C.T. Transformation Ratio x Rated C.T. Secondary Current).

66 kV line (Melkspruit-Riebeek)

1) C.T Ratio = 200/5

   TMS = 0.1

   Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current
   = 1 x 5
   =5

   Multiple of set current (PSM) = 13.50 kA/200 A
   = 67.50

   t_1 = (0.14 x 0.1) / $(67.50)^{0.02}$ - 1
   = 0.16 sec

2) C.T Ratio = 800 / 5

   We assume co-ordination time as 0.16 sec.

   t_2 = 0.15 + 0.16
   = 0.31 sec.

   Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current
   =1 x 5
   = 5

   Multiple of set current = 13.5 kA/800 A
   = 16.88

   TMS = 0.3 x (($(16.88)^{0.02}$ - 1) / 0.14
   = 0.12

See figure 57 which illustrates the for PowerFactory simulation results

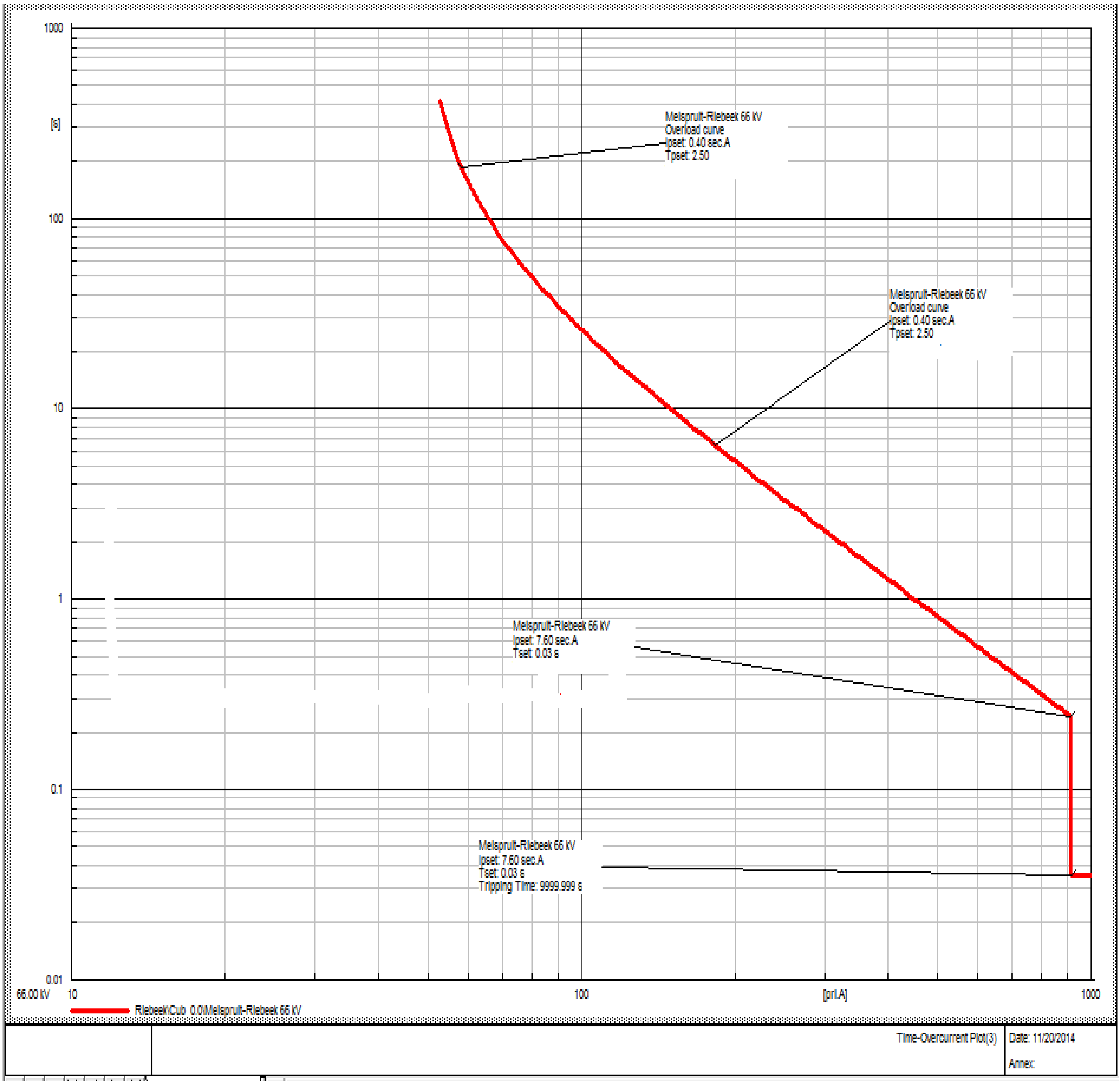


Figure 57: Relay Co-ordination for Melkspruit Substation

The above simulation (figure 57), executed in DigSilent was carried out to verify the accuracy of Key Customers relay settings and ESKOM relay settings, the simulation was executed after applying all the calculated settings. Allowed for all necessary work to ensure that the settings were correct and the updating of the model as required. Any discrepancies found were updated and studies executed once again. Tabulated results are shown in figure 58.

```
-----------------------------------------------------------------------------------------------------------------------------------
| Fault Distance from      Terminal i:    ... Southern HV\Melkspruit\66kV Bus 1       Absolute                               0.00 km |
| Line:     \Athini Pantshwa\00. Hlobo Connection Studies(1)\Network Model\Network Data\Southern HV\Southern HV Lines\Melkspruit -
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Southern HV                                                      | System Stage: Southern HV                                  |
-----------------------------------------------------------------------------------------------------------------------------------
|                    rtd.V.     Voltage      c-       Sk"              Ik"          ip        Ib      Sb         Ik      Ith  |
|                    [kV]    [kV]   [deg]  Factor   [MVA]        [kA]      [deg]     [kA]      [kA]    [MVA]      [kA]     [kA] |
-----------------------------------------------------------------------------------------------------------------------------------
|Fault Location:                                                                                                                 |
|   Melkspruit - Riebeek      0.00     0.00    1.00    162.42        1.42     -75.71     2.97      1.42   162.42      1.42     1.43 |
-----------------------------------------------------------------------------------------------------------------------------------
□-------------------------------------------------------------------------
|                          |   DIgSILENT  | Project:                     |
|                          | PowerFactory |------------------------------
|                          |    15.0.2    | Date:  11/20/2014            |
------------------------------------------------------------------------
| Melspruit-Riebeek 66 kV          Relay Type : 7SJ50_OL                 |
|   Location      :  Cubicle       : Cub_0.0     Branch     : Melkspruit - Riebeek|
|                    Busbar        : 66kV Bus 1            / Riebeek     |
|-----------------------------------------------------------------------|
|   Current Transformer                             Ratio      : 600A/5A |
|     Connection     : Y                                                 |
|                                                                        |
|   Measure                                                              |
|     Nominal Current ( 1.0 - 5.0      A     ) :     1.00 A              |
|                                                                        |
|   I>              ( IEC: I>t   ANSI: 51    )       Out of Service    : No |
|     Tripping Direction                      : None                    |
|     Current Setting ( 0.4 - 3.55     p.u.  ) :     0.400 p.u.         |
|     Time Dial       ( 2.5 - 80.0            ) :     2.500              |
|     Characteristic                          : Overload curve          |
|                                                                        |
|   I>>             ( IEC: I>>   ANSI: 50    )       Out of Service    : No |
|     Tripping Direction                      : None                    |
|     Pickup Current  ( 2.0 - 19.0     p.u.  ) :    19.000 p.u.         |
|     Time Setting    ( 0.025 - 0.8    s     ) :     0.025 s            |
|                                                                        |
|   Ie>             ( IEC: IE>>  ANSI: 50N   )       Out of Service    : No |
|     Tripping Direction                      : None                    |
|     Pickup Current  ( 0.1 - 3.3      p.u.  ) :     0.100 p.u.         |
|     Time Setting    ( 0.05 - 1.6     s     ) :     0.300 s            |
|                                                                        |
|   Logic                                             Out of Service    : No |
|     Breaker                         Cubicle     Branch                 |
|      T_6                \ Riebeek     Cubicle_S  S0.1.1                |
------------------------------------------------------------------------
```

Figure 58: Relay Co-ordination for Melkspruit Substation

The results in figure 58 are the same results as shown in a graph format in figure 57, they are showing the time delay tripping times.

132 kV Line (Melkspruit-Dreunberg)

3) C.T Ratio = 1200 / 5

   We assume co-ordination time as 0.1 sec.

   t_3 = 0.3 + 0.1

   = 0.4 sec.

   Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current

   = 1 x 5

   = 5

   Multiple of set current = 19.7 kA / 1200 A

   = 16.42

   TMS = $0.4 \times ((16.42)^{0.02} - 1) / 0.14$

   = 0.16

4) C.T Ratio = 1200 / 5

   We assume co-ordination time as 0.2 sec.

   t_4 = 0.4 + 0.2

   = 0.6 sec.

   Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current

   = 1x 5

   =5

   Multiple of set current = 19.7 kA / 1200 A

   = 16.42

   TMS = $0.6 \times ((16.42)^{0.02} - 1) / 0.14$

   = 0.25

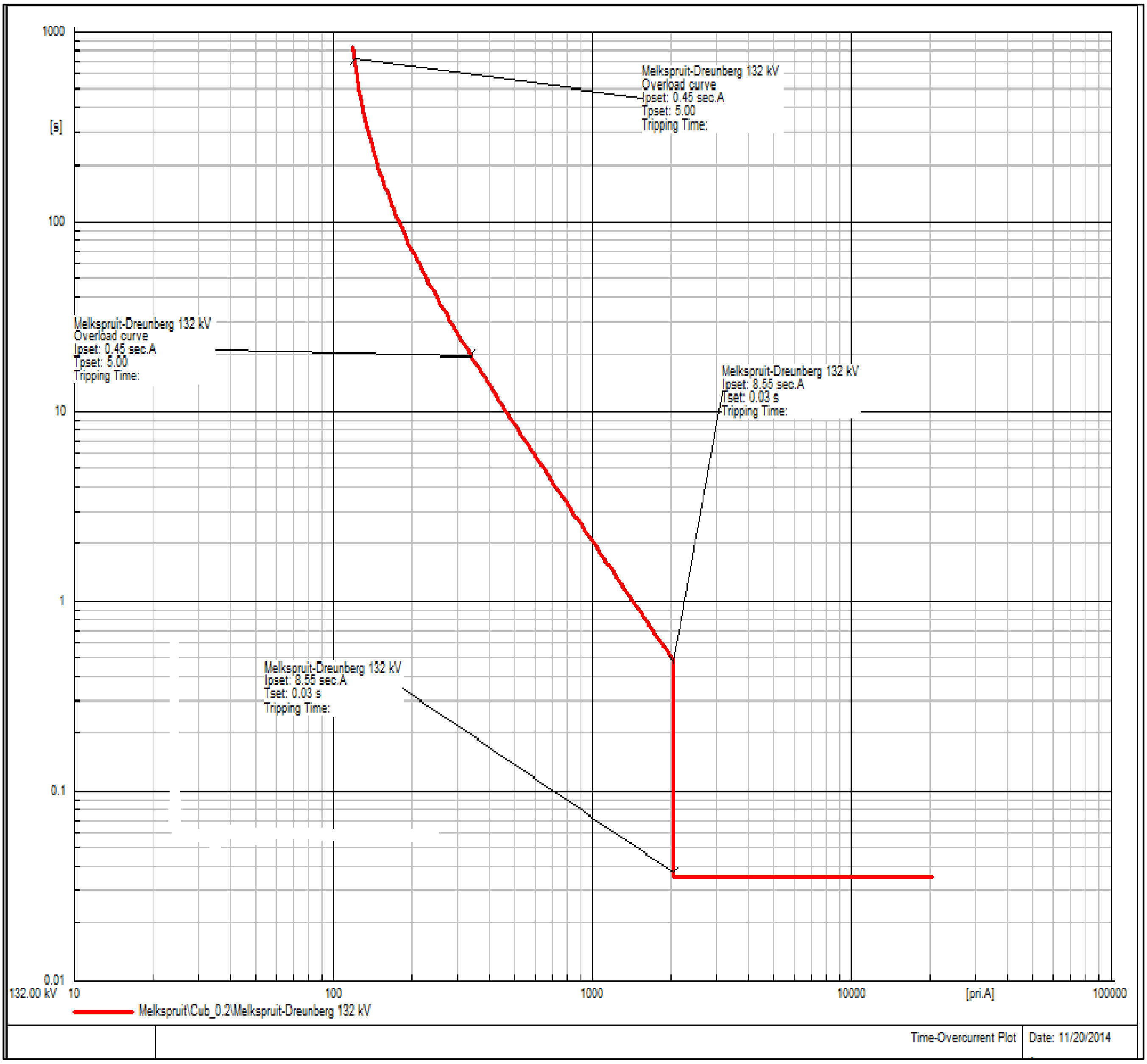


Figure 59: Relay Co-ordination for Melkspruit Substation

On figure 59 the simulation was executed to perform new grading studies with the revised network model up to and including the (Large Power Users) LPU's, to verify the calculated settings and adjust accordingly. Thus verify the accuracy of the grading study results. Allowed for all necessary work to ensure that the results were correct and upgrading of the model required. Discrepancies found were updated and executed once again figure 60 illustrates the simulated results in a tabulated format.

```
-----------------------------------------------------------------------------------------------------------------------------------
| Fault Distance from      Terminal i:    ... Southern HV\Dreunberg\132kV Bus 1       Absolute                             0.00 km |
| Line:     \Athini Pantshwa\00. Hlobo Connection Studies(1)\Network Model\Network Data\Southern HV\Southern HV Lines\Dreunberg - M
-----------------------------------------------------------------------------------------------------------------------------------

-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Southern HV                                                       | System Stage: Southern HV                              |
-----------------------------------------------------------------------------------------------------------------------------------
|                     rtd.V.     Voltage      c-       Sk"                 Ik"          ip         Ib       Sb          Ik      Ith  |
|                     [kV]    [kV]    [deg]  Factor   [MVA]        [kA]       [deg]     [kA]       [kA]    [MVA]        [kA]    [kA] |
-----------------------------------------------------------------------------------------------------------------------------------
|Fault Location:                                                                                                                   |
|    Dreunberg - Melkspru      0.00     0.00   1.00    423.81       1.85     -68.21     3.47      1.85   423.81      1.85     1.86 |
-----------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------
|                                 |   DIgSILENT  | Project:                     |
|                                 | PowerFactory |------------------------------
|                                 |    15.0.2    | Date:  11/20/2014            |
-------------------------------------------------------------------------------
| Melkspruit-Dreunberg 132 kV      Relay Type : 7SJ50_OL                        |
|   Location      :  Cubicle        : Cub_0.2    Branch     : Dreunberg - Melkspru|
|                    Busbar        : 132kV Bus 1          / Melkspruit          |
|-------------------------------------------------------------------------------|
|   Current Transformer                           Ratio      : 1200A/5A         |
|     Connection     : Y                                                        |
|                                                                               |
|   Measure                                                                     |
|     Nominal Current ( 1.0 - 5.0     A     ) :     1.00 A                      |
|                                                                               |
|   I>              ( IEC: I>t   ANSI: 51   )       Out of Service   : No       |
|     Tripping Direction                     : None                             |
|     Current Setting ( 0.4 - 3.55    p.u.  ) :     0.450 p.u.                  |
|     Time Dial       ( 2.5 - 80.0           ) :     5.000                      |
|     Characteristic                         : Overload curve                   |
|                                                                               |
|   I>>             ( IEC: I>>   ANSI: 50   )       Out of Service   : No       |
|     Tripping Direction                     : None                             |
|     Pickup Current  ( 2.0 - 19.0    p.u.  ) :    19.000 p.u.                  |
|     Time Setting    ( 0.025 - 0.8   s     ) :     0.025 s                     |
|                                                                               |
|   Ie>             ( IEC: IE>>  ANSI: 50N  )       Out of Service   : No       |
|     Tripping Direction                     : None                             |
|     Pickup Current  ( 0.1 - 3.3     p.u.  ) :     0.100 p.u.                  |
|     Time Setting    ( 0.05 - 1.6    s     ) :     0.050 s                     |
|                                                                               |
|   Logic                                           Out of Service   : No       |
|     Breaker                          Cubicle    Branch                        |
|      T_3                \ Melkspruit  Cubicle_S  S0.0.1                       |
--------------------------------------------------------------------------------
```

Figure 60: Relay Co-ordination for Melkspruit Substation

The results in figure 60 are the same results as shown in a graph format in figure 59, they are showing the time delay tripping times.

22 kV line (Sterkspruit-LowerTelle)

5) C.T Ratio = 600 / 5

We assume co-ordination time as 0.1 sec.

t_5 = 0.6 + 0.1

= 0.7 sec.

Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current

= 1 x 5

= 5

Multiple of set current = 8.76 kA / 600 A

= 14.6

TMS = $0.7 \times ((14.6)^{0.02} - 1) / 0.14$

= 0.28

6) C.T Ratio = 1500 / 5

We assume co-ordination time as 0.2 sec.

t_6 = 0.7 + 0.2

= 0.9 sec.

Rated C.T. Secondary Current = Plug Setting x C.T. Secondary Current

= 1 x 5

= 5

Multiple of set current = 8.76 kA / 1500 A

= 5.84

TMS = $0.9 \times ((5.84)^{0.02} - 1) / 0.14$

= 0.23

We know the actual time required for operation of relay will be the time of operation we have assumed and time multiplier setting.

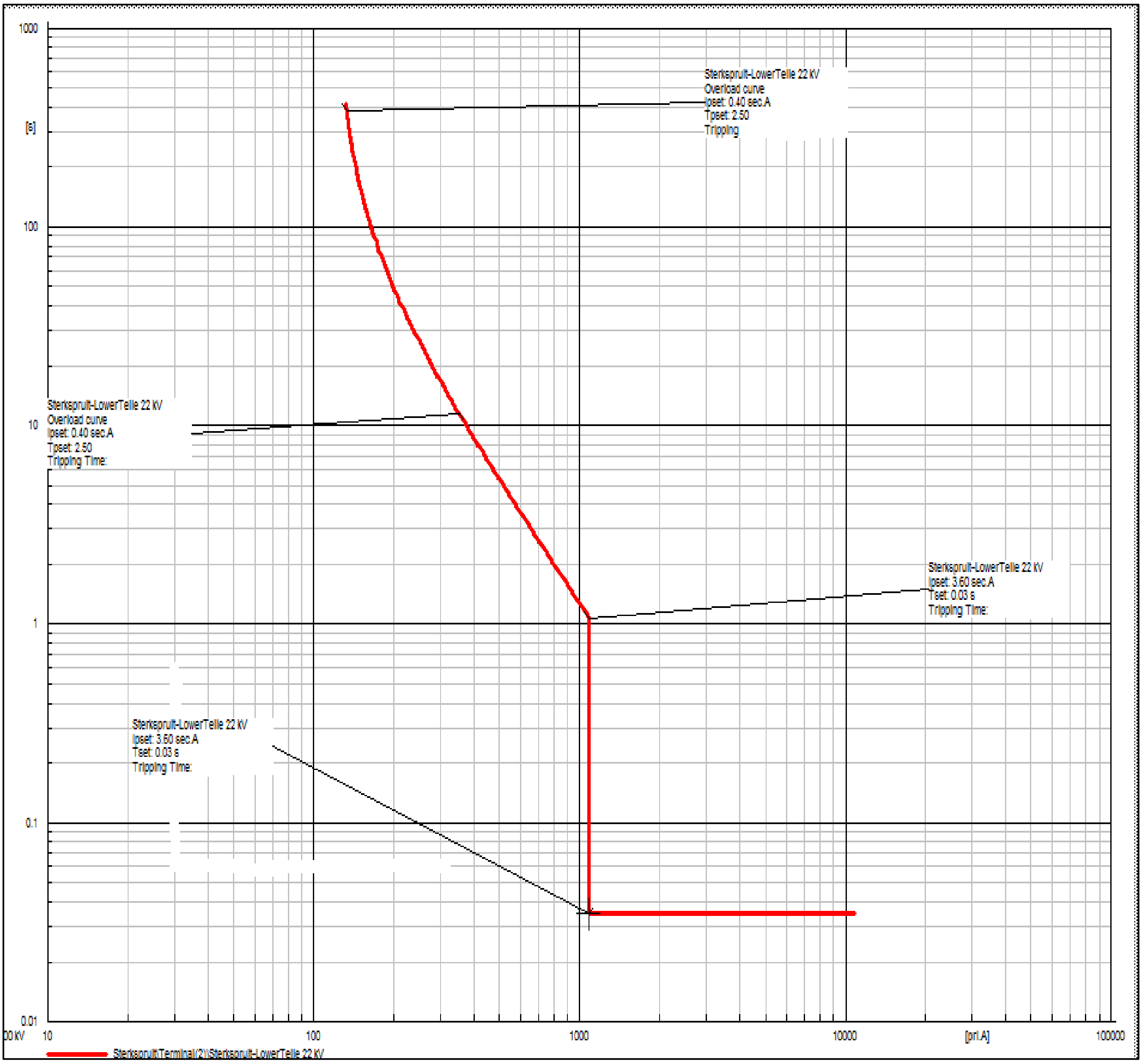


Figure 61: Relay Co-ordination for Melkspruit Substation

In figure 61 DigSilent simulations verified the correctness and validity of the Protection Grading Philosophy used for application to Aliwal North distribution network. Allowed for necessary work to ensure that the Protection Grading Philosophy was suitable for application to the network. Generated settings data for settings calculated on per substation and feeder basis, up to and including the Aliwal North supply point of the LPU's. Therefore, this lead to a compilation of a protection grading report per LPU, substation and feeder basis as shown in figure 62.

```
-----------------------------------------------------------------------------------------------------------------------------
| Grid: Southern HV          System Stage: Southern HV     |                                       | Annex:            / 1      |
-----------------------------------------------------------------------------------------------------------------------------
|              rtd. V   Voltage l-g     c-       Sk"              Ik"           ip        Ib        Sb         Ik        Ith   |
|                [kV]    [kV]   [deg]  Factor    [MVA]       [kA]       [deg]     [kA]      [kA]      [MVA]      [kA]      [kA]  |
-----------------------------------------------------------------------------------------------------------------------------
|  22kV Bus 1  22.00    0.00    0.00   1.00     49.41        1.30      -67.75     2.40      1.30      49.41      1.30      1.30  |
-----------------------------------------------------------------------------------------------------------------------------
□--------------------------------------------------------------------------------
|                                |   DIgSILENT   | Project:                       |
|                                | PowerFactory  |--------------------------------
|                                |    15.0.2     | Date:  11/20/2014              |
---------------------------------------------------------------------------------
| Sterkspruit-LowerTelle 22 kV     Relay Type : 7SJ50_OL                          |
|   Location      :  Cubicle        : Cub_3      Branch       : Sterkspruit 22kV Loa|
|                    Busbar         : 22kV Bus 1              / Sterkspruit        |
|--------------------------------------------------------------------------------|
|   Current Transformer                           Ratio       : 1500A/5A          |
|     Connection     : Y                                                          |
|                                                                                 |
|   Measure                                                                       |
|     Nominal Current ( 1.0 - 5.0      A      ) :     1.00 A                      |
|                                                                                 |
|   I>               ( IEC: I>t    ANSI: 51    )       Out of Service    : No     |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.4 - 3.55     p.u.  ) :     0.400 p.u.                   |
|     Time Dial       ( 2.5 - 80.0            ) :     2.500                        |
|     Characteristic                           : Overload curve                    |
|                                                                                 |
|   I>>              ( IEC: I>>    ANSI: 50    )       Out of Service    : No     |
|     Tripping Direction                       : None                              |
|     Pickup Current  ( 2.0 - 19.0     p.u.  ) :     9.000 p.u.                   |
|     Time Setting    ( 0.025 - 0.8    s      ) :     0.025 s                      |
|                                                                                 |
|   Ie>              ( IEC: IE>>   ANSI: 50N   )       Out of Service    : No     |
|     Tripping Direction                       : None                              |
|     Pickup Current  ( 0.1 - 3.3      p.u.  ) :     0.100 p.u.                   |
|     Time Setting    ( 0.05 - 1.6     s      ) :     0.050 s                      |
|                                                                                 |
|   Logic                                              Out of Service    : No     |
|     Breaker                                  Cubicle    Branch                   |
|      Terminal(1)          \ Sterksprui  Cub_2      Breaker/Switch(4)             |
---------------------------------------------------------------------------------
```

Figure 62: Relay Co-ordination for Melkspruit Substation

The relay current and time settings for all other relays in the system are shown in the relay report for all the voltage levels. The earth fault settings for the relays is generally 20 -30% of the rated current of the system. The time interval that must be allowed between the operation of two adjacent relays in order to achieve correct discrimination between them is called the grading margin. If a grading margin is not provided, or is insufficient, more than one relay will operate for a fault, leading to difficulties in determining the location of the fault and unnecessary loss of supply to some consumers, which contributes severely in unreliable network.

4.5.3 Short Circuit Analysis Single Phase Faults

At Melkspruit substation the 132kV yard is solidly earthed and the healthy phases have a voltage magnitude that is about 60% of nominal phase to phase voltage but the fault current on the unhealthy phase is very high (6∟74.9° kA. According to SABS 0200 code of practise, a solidly earthed system will ensure that healthy phase voltage magnitudes are limited to 80% of the nominal phase to phase voltage but the demerits of solidly earthed systems is the excessively high earth fault currents. The purpose of having effectively earthing the Melkspruit 132kV yard is due to insulation requirements for transformer windings. The winding insulation is fully graded and the voltage rise permitted at the star point is limited and therefore this accomplishes a cost saving concerning to the amount of insulation required for the safe operation of the transformer.

Melkspruit-SABC Kramberg 22kV feeder overcurrent relay must grade with the reclosers for proper protection correlation and also it provides back up for this nulec recloser. The relay is selected to use the standard inverse define time characteristics curve, therefore the formulae applied to determine the time set multiplier is for the standard inverse define time characteristics. The types of relays that will be used at Mapassa substation are numerical relays therefore the grading margin that will be used is 0.3. The time desired is 0.18+ 0.3 = 0.48sec.

$$PSM_{min} = \frac{I_{Fmin}}{ES} \qquad PSM_{min} = \frac{1880}{285}$$

$$PSM_{min} = 6.596$$

$$t_{(TSM=1)} = \frac{0.14}{{PSM_{min}}^{0.02} - 1} \qquad t_{(TSM=1)} = \frac{0.14}{6.596^{0.02} - 1}$$

$$t_{(TSM=1)} = 3.641sec$$

$TSM = \frac{t_{desired}}{t_{(TSM=1)}}$ $TSM = \frac{0.48}{3.641}$

$$\boldsymbol{TSM = 0.131\ s\ set\ to\ 0.15\ \ s}$$

Calculating trip time at Maximum fault, the maximum fault level at 22kV busbar is 7309A.

$PSM_{max} = \frac{I_{Fmax}}{ES}$ $PSM_{max} = \frac{7309}{285}$

$PSM_{max} = 25.645$

$t_s = \frac{0.14}{PSM_{max}{}^{0.02} - 1}$ * TSM $t_s = \frac{0.14}{25.645^{0.02} - 1}$ * 0.15

$\boldsymbol{t_s = 0.313 sec}$ **at max fault level**

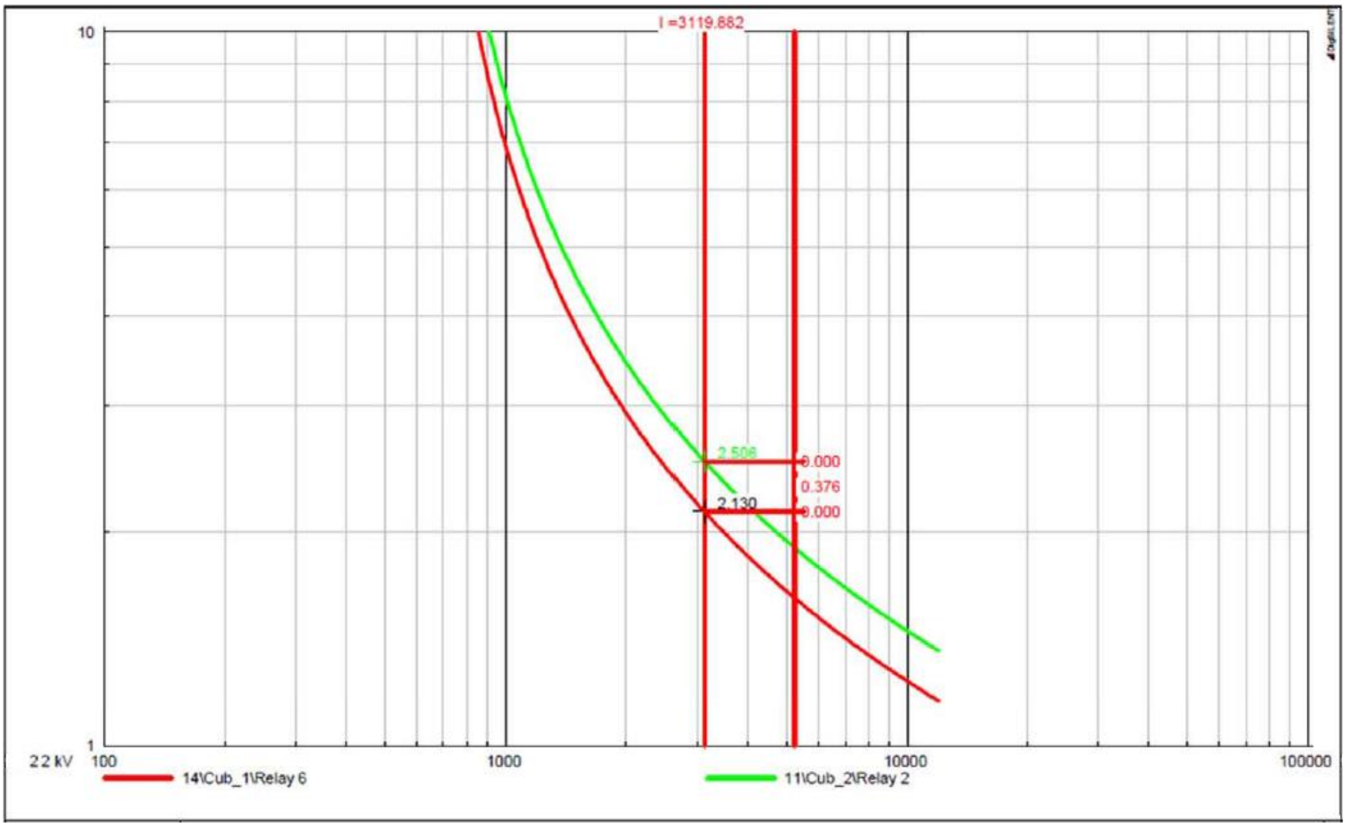


Figure 63: Relay Coordination for Single phase to ground faults

4.5.4 Short Circuit Analysis Dual Phase (Phase-to-Phase) Faults

The results in this section are provided to demonstrate the performance of the individual relays for faults in their primary and backup protection zones. The performance is analysed by looking at the grading margin, operating time for primary zone fault and operating time for backup zone fault for each algorithm.

Figures 64 and 65 show the coordination curves for the selected relay coordination pair for Siemens and Reyrole algorithms. The main relay for the selected pair is Relay 12 and the backup relay is Relay 6. For this relay pair, a phase to phase fault was simulated in front of Relay 12. This fault is in the primary zone of protection for relay 12 and in the backup zone of protection for Relay 6.For this fault Relay 12 measures 12674 A and Relay 6 measures 1854A. For Siemens, Relay 12 operates in 0.521 seconds and Relay 6 operates in 1.043 seconds. The relays operated properly with the grading margin of 0.522 seconds which is above the coordination time interval of 0.3 seconds. For Reyrole, Relay 12 operates in 0.499 seconds

and Relay 6 operates in 0.920 seconds. The relays operated correctly with the grading margin of 0.422 seconds which is above the coordination time interval of
0.3 seconds. For SEL, Relay 12 operates in 1.156 seconds and Relay 6 operates 3.130 seconds. In terms of coordination, the relays operated properly with the grading margin of 1.973 seconds which is above the coordination time interval of 0.3 seconds. However, the response of the relays for the fault is much longer than is the case for Reyrole and Siemens. This violates one of the principles of protection which is to isolate a fault from the power system as quickly as possible. It can be seen that the three evolutionary algorithms provides coordination for all relay pairs. However, in general, for SEL the response of the relays is much longer than for both the Siemens and Reyrole.

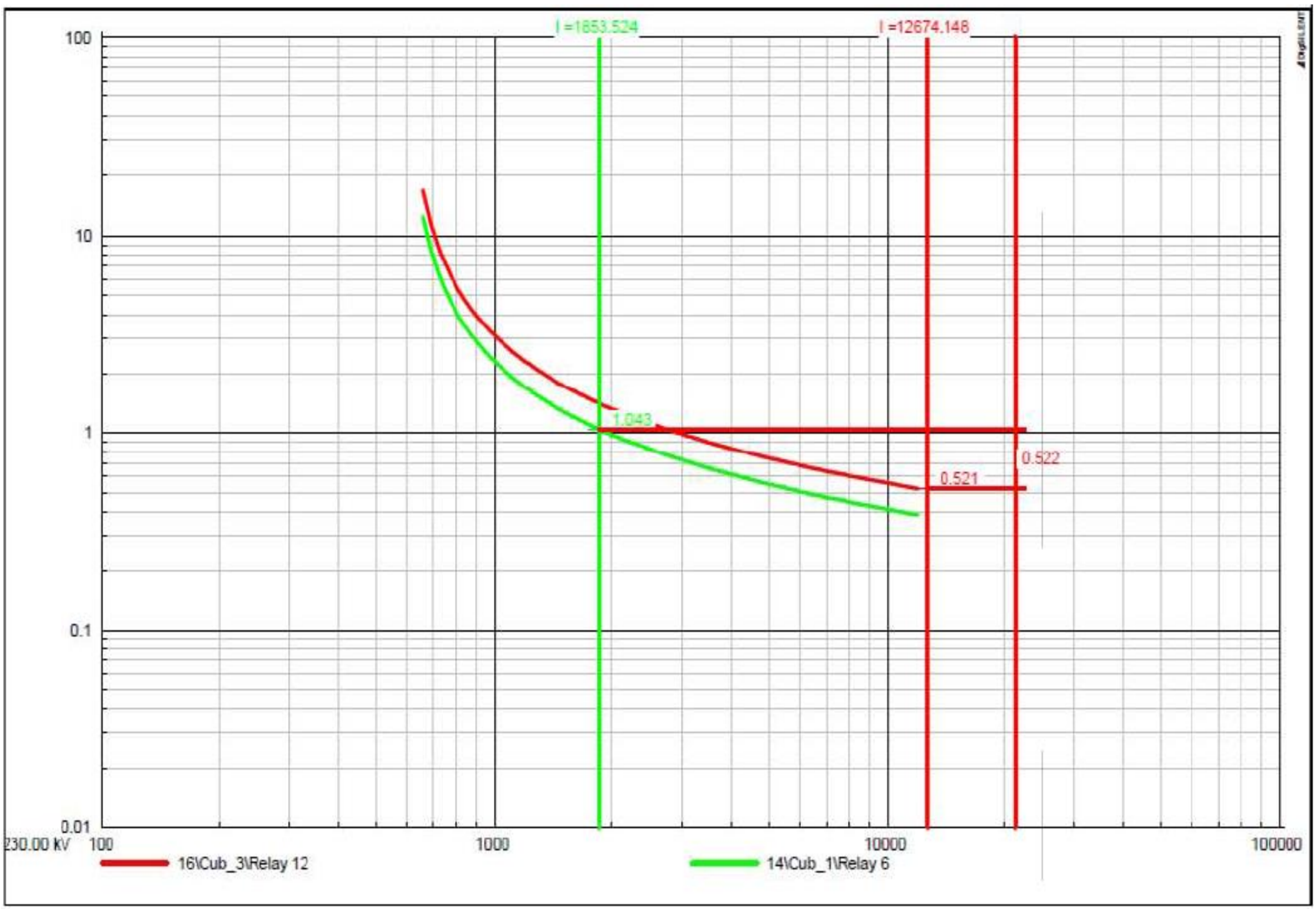


Figure 64: Performance of Relay Coordination at Riebeek Substation

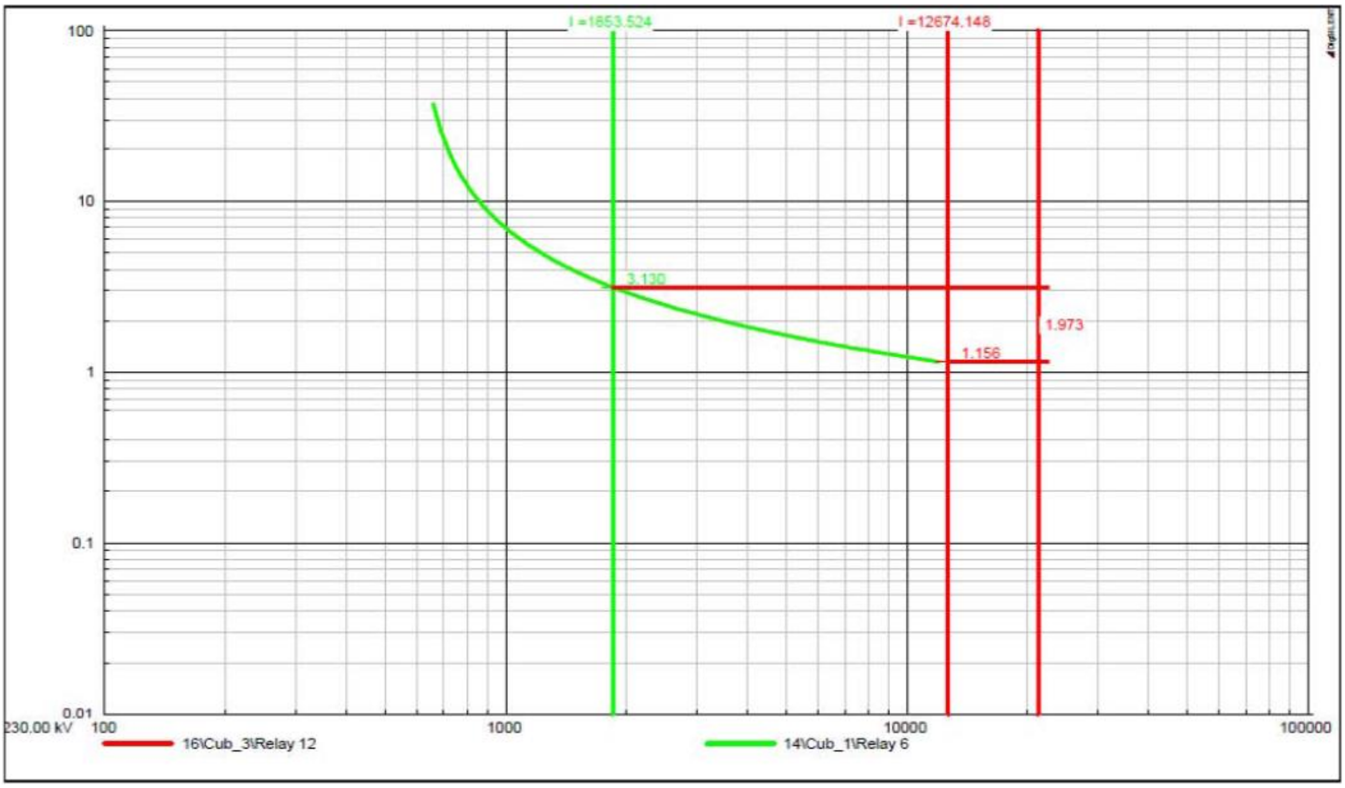


Figure 65: Performance of Relay Coordination at Riebeek Substation

4.5 Benefit to Cost Analysis

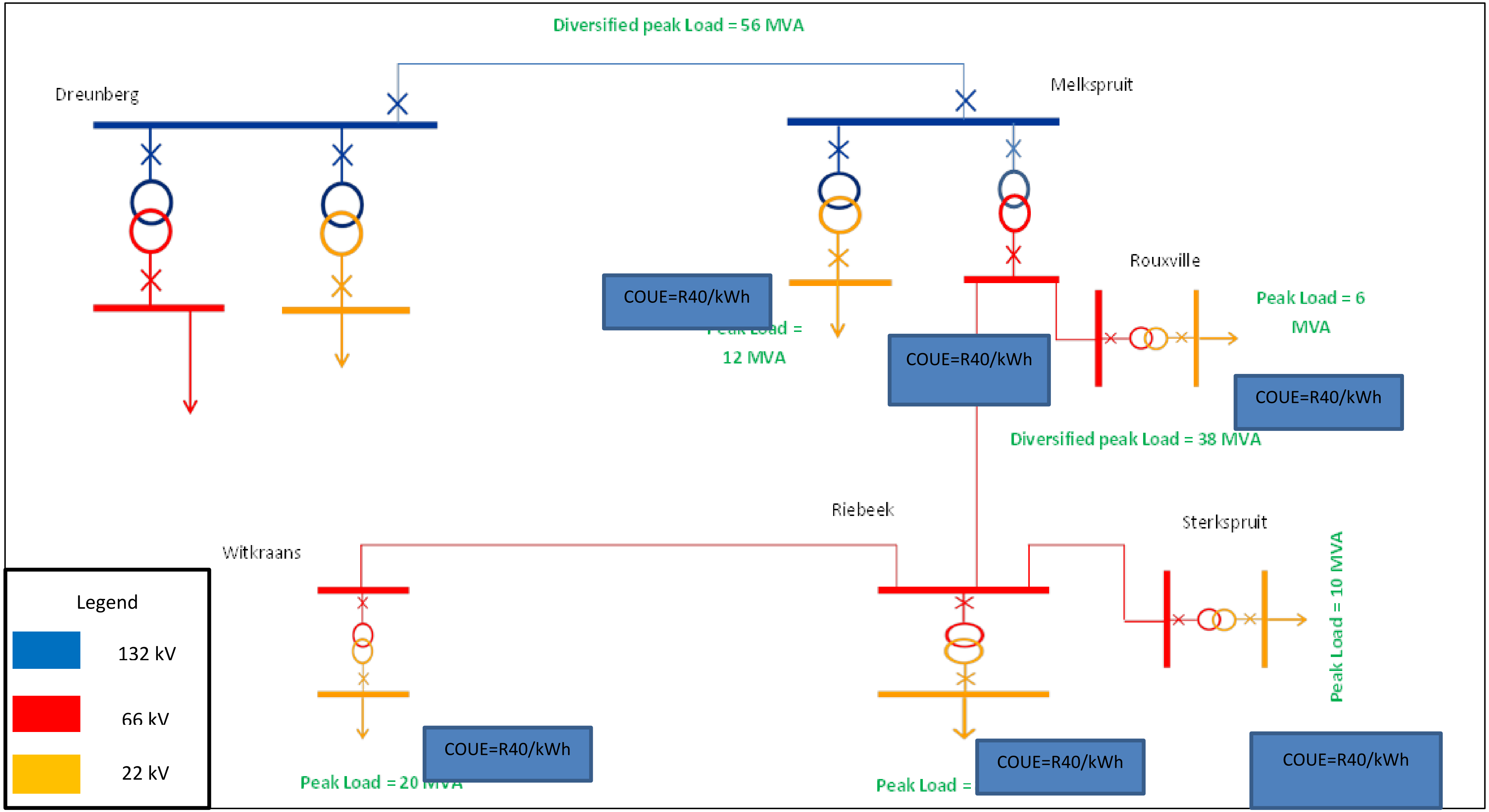


Figure 66: Calculating load at risk – radial network

The load at risk is the load that will be lost if a line fails. This can be calculated in the simulation software by shedding load until all technical criteria (thermal and voltage) are met for the contingency being analysed. In the example in figure 66 above diversity factor of 1 has been assumed for the sake of simplicity. Furthermore the load at risk is determined based on thermal limits only. In reality load flow calculations are required to establish how much load must be shed for a given contingency in order to comply with thermal loading and voltage limit criteria.

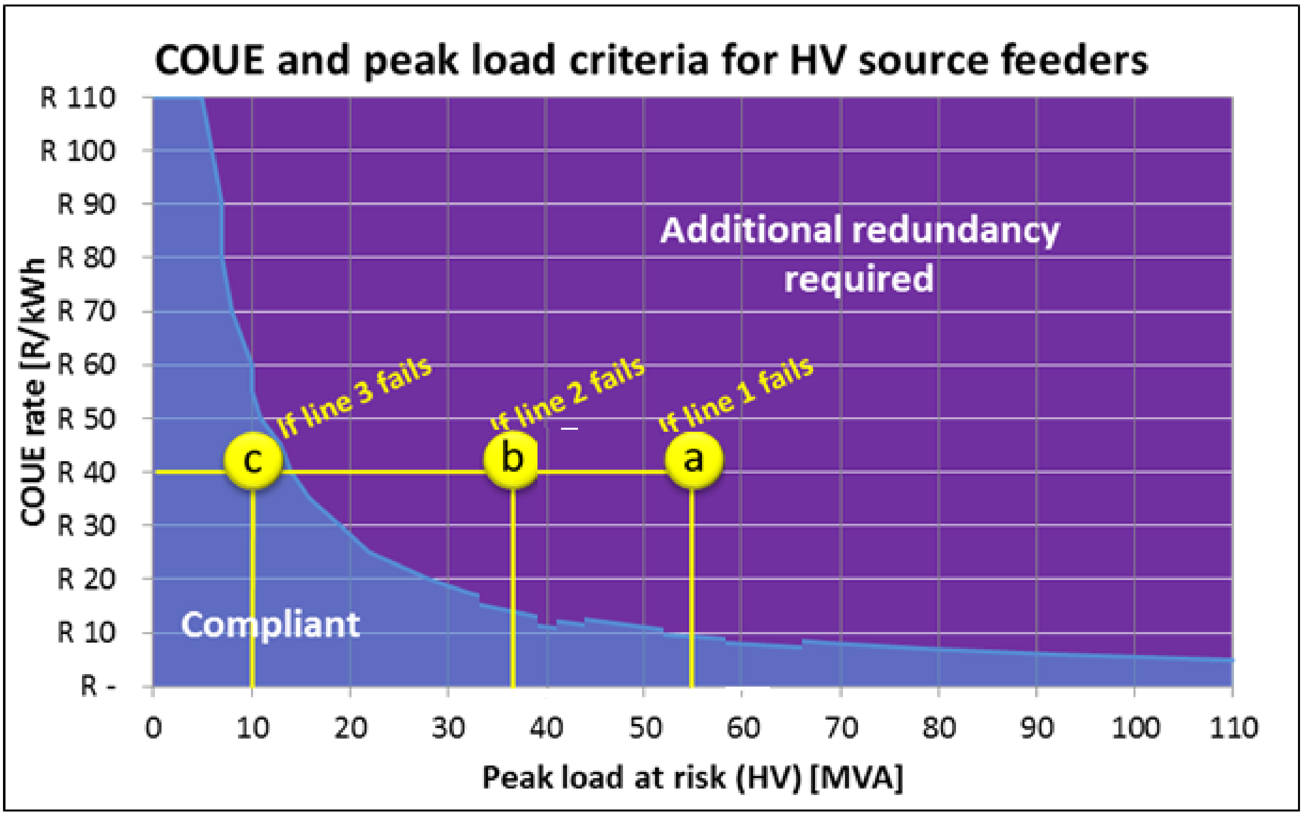


Figure 67: Calculating load at risk – radial network

Table 12: Calculating load at risk – radial network

LINE FAILURE	PEAK LOAD AT RISK (MVA)
Dreunberg-Melkspruit 132 kV	56
Melkspruit-Riebeek 66 kV	38
Sterkspruit-LowerTelle 22 kV	10

In this scenario the substations have similar (Cost of Unserved Energy) COUE rates as shown in Figure 66. The effective COUE rate for the load at risk for each substation is calculated as follows:

a) If Dreunberg-Melkspruit 132 kV line (line 1) fails, 56 MVA will be lost to the entire substations supplied by this feeder. The equivalent COUE rate of the load lost is:

$$\text{Equivalent COUE rate} = \frac{(56\ \text{MVA} \times \text{R40/kWh})}{56\ \text{MVA}}$$

$$= \text{R40 / kWh}$$

This is indicated by point "a" in Figure 67. A second line is therefore economically justified. Hence, based on the above analysis, additional redundancy is required to provide alternate supplies for the failure of lines 1. This justifies the reason to have an alternate source of supply to formulate a ring in this network see figure 68 below.

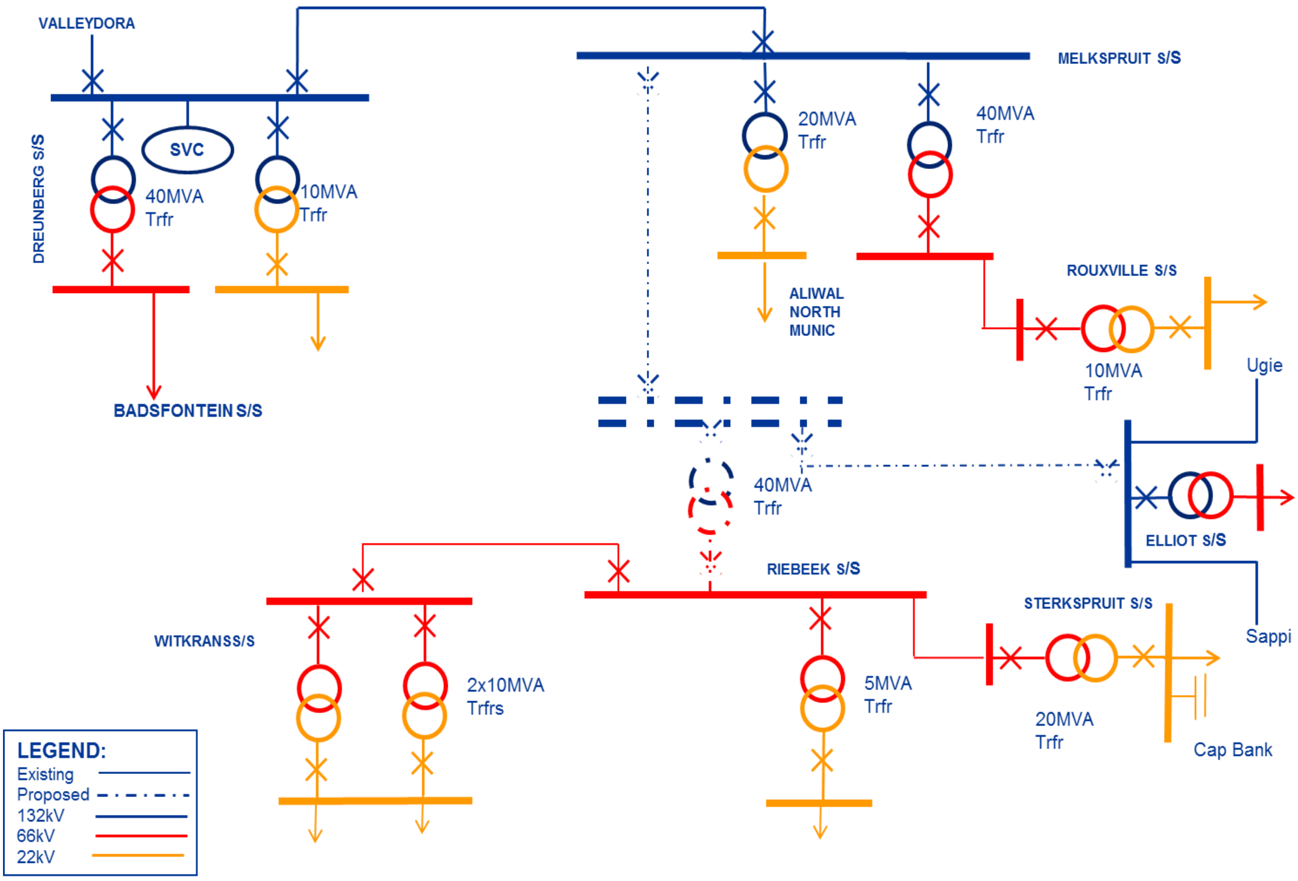


Figure 68: Solution to the reliability of Aliwal North Network

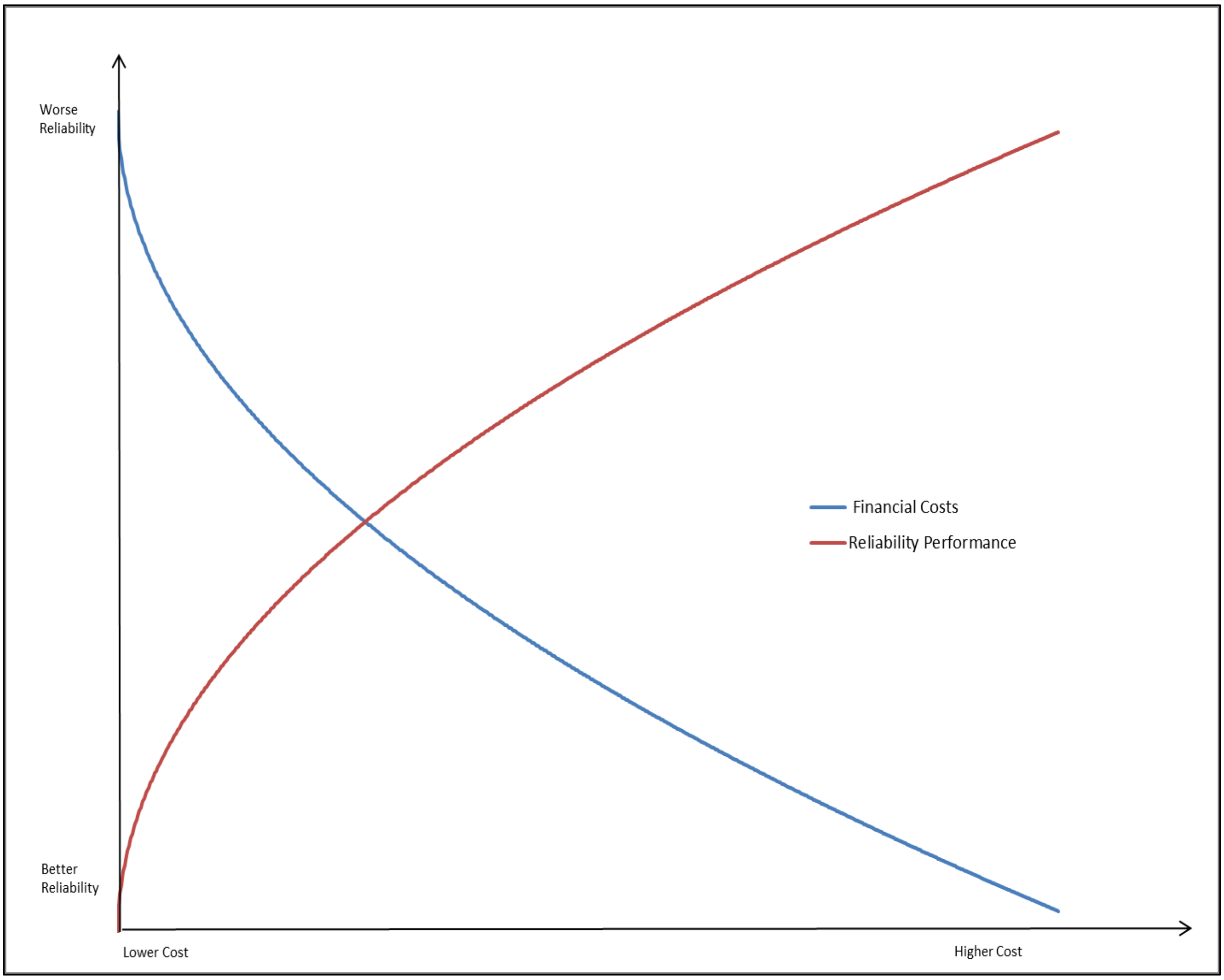


Figure 69: Solution to the reliability of Aliwal North Network (Data from network performance)

From the review of the above drivers for improved network reliability it is clear that:

- Eskom is incentivised by, and needs to adhere to the MYPD rules set by NERSA, and by implication to the requirements of the Distribution Network Code, in order to recover its investments or other costs through the NERSA approved tariff.
- Investments that don't sufficiently address quality of supply, as well as reliability and operational requirements determined by NERSA, may not be included in allowed costs, and may therefore ultimately jeopardize Eskom's financial sustainability.
- At the same time, there are strong drivers such as Eskom's strategic intent to be a top 5 utility compared to international benchmarks, and internal SAIDI targets, to improve Distribution's SAIDI in the long term.

Decisions to invest in network reliability interventions therefore need to be informed by a combination of financial costs and potential COUE implications, and the impact on performance levels. The criteria to be used when selecting network investments are prescribed by the “Distribution Network Investment Criteria” Standard (240-497385861, Rev 0, October 2012).

With respect to shared network investments, e.g. strengthening and refurbishment, the objective is to select investments that minimize total life cycle cost (i.e. initial capital investment as well as expected operating and maintenance costs over the life of the project). This means those investments alternatives need to be selected that minimize Eskom’s least life cycle cost as well as the least life cycle cost to the economy, while meeting minimum Eskom reliability standards. Economic cost in this context is typically monetised in terms of the cost of unserved energy (COUE).

The prescribed investment approach (also formerly known in Eskom Distribution planning circles as value-based planning) is illustrated in Figure 69.

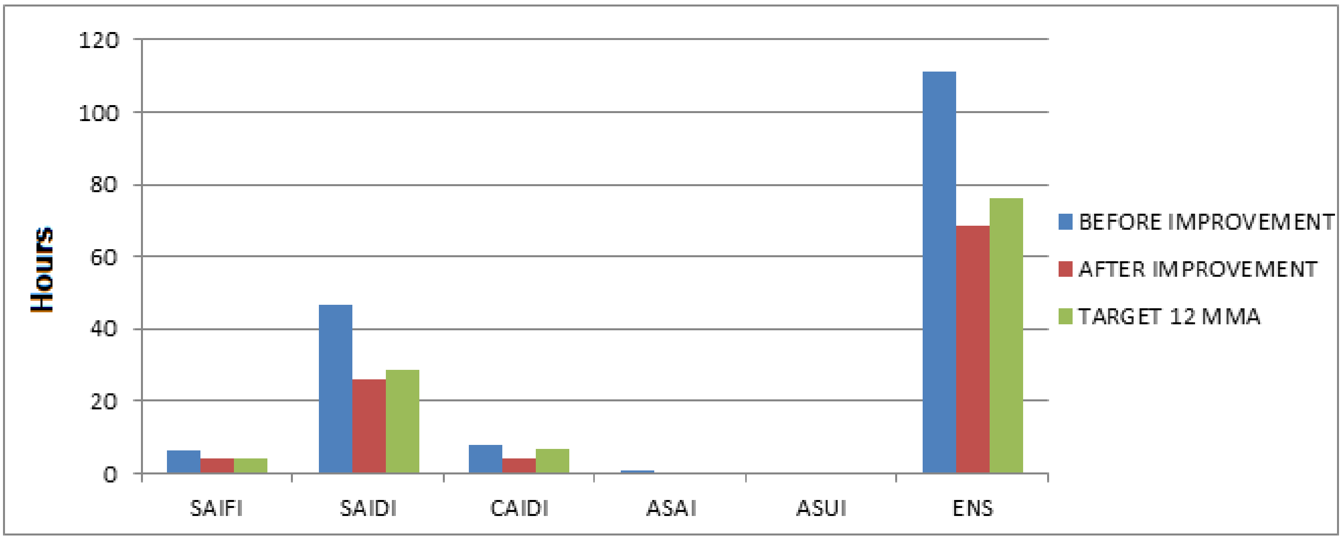


Figure 70: Aliwal Reliability indices before and after improvement.

Figure 70, shows the predictive DigSilent results taking the consideration of using solution 3 as the remedial strategy to the poor reliability performance of the Aliwal North sector. The above comparison was carried out using the ECOU target for the 2014/2015 financial year (12 Month Moving Average – MMA). The result were computed using the average reliability evaluation results for all the voltage levels i.e. 132/66/22 kV.

CHAPTER 5: CONCLUSIONS

The primary concept of power system reliability evaluation purpose is to satisfy customer requirements and since the proper functioning and longevity of the system are found to be essential requisites for continued satisfaction, hence it is necessary that both demand and supply side considerations are appropriately included in the planning and analysis. Reliability planning and investment should ensure that Distribution networks meet the minimum quality of supply, reliability and operational requirements as specified in the Distribution Network Code.

The focus should be on improving power quality on constrained networks first, then reliability. Therefore for the Aliwal North power system network it is imperative that Eskom invest on the reliability of this network. This Dissertation also analysed load reflected economic benefit versus performance expectations that should be optimised through achieving a balance between network performance (SAIDI) improvement and total life cycle cost (to Eskom as well as the economy).

The Aliwal North power system network was used as a case study to conduct reliability analysis; it was therefore found that this system is vulnerable to faults, planned and unplanned outages (unreliable network). Reliability evaluation studies was carried out on the 132/66/22 kV power system using DigSilent software in conjunction with FMEA these two models gave accurate results with a variance of ± 6% in most indices except for the ENS where the variance was quite significant. The cause of this significant difference was due to the fact that PowerFactory does not ignore conductor parameters such as resistivity, type, length and diameter whereas FMEA is an excel spreadsheet where most parameters are assumed or given a constant value. The final verdict was that DigSilent results are the most accurate results in all three reliability evaluation scenarios for the Aliwal North Power System (132/66/22 kV network). It is shown in figure 70 using the predictive approach simulation in DigSilent that after implementing the suggested solution the reliability indices improved and are below the target.

It was outlined in chapter one that load flow forms part of dissertation sub-problems. Therefore PowerFactory was used to perform load flow analysis of the Aliwal North power system, the network was scaled using the peak demand. Findings were that the system is currently experiencing high and low voltages in particular the 66 kV network, where most busbars were measured to be lower or higher than the declare (nominal) voltage as per NRS048-4 standard and see table 7 that contains upper and lower limits for different voltage levels. Reliability improvement project is necessary for system as it will also address the load flow challenges that are found, it further support implementation of solution number 3 from the dissertation proposal as it is the only solution out of the three that solves load flow problems encountered or experienced by this radial network.

Due to the significant expansion of the Aliwal North power system to achieve a high degree of reliability in that area. It became imperative for this dissertation to assess the impact that the additional power system components such as 132 kV line, capacitor banks, voltage regulators etc. would have in power quality of this network. Therefore this dissertation assessed power quality components such voltage unbalance, voltage flickers, voltage dips, voltage regulation, voltage swells and harmonics.

Sterkspruit – LowerTelle 22 kV network had voltage unbalanced problems (see figure 38) of the voltage unbalanced profile, which was caused by high loads connected to the same phases throughout the line. DigSilent (PowerFactory) was used to simulate the voltage imbalances and the simulations gave the clear indication that phases A and B are the most affected phases. Therefore a simpler load balancing technique that uses a spreadsheet was used to solve the problem see table 9, it gave positive results and this will assist the future network expansion such electrification projects and connection of high load to follow the same approach.

Large water supply pump motors of Sterkspruit municipality draws fluctuating currents on a continuous basis on the Sterkspruit-LowerTelle 22 kV line. It was observed that the large currents drawn by these motors gave rise to voltage changes when switched on and it resulted to voltage flicker. Assessment of voltage flicker was carried out considering the fact that Sterkspruit Munic wants to add two more water pump motor, analysis showed that the additional two motors will result in severe voltage flicker. The remedial strategy to the problem was to install a capacitor bank rated at 800 kVar at the 22 kV busbar where the four motors are connected and this will improve power factor control and compensate for voltage variations see figure 41.

Aliwal North power system network is exposed to too much lightning during summer season and this causes the network to experience voltage dips. The cause of the voltage dip is mainly due to the lightning strike on the power lines in particular Dreunberg/Melkspruit 132 kV line as it is built in an area of high lightning density. Analysis proved that the 66 kV network being fed from the aforementioned 132 kV line does experience voltage dips. This has an impact of about 35% on the cost of unserved energy. An alternative source of supply to this network is the perfect solution, that alternative source of supply is none other than that of solution three of the dissertation introduction chapter.

Aliwal North Power system networks do not have problems with voltage swells. The analysis of the past performance for the network using the historical data from the SCADA system shows that the voltage swells were still within normal operating limits as NRS048-2.

Due to large number of customers and line length, Sterkspruit/LowerTelle 22 kV feeder experiences low voltage further down the line. This has caused this feeder not conform to voltage regulation standards as per NRS048-2. Retic Master simulation tool was used to conduct analysis of this 22 kV network; various options were used such as on-load tap changers, shunt capacitor banks and voltage regulators. The analysis shows that voltage regulators are the best solution; they are effective in alleviating low voltage conditions at the ends of the radial Sterkspruit/LowerTelle 22 kV distribution feeder as show in figure 47.

The installation of the two shunt capacitor banks at Sterkspruit substation 22 kV busbar, to improve power factor control resulted in higher Total Harmonic Distortion (THD) as shown in figures 51 and 52 due to parallel resonance that it causes at that point. In order to assess the problem and confirm the network simulation results, monitors were installed at Sterkspruit on the 22 kV busbar to measure all the outgoing feeders as well as the two shunt capacitor banks and transformers as shown in figures 48 and 49. The chosen solution was to move one of the shunt capacitor banks to a downstream of the Sterkspruit/LowerTelle 22 kV line, which reduces the THD on the 22 kV busbar see figure 50. The move, however, changed the harmonic impedance at some of the other MV spur lines of Sterkspruit/LowerTelle 22 kV feeder, which led to an increase in THD values measured on the busbars see figure 52. Subsequently, a harmonic filter bank at Sterkspruit substation needs to be installed to address the 3rd harmonic problem.

Due to network adjustments and reconfigurations that will be in done in the process of reliability improvement, it is important to include the impact of protection (relay) coordination analysis on the system reliability assessment procedure to obtain more realistic system reliability information. Relay coordination analysis was done considering three phase faults, phase to phase faults and single phase to ground faults. Protection analysis was done using the DigSilent (PowerFactory) simulation tool and manual calculations. The results shows that current existing protection coordination on the Aliwal North network requires no adjustment or improvement as the relay setting and tripping times are operating as expected see figures 57 to 62 of relay operating and tripping times on the protection analysis. Most of all, the protection configuration on the 132 / 66 / 22 kV system is well configured and maintain proper coordination for all voltage levels.

The conceptual objective of undertaking reliability cost benefit analysis makes it necessary to independently asses the cost of providing reliability and worth of having it. In order to render a rational means of decision making on the necessity of changing service continuity levels experienced by customers, utility cost and the cost incurred by customer associated with interruptions of service must be incorporated considering operating practices. Electrical system reliability cost and worth assessment approach provides an opportunity to justify future system expansion project. Benefit to cost analysis was carried out based on the proposed solution 3 from the proposal (Chapter one) of the dissertation to demonstrate the benefits that the utility will have by implementing the proposed option. Using the reliability guideline of the power system reliability improvement, considering the COUE concept. The analysis shows that the economic benefit versus performance expectations will be optimised through achieving a balance between performance (SAIDI) improvement and total life cycle cost to Eskom as well as the economy by implementing the solution 3 to achieve a better reliability in the Aliwal North power system.

CHAPTER 6: RECOMMENDATIONS

In order to achieve better results for reliability analysis, to judge the present performance and to improve the reliability in the Aliwal North power system network the following recommendations are presented below.

- Focused research need to be conducted by Eskom regarding specific network and equipment failure rates and performance. This will serve the dual purpose for reliability modelling as well as provide information required in support of asset management strategies and implementation.

- More accurate customer sector and type information need to be obtained and maintained for this modelling to be more accurate of especially financial and cost of Un-served energy implications.

- The present data recording system should be modernised from manual to computer aided system. All the events should be specific and the step restorations made should be recorded accordingly so that true reliability indices are obtained. The failure of individual components in the system should be recorded so the probability of failure represents its true system. Its repair time and sectionalizing time should be separated since it has high impact on the reliability indices during predictive analysis.

- Reliability of 22kV system could be further improved by installing Voltage Regulator at structure LTE-STS-36 of Sterkspruit-LowerTelle 22 kV line

- The failure rates of all components in a network should be taken into account when evaluating the reliability of a network. Assuming components are always operable in a system is nonsensical and should not be done.

- With adequate time for future expansion of this dissertation, the author will strongly recommends a full protection analysis in this topic e.g. phase to earth and phase to phase analysis.

REFRENCES

[1] Wang Saiyi: “An Effective and Applied Method on Evaluation of Distribution Network Planning”. China International Conference on Electricity Distribution 20 – 23 Sep. 2010.

[2] Jin Yi-xiong, Li Hong-zhong, Duan Jian-min: “Algorithm Improvement for complex Distribution Network Reliability Evaluation and its programming”, 2010.

[3] G.E. Shau-yun, Cheng Peng, Liu Hong, Li Da, Li Xiao-hui, XU Jing: “Research on the Comprehensive Evaluation Index System of Distribution Network Reliability”: 20-23 Sept. 2010 China International Conference of Electricity Distribution.

[4] M Schwan, A Ettinger, S Gunaltay: “Probabilistic Reliability Assessment in Distribution Network Master Plan Development and in Distribution Automation Implementation”, 2012.

[5] José A. Rosendo, Antonio Gómez-Exposito, Gabriel Tevar, Manuel Rodriguez: “Evaluation and Improvement of Supply Reliability Indices for Distribution Networks”: 2009.

[6] Navan M. Pindoriya: “Power System reliability Analysis”: - 2nd edition 2012.

[7] M. Al-Muhaini, G.T. Heydt, A. Huyn: “The Reliability of Power System of Power Distribution System as calculated using system theoretic concepts”. In Proc, IEEE Conf. Power and Energy Society General Meeting, USA 2010.

[8] L. Goel, R. Billinton: “Determination of Reliability Worth for Distribution System Planning. IEEE Transactions on Power Delivery.

[9] R. Billinton, RN, Alan: “Reliability Assessment of Large Electric Power System. Springer, 1st edition – 1998.

[10] M.A. Van Harte: “Network Planning Reliability Guidelines Eskom”, August 2010.

[11] W. Li: “Risk Assessment of Power System Models, Methods and Applications”. Wiley – IEEE Press, 2009.

[12] S.R.L. Goel, P. Wang: "Modelling Station-originated outages in composite system using duration sampling simulation approach computers & electrical engineering, vol. 27 2009.

[13] R.U. Nighot: "Incorporating Substation and Switching Station related Outages in Composite System Reliability Evaluation", 2008.

[14] M.H.J. Bollen: "Effects of adverse weather and aging on power system reliability", Industry Application, IEEE Transactions, 2001.

[15] G. Pulcini: "Modelling the failure data of repairable equipment with bathtub type failure intensity", 2009.

[16] U.S. Canada Power System Outage Task Force: "Final Report on the August 14th Blackout in the United States and Canada ", Department of Energy and National Resources, Canada 2004.

[17] S.T. Lee: "Probabilistic Reliability Assessment for Transmission Planning and Operation including Cascading Outages". In Power Systems Conference and Exposition, 2009. PSCE 09.IEEE/PES, 2009 pp. 1-8.

[18] K. Yamashita, L. Juan, Z. Pei, and L. Cheng-Ching: "Analysis and Control of major Blackout events", Power System Conference and Exposition, 2009. PSCE 09.IEEE/PES, 2009, pp. 1-4.

[19] M. Schwan, S. Sanchez, D. Rondan, C. Rodelo, C. Nabte: "Reliability centered asset management – case study for Mexican Sub-transmission Networks – Cidel Argentina 2010, International Congress and Electricity Distribution.

[20] M. Schwan, M. Esquivel, C. Nabte, S. Sanchez, E. Arroyo: "Application of new Asset Management methods to Sub-transmission Networks in Mexico", C (Proceedings CIGRE, Paris, 2010).

[21] U. Zickler, A Schnettler, M. Schwan: "Impact of Maintenance on Component Condition and System Supply Reliability in Distribution Networks", (Proceedings 20th CIRED. Prague, 2009).

[22] End use perceptions of Power Quality – A European Perspective, Roman Targosz, EPRI PQA 2009.

[23] Towards Voltage Quality Regulation in Europe – An ERGEG conclusions Paper Ref: E07-EQS-15-04.

[24] NRS-048-2, Electricity Supply – Quality of Supply Part 2: Voltage Characteristics, Compatibility levels, limits and assessment methods, 2009.

[25] Milanovic, J.V., David, T.M.: “Stability of Distribution Networks with Embedded Generators and Induction Motors”, 2008.

[26] Wayte, A. Vu Van, T. Belmans, R. Nijs, J: “Voltage Fluctuations and Distribution level Introduced by Photovoltaic Systems”, IEEE Trans. On Energy Conversion, 2011.

[27] Kundur, P.: “Power System Stability and Control”, McGraw-Hill, New York, 1994.

[28] T. Belmans, R. Michiels, W. Vandenput, A Geysen: “Transient torques in Wind Turbine driven Induction Generators”. Symposium on Electric Power Systems in Fast Developing Countries.

[29] G.D. Antona, C. Muscas: “Localisation of Non-linear loads in Electric Systems through Harmonic Source Estimation”. International Instrumentation and Measurement Technology Conference, Singapore.

[30] M. Hadow, N. Abdalla, P. Abdul: “Reliability Assessment for Electric Power System considering System and Load points”, Australian Journal of Basic and Applied Sciences, 4(12): 6506-6511, 2010.

[31] A. Robin Wallace, Gareth P. Harrison: “Planning for Optimal accommodation of dispersed generation in distribution networks, 2009.

[32] A. Salem Nia, A. Belk-khoimizi: “Impact of TCSC Reliability Model on HLII Reliability indices of Power System”, - Proceedings of the 9th International Conference on Power Systems – 2010.

[33] Dong Lei, Lao Liyuan, Yang Yihan, Lou Jing: “Probabilistic Load Flow Analysis considering Power System random factors and their relevance”. IEEE 2011.

[34] M.J. Katira, K.B. Porate: “Load Flow Analysis of 132/11 kV Distribution Substation using Static Var Compensator for voltage Enhancement – A case study, 2009

[35] Mingye Zhang, Qinglai Gou: “Sensitivity Based Simplified Model for Security Constrained Optimal Power Flow – IEEE ISGT Asia, 2012.

[36] Dawn Layden, B. Jeyasurya: “Integrating Security Constraints in Optimal Power Flow studies”. 2009.

[37] Su Ching-Tzong, Ji-Jen Wong: “System and Load points Reliability Evaluation for Electric Power System”, 2007 1st Annual IEEE System Conference Waikiki Beach, Honolulu, Hawaii, USA 9-12 April 2007. (POWER FLOW)

[38] Liu Huijia, Hu Hammei: “An Improved Network-equivalent Method of Reliability Evaluation for Complex Medium-Voltage Distribution System based on feeder Partition”, IEEE 2009. (POWER FLOW)

[39] Hurford, G (2013 May 24). Loading Types in Eskom. (J. Lavagna, Interviewer) Germiston, Gauteng, RSA. (POWER QUALITY)

[40] National Energy Regulator of South Africa (NERSA). 2012. Grid Connection Code for Renewable Power Plants (RPPS) Connected to the Electricity Transmission System (TS) or Distribution System (DS) in South Africa. Version 2.6. (POWER QUALITY)

[41] A. Moreno-Muñoz, J.J.G. de la Rosa*, M.A. López, A.R. Gil de Castro: “Distributed Resources Standards: the case of Spain”, IEEE International Symposium on Industrial Electronics, ISIE 2009. (Standards)

[42] The Allen Consulting Group: “Benchmarking the National Energy regulator of South Africa against international good practice, 2009.” (Standards)

[43] P. Doren: “Strangulation by Regulation”, The National Review, 2000. (Standards)

[44] S. Andrei: “Efficient Regulation”. Harvard University and NBER. (Standards)

[45] B. Robert, C. Martin, L. Martin: “Understanding Regulation Theory, Strategy and Practice. Oxford University Press, 2012. (Standards)

[46] National Energy Board Office national de l’ènergie: “National Energy Board’s Reliability oversight of International Power Lines (IPL)”, File: OF-Fac-ElecGen-Rel-ERO 03, 2008. (Standards)

[47] IEEE Standard 738: "Standard for Calculating Current – Temperature Relationship of Bare Overhead Conductors.

[48] NERA: "A – Z of regulation Training" by NERA Economic consulting. Midrand, SA.

[49] Government of South Africa: "The White paper on Energy Policy", South Africa, 1998.

[50] W. Olson: "Secrecy and Utility Regulation". The Electricity Journal. Elsevier Inc. 2005.

[51] N. Nunes, B.G. Chatterton, V. Singh, M.N. Bailey: "Distribution Network Performance Key Performance Indicators Definitions Standards". Distribution Standard – Part 4: 34-1188, August 2010.

[52] North American Electric Reliability Corporation: "Mandatory Reporting of Conventional Generation Performance Data". 2011.

[53] G. Hoogendorp, M. Popov, L. van der Sluis: "Lightning Induced Overvoltages in Mixed 380 kV OHL-Cable-OHL connections". International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

[54] H. Ahmadi, S. Mohseni, A.A. Shayegani Akmal: "Electromagnetic fields near Transmission Lines-Probleme and Solutions". February 2010.

[55] Corren.se, www.corren.se. May 2011.

[56] Kungliga Vetenskapsakademien, www.kva.se. May 2011.

[57] P. Schavemaker, L. van der Sluis: "Electrical Power System Essentials". John Wiley & Sons Ltd, England. 2009.

[58] Pacific cabling Solutions Ltd, www.pacificcabling.com. May 2011

[59] CIGRÉ: "Sag-tension calculation methods for overhead lines". 2007

[60] Golder Associates: "Study on the comparative merits of Overhead Electricity Transmission Lines versus Underground Cable". 2007.

[61] R.V.R. de Cravalho, F.H.T. Viera, S.G. de Araújo, C.R. Lima: “A Protection Coordination Scheme for Smart Grid Based Distribution System Using Wavelet Based Fault Location and Communication”. 2013.

[62] H. Clemens, K. Rothe: “Schutztechnik in Elektroenergiesystemen”. Technik Verlag. Auflage 5. ISBN 3-341-00828-4. 1991.

[63] W. Deomeland: “Handbuch Schutztechnik”. Technik Verlag. ISBN 3-341-01093-9. 1995.

[64] H.J. Hermann: “Digitale Schutztechnik”. Grundlagen, Software Ausführungsbeispiele. VDE-Verlag. 2007. ISBN 3-8007-1850-2.

[65] A.G. Phadke, J.S. Thorp: “Computer Relaying for Power Systems”. Research Studies Press, Ltd., 2008.

[66] H. Ungrad, W. Winkler, A. Wiszniewski: “Schutztechnik in Elektroenergiesystemen”. Grundlagen, Stand der Technik, Neuentwicklungen. Springer Verlag. 1991.

[67] www.cyme.com, www.neplan.com, www.advantica.biz, www.digsilent.com .

[68] H.J. Hermann: “Digitale Schutztechnik im Elektroenergiesystem – Algorithmen für den Staffelschutz”. Elecktrie. Berlin 44. Heft 3. 1990.

[69] DigSILENT\PF140\Help\sigsi_e.chm::/PF_Manual_E29.html

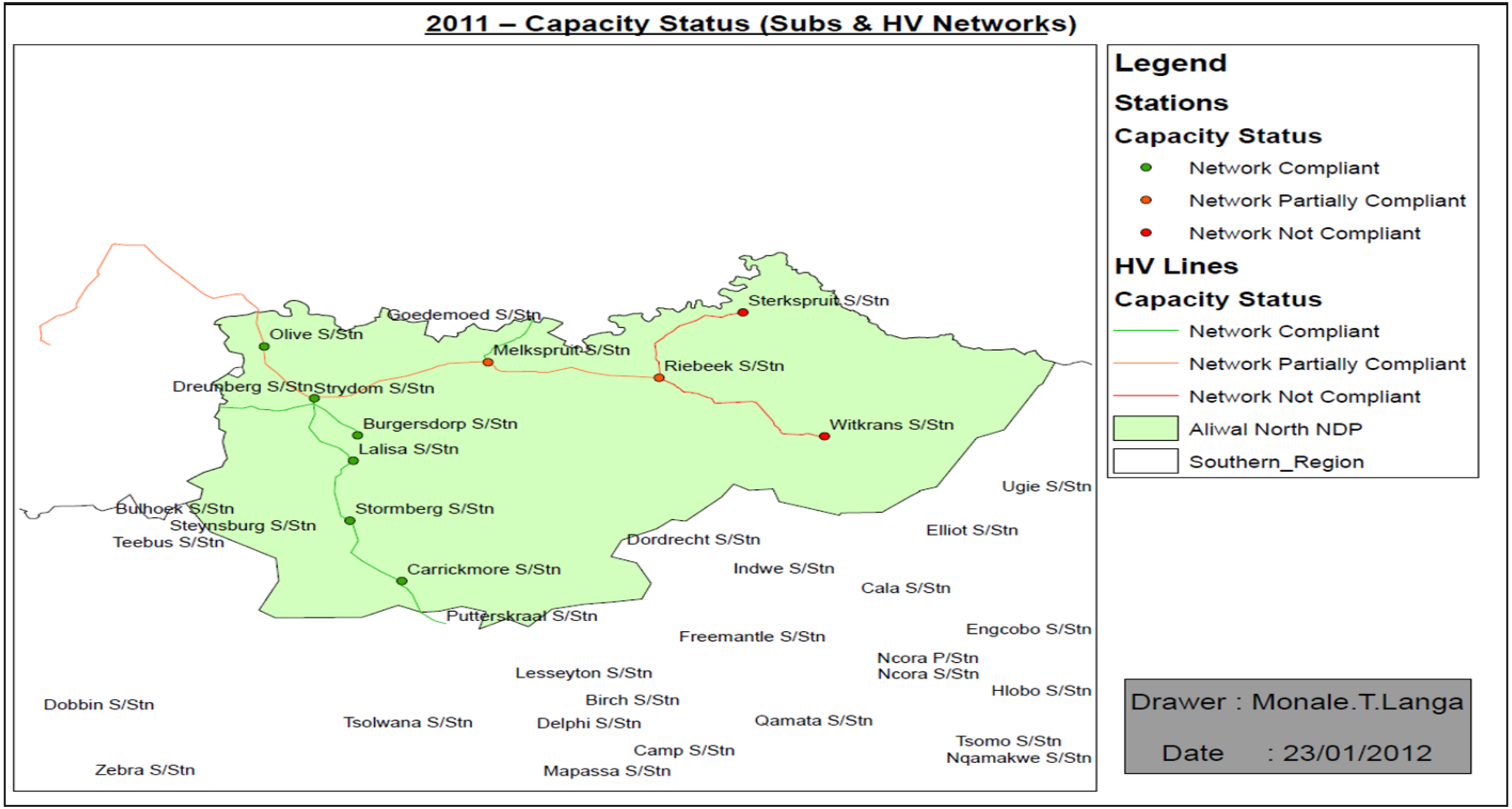
[70] J.A. Momoh: “Electric Power Distribution, Automation, Protection, and Control”. New York: CRC Press, 2008.

[71] R. Billinton, A. Ronald: “Reliability Evaluation of Power Systems, Second Edition, New York, Plenum Press, 1996.

[72] R. Billinton, R.N. Allan: “Reliability Evaluation of Engineering Systems, Plenum Publishing – New York, 1983.

APPENDICES

Appendix A: Geographical Representation of Aliwal North Power System



Appendix B: Performance of the Aliwal North Network

ZONE	LINE AFFECTED	MONTH	DURATION (HRS)	MAX_TRANSFORMERS OUT (HRS)	CUSTOMERS AFFECTED	LOAD AT RISK_MVA
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/09	28.819	27.193	10115	212.1814947
Aliwal North Zone	Melkspruit/Riebeek 2 66kV Overhead Line	2014/06	6.662	6.628	34008	388.5697569
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/09	10.196	10.196	10115	85.45593528
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/02	5.655	5.655	7886	34.59333417
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/01	16.252	12.024	7884	22.75522694
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/10	3.489	3.441	7882	21.05097583
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/05	5.891	5.891	7899	17.55273028
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/04	2.138	2.148	7902	13.1362575
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/07	5.845	5.839	7869	10.40232417
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/09	1.321	1.321	7879	8.077838333
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/10	1.517	1.517	5393	6.594466667
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/09	1.17	11.153	655	6.602773333
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/11	1.052	0.655	7882	4.006635
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/02	3.318	3.318	1524	5.656811111
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/10	3.819	3.197	1543	5.450790278
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/12	1.823	20.933	875	1.687215
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/12	0.12	0.12	30982	2.861050556
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/03	0.349	0.349	7891	2.132454167
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/02	2.149	1.516	7884	1.880713333
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/08	7.508	7.483	1536	2.319078611
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/07	3.246	2.664	703	1.315961111
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2014/06	0.64	19.151	342	0.694746667
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/12	2.534	2.534	669	1.2392075
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/09	1.061	0.986	1542	1.790723611
Aliwal North Zone	Sterkspruit/Lower Telle 1 22kV Overhead Line	2013/10	9.033	9.033	178	0.740687778

EVENT_NOTES WITH THE CAUSES OF FAULTS
Outage late because the 22KV B/S bkr @ Melkspruit failed to close because of a loose connection on trfr 3 22 KV bkr and also @ Dreuberg S/S the 132KV B/C bkr tripped cause of suspected inrush currents.Then @ Sterkspruit S/S the Trfr 66 & 22 kv brkr s trip
Load shed STAGE 3 issued by Natioal control at 08h14Load shed for 08 to 10 = 264MWLoad shed for 10 to 12 = 244MWLoad shed for 12 to 14 = 306MW & reduced to to stage 2 at 13h06 drop load to 179MWLouterwater Trfr1 & 2 failed to close via supervisory.
Bph conductor on the ground @ LTE-STS-4/5 across the mountain.Bph long rod failed.
R, W & Bph E/F 30km away from ss.Between 2mel-rie-166&167 Rph conductor on the ground..G.Adrianzen confirmed all 3 phases correct @ melkspruit-riebeek2 66kv line. ECA=20.7MW
Bph conductor broken at KJGU002-56/57.Trfr blown knju002operator to continue morning due to bad weatherSpice failed @ KJGU002-100&101Operator is tired and will continue.Broken conductor KJGU002-36-37.IN: Revive RET106460 OUT: RET 66563 Revive Operator wil
conductor damaged @ riebeek-sterkspruit 66kv line.Still waiting for work order .
CROSSARM STRUCK BY LIGHTNING @ KNEK014-1
NHA-6&7 conductors down.Links opened @ KNFN002-1 & NHA-96, Operator to come back tomorrow, no access to fault findR & Bph conductors broken @ KNFP008-5 & 6
Outage came back late: Waiting for operators to report back on the line.
X-arm broken @ MJI-MTH-115R ph & Bph conductors broken between MJI-MTH-114 & 115
Rph COS burnt @ SUL-52,refer to FMS 2001104151 Reset to Normal by L.L Dyushu on 23/01/2014
Opened Sulenkama 1 for emergency switching.Bph COS burnt @ SUL-35.Temp jumper applied. Refer to FMS 2001029391
Bph conductor broken @ 1RB-STS-95 & 96 JUMPERS BROKEN @ 1RBG-STS-96NO CUSTOMERS AFFECTED FAULT WILL BE FIXED IN THE MORNING
Refer to FMS 2000924436.White phase jumper clashing with blue phase.
JMKL016-1 + JMKM010-4 Declared openTrfr blown jmjm001Trfr in:Revive Trfr out:ReviveS/N:RET103363 S/N:RET75804
fault finding using FPI@ DGK26 Bph jumper broken
Faulty trfr @ JMKJ008IN: Revive RET 112280OUT: Alstom 00075998
At TSH -30 ,31 B ph conductor down
White ph conductor broken down @ 2MJI-QUM-19Jumpers broken @ 2MJI-QUM-21, NOP @ 2QUM-SAP-L-2 closed to backfeed customers on the Mjika 22kV line
Trfr 1 66/22kV Bkr tripped upon closing in-line Bkr @ IDA17-2.Refer to FMS: 200 119 7218.EDFS to investigate 66/22kV Bkr settings on TRFR 1.Ratio error on the Bph of the Ref core CCT .The Ref protection relay causing the Trfr to Trip was removed as per Ga
Trfr blown at KNER006.Jumpers broken at TrfrIN: Revive RET 111120 OUT:alstom 0099499M
w ph jumper off @ car-mol-80.
Bph jumper broken @ QBU25-38.Jumpo jumper applied.see FMS 2001111810

EVENT_NOTES WITH THE CAUSES OF FAULTS
R & Bph conductors broken btwn E-SKZ-12-24 & 25
Blown TRFR @ JNVS001.Trfr out : ALSTOMSerial no : 00066041Trfr in : ReviveSerial no : RET104759
done emergency switching, incoming red phase link is burning @ SUL-53.
Breaker failed to close via SUP and from relay room.No fault found.
Bkr tripped for Emergency switching . Wph conductor broken betweenMJI-SAP-47 and TLO63-1 reported by Ngamlana (073384 1407)
Line passing through the forest as per Ntamo and its muddy @ site. They will continue tomorrowWph conductor Broken at the end of the rap lock tiebetween KNEP012-10 and KNEP012-11
jumpers broken @ MJI-MTH-135 and 136
R & Bph c.o.s burnt @ nha191 incoming links of brkrbrkr on bypasssee fms2001149582
O,I to create a safety panel to string LV ABCunder MV line.
Trfr still energised via 66kv network . Busy changingNOP'son the system.LV O/C trip .
At Str KNAS001-10 the W ph L bracket came loose due to the coach screw falling out and the W ph conductor made contact with the other conductors
Blue phase conductors broken at kngv008-31-33.
Relay on the buz zone panel failed to reset .Didfault finding in the S/S to try find the fault, there is a cross trip between the two trfrs and the Bus section brkrs.No alarm came up to indicate alarm on buzzone panel. ABN applied.
Rph long rod touches the stay wire @ E-OLO32-12
Jumpers broken @ DAH-STS-152Metering unit, DAH-STS-152 on bypass Reset to Normal by AJ PETERS on 07/02/2014All back to normal, metering unit off bypass, jumper fixed
TRFR blown @ KNAR011TRFR IN : Revive.Serial no:112103TRFR OUT: ALSTOMSerial no : 0097131m
The trfr @KKNDT071 Is sparking so they opened the links. Cable fault @ KNDT071
At JNVS008-5 Brkr faultyon bypassSee FMS 2001371316
Bph broken conductor @ struct TLO67-25 Emergency switching done by Nhlebi broken Conductor
Conductor Clashingbetween KJGU002-27 & 28.
Refer to FMS: 2000 924 501 for abnormality.Fault not found-operator will attend later to fault.Broken pole @ JMMP001-13/14.Replaced solids with fuses @ JMMP001-2.
Blown trf @ KNJQ001See FMS 2001048072
NO FAULT FOUND.
No Fault found

APPENDIX C: ECOU Fault Levels and that of Aliwal North Power System

Station Name	Bus Bar Name	Voltage (L-L)	Ik(3 ø Fault)	Ik,Angle	Sk(3 ø Fault)	R 1	X_1	Z_1
		kV	kA	deg	MVA	Ohm	Ohm	Ohm
Badsfontein	11kV Bus1	11	1.28	-61.717	146	14.128	26.257	29.816
Badsfontein	66kV Bus1	66	0.67	-85.512	13	0.742	9.45	9.479
Beisiespoort Traction	132kV Bus 1	132	2.15	-68.249	492	13.12	32.884	35.404
Berlin Traction	132kV Bus 1	132	5.75	-76.538	1314	3.087	12.896	13.26
Birch Traction	132kV Bus 1	132	5.83	-77.528	1333	2.823	12.762	13.07
Burgersdorp	22kV Bus 1	22	1.73	-81.535	66	1.078	7.243	7.323
Burgersdorp	66kV Bus 1	66	1.43	-72.083	163	8.2	25.363	26.656
Butterworth	132kV Bus 1	132	3.89	-83.556	148	0.367	3.246	3.267
Butterworth	22kV Bus 1	22	2.89	-68.73	660	9.575	24.596	26.393
Butterworth	22kV Bypass Bus	22	2.73	-75.18	312	3.568	13.484	13.948
Butterworth	66kV Bus 1A	66	2.73	-75.18	312	3.568	13.484	13.948
Cala	22kV Bus 1	22	3.39	-75.817	129	0.918	3.634	3.748
Cala	66kV Bus 1	66	2.46	-64.379	282	6.688	13.946	15.467
Camp Traction	132kV Bus 1	132	3.64	-71.585	832	6.614	19.864	20.936
Carolus	132kV Bus 1	132	2.22	-72.763	507	10.194	32.855	34.4
Carrickmore	132kV Bus 1	132	3.62	-83.472	138	0.399	3.487	3.51
Carrickmore	22kV Bus 1	22	2.52	-69.191	576	10.751	28.287	30.261
Carrickmore Traction	132kV Bus 1	132	2.52	-69.191	576	10.751	28.287	30.261
Cedarville	132kV BB 1	132	3.76	-80.753	143	0.543	3.338	3.382
Cedarville	22 TBB 1	22	3.76	-80.753	143	0.543	3.338	3.382
Cedarville	22kV BB 1	22	2.04	-67.056	466	14.568	34.414	37.371
Central Injection	11kV Bus	11	7.2	-81.894	137	0.124	0.873	0.882
Central Injection	66kV Bus	66	2.89	-73.502	330	3.743	12.639	13.181
Central Injection SW	66kV Tee	66	3.1	-74.077	355	3.367	11.803	12.274
Chaba	132kV bus	132	3.87	-84.109	147	0.337	3.268	3.285
Chaba	22kV Bus 1	22	3.14	-69.464	718	8.512	22.722	24.264
Chatty	132kV Bus	132	12.09	-82.158	2764	0.86	6.244	6.303
Cintsa	11kV Bus 1	11	6.28	-74.265	120	0.274	0.974	1.012
Cintsa	11kV Bypass Bus	11	2.08	-63.012	238	8.301	16.299	18.291
Coega Main	132kV Bus	132	12.08	-82.176	2763	0.859	6.248	6.307
Colesburg	11kV Bus1	11	3.45	-75.308	66	0.466	1.779	1.839
Colesburg	66kV Bus1	66	1.58	-51.53	181	14.985	18.859	24.087
Collett Traction	132kV Bus 1	132	1.95	-73.693	446	10.979	37.527	39.1
Committees	22kV Bus 1	22	1.47	-64.829	169	10.995	23.397	25.851
Committees	66kV Bus 1	66	1.1	-82.373	42	1.528	11.414	11.516
Corinth	Corinth 132kV bus	132	2.26	-76.949	517	7.617	32.861	33.732

Station Name	Bus Bar Name	Voltage (L-L)	Ik(3 ø Fault)	Ik,Angle	Sk(3 ø Fault)	R 1	X_1	Z_1
		kV	kA	deg	MVA	Ohm	Ohm	Ohm
Cradock Traction	132kV Bus 1	132	2.23	-75.228	509	8.729	33.101	34.232
Cuprum	132kV Bus	132	0	0	0	0	0	0
Debenek	11kV Bus 1	11	8.14	-82.932	155	0.096	0.774	0.78
Debenek	132kV bus	132	4.02	-73.641	459	2.67	9.097	9.481
Debenek	22kV trfr2 tertiary	22	4.02	-73.641	459	2.67	9.097	9.481
Debenek	22kV trfr3 tertiary	22	2.72	-70.171	623	9.489	26.315	27.974
Debenek	66kV Bus 1	66	1.78	-80.417	68	1.191	7.055	7.155
Debenek	66kV Bus 2	66	1.78	-80.417	68	1.191	7.055	7.155
Dedisa	Dedisa 132 BB1	132	13.16	-82.986	3009	0.707	5.748	5.791
Dedisa	Dedisa 132 BB2	132	13.16	-82.986	3009	0.707	5.748	5.791
Dedisa	Dedisa 400 BB1	400	13.16	-82.986	3009	0.707	5.748	5.791
Dedisa	Dedisa 400 BB2	400	13.16	-82.986	3009	0.707	5.748	5.791
Delphi	Delphi 132 BB1	132	8.06	-78.943	5582	5.498	28.133	28.665
Delphi	Delphi 132 BB2	132	8.06	-78.943	5582	5.498	28.133	28.665
Delphi	Delphi 400 BB1	400	7.64	-83.289	1746	1.166	9.909	9.977
Delphi	Delphi 400 BB2	400	7.64	-83.289	1746	1.166	9.909	9.977
Dieprivier	22kV Bus 1	22	1.89	-79.481	72	1.224	6.591	6.704
Dieprivier	66kV Bus 1	66	1.59	-66.625	182	9.509	21.999	23.967
Dimbaza	11kV Bus 1	11	7.86	-82.307	150	0.108	0.801	0.808
Dimbaza	66kV Bus 1	66	3.83	-71.573	438	3.144	9.435	9.945
Dimbaza	66kV Bus 2	66	3.83	-71.573	438	3.144	9.435	9.945
Dobbin Traction	132kV Bus 1	132	2.03	-74.637	464	9.952	36.223	37.565
Dohne Traction	132kV Bus 1	132	3.35	-69.927	766	7.808	21.367	22.749
Dordrecht	11kV Bus 1	11	0.64	-51.796	12	6.144	7.807	9.935
Dordrecht	22kV Bus 1	22	0.4	-41.091	15	23.793	20.749	31.569
Drennan Traction	132kV Bus 1	132	3.01	-76.841	687	5.771	24.683	25.349
Dreunberg	132kV Bus 1	132	21.32	-85.215	188	0.012	0.138	0.138
Dreunberg	132kV Bus 2	132	3.17	-71.293	724	7.716	22.786	24.057
Dreunberg	22kV Bus 1	22	3.17	-71.293	724	7.716	22.786	24.057
Dreunberg	5.1kV Bus SVC	5.1	2.2	-82.191	252	2.349	17.131	17.292
Dreunberg	66kV Bus 1	66	2.06	-86.116	79	0.417	6.137	6.151
Droerivier	Droerivier 132 BB1	132	14.47	-78.638	10026	3.144	15.646	15.958
Droerivier	Droerivier 132 BB2	132	14.47	-78.638	10026	3.144	15.646	15.958
Droerivier	Droerivier 22 BB1_1	22	14.47	-78.638	10026	3.144	15.646	15.958
Droerivier	Droerivier 22 BB1_2	22	14.47	-78.638	10026	3.144	15.646	15.958
Droerivier	Droerivier 22 BB1_3	22	8.94	-86.638	2043	0.5	8.513	8.528
Droerivier	22 BB Bypass	22	8.94	-86.638	2043	0.5	8.513	8.528
Droerivier	Droerivier 400 BB1A	400	5.6	-89.649	213	0.014	2.269	2.269
Droerivier	Droerivier 400 BB1B	400	5.6	-89.649	213	0.014	2.269	2.269

Appendix D: Busbar Voltages on the System

ZONE	Station	Bus-Bar	Nominal Voltage (kV)	Simulated Voltage (kV)	Simulated Voltage (p.u.)	Angle (Deg)
LIWAL NORTH	Badsfontein	66kV Bus1	66	66.82	1.01	-55.12
ALIWAL NORTH	Burgersdorp	66kV Bus1	66	67.67	1.03	-67.18
MTHATHA	Cala	66kV Bus	66	66.13	1.00	-74.27
ALIWAL NORTH	Carrickmore	132kV Bus	132	133.11	1.00	-67.27
ALIWAL NORTH	Dreunberg	132kv Bus1	132	132	1.00	-65.86
ALIWAL NORTH	Dreunberg	132kV Bus2	132	132	1.00	-65.86
ALIWAL NORTH	Dreunberg	66kV Bus West	66	68.34	1.04	-66.69
ALIWAL NORTH	Melkspruit	132kV Bus1	132	126.58	0.96	-68.67
ALIWAL NORTH	Melkspruit	66kV Bus1	66	67.74	1.03	-72.55
ALIWAL NORTH	Melkspruit	66kV Bus2	66	0.00	0.00	0.00
ALIWAL NORTH	Middelburg	66kV Bus1	66	66.21	1.00	-58.34
PORT ELIZABETH	Peddie	66kV Bus1	66	62.56	0.95	-80.55
ALIWAL NORTH	Riebeek	66kV Bus1	66	62.51	0.95	-76.67
ALIWAL NORTH	Rooiwal	66kV Bus1	66	67.23	1.02	-54.84
ALIWAL NORTH	Rouxville	66kV Bus1	66	65.38	0.99	-73.84
EAST LONDON	Royston	66kV Bus1	66	67.30	1.02	-71.75
ALIWAL NORTH	Ruigtevallei	132kV Bus 1	132	135.91	1.03	-51.88
ALIWAL NORTH	Ruigtevallei	132kV Bus 2	132	135.91	1.03	-51.88
ALIWAL NORTH	Ruigtevallei	66kV Bus 1	66	67.79	1.03	-54.44
ALIWAL NORTH	Ruigtevallei	66kV Bus 2	66	67.79	1.03	-54.44
MTHATHA	Sappi	66kV Bus1	66	65.23	0.99	-72.95
MTHATHA	Sipakweni	132kV Bus	132	130.35	0.99	-58.38
ALIWAL NORTH	Sterkspruit	66kV Bus1	66	59.12	0.90	-79.35
PORT ELIZABETH	Tsitsikamma	66kV Bus	66	61.26	0.93	-82.96
EAST LONDON	Tyalara	132kV Bus1	132	127.75	0.97	-68.53
EAST LONDON	Tyalara	66kV Bus1A	66	67.31	1.02	-66.91
EAST LONDON	Tyalara	66kV Bus1B	66	67.14	1.02	-66.91
EAST LONDON	Tyume	66kV Bus1	66	61.79	0.94	79.84
MTHATHA	Ugie	132kV Bus1	132	126.47	0.95	-65.77

Appendix E: Voltage Dips on the Aliwal North Power System

VOLTAGE DIPS FOR MULTIPLE METERING POINTS					
NAME	DIP DATE	MILLISECOND	PHASES	MAX_DEPTH	MAX_DURATION
Melkspruit 132/22kV	2013/04/01 00:04	430	RW	29.7	1550
Sterkspruit 66/22kV	2013/04/01 00:04	470	W	18.3	1550
Melkspruit 132/22kV	2013/04/01 04:03	320	R	31.9	60
Sterkspruit 66/22kV	2013/04/01 04:03	350	WB	53.7	70
Melkspruit 132/22kV	2013/04/01 04:04	0	R	31.7	60
Sterkspruit 66/22kV	2013/04/01 04:04	30	WB	53.9	70
Melkspruit 132/22kV	2013/04/01 04:14	250	R	31.1	60
Sterkspruit 66/22kV	2013/04/01 04:14	280	WB	53.7	70
Melkspruit 132/22kV	2013/04/01 04:14	370	R	30.7	60
Sterkspruit 66/22kV	2013/04/01 04:15	410	WB	51.6	60
Melkspruit 132/22kV	2013/04/01 04:17	350	R	31.2	70
Melkspruit 132/22kV	2013/04/01 04:17	980	R	31.7	60
Sterkspruit 66/22kV	2013/04/01 04:17	390	WB	52.6	70
Sterkspruit 66/22kV	2013/04/01 04:17	10	WB	53.5	70
Melkspruit 132/22kV	2013/04/01 04:18	720	R	32.1	60
Melkspruit 132/22kV	2013/04/01 04:19	280	R	31.7	60
Sterkspruit 66/22kV	2013/04/01 04:19	750	WB	54	70
Sterkspruit 66/22kV	2013/04/01 04:19	310	WB	54.4	70
Melkspruit 132/22kV	2013/04/05 05:20	910	RWB	51.4	100
Sterkspruit 66/22kV	2013/04/05 05:21	940	RWB	51.8	110
Dreunberg 132kV	2013/04/05 05:22	760	W	67.2	90
Melkspruit 132/22kV	2013/04/07 03:30	810	RWB	65.5	100
Sterkspruit 66/22kV	2013/04/07 03:30	850	RWB	66.2	100
Dreunberg 132kV	2013/04/07 03:30	670	W	84.6	90
Melkspruit 132/22kV	2013/04/07 03:31	770	RWB	66.7	100
Sterkspruit 66/22kV	2013/04/07 03:31	810	RWB	67.7	100
Dreunberg 132kV	2013/04/07 03:31	630	W	85.3	90
Sterkspruit 66/22kV	2013/04/07 08:21	230	RWB	60.1	160
Sterkspruit 66/22kV	2013/04/09 23:07	700	B	21.7	1290
Sterkspruit 66/22kV	2013/04/09 23:07	200	B	21.1	1030
Melkspruit 132/22kV	2013/04/10 11:29	840	RWB	44.1	60
Sterkspruit 66/22kV	2013/04/13 15:57	470	RWB	45.8	190
Sterkspruit 66/22kV	2013/04/13 15:59	880	RWB	57.9	460
Sterkspruit 66/22kV	2013/04/13 15:59	370	RWB	56.7	470
Sterkspruit 66/22kV	2013/04/13 15:59	860	RWB	55.9	460
Sterkspruit 66/22kV	2013/04/13 15:59	350	RWB	57.5	450
Sterkspruit 66/22kV	2013/04/13 16:04	240	RWB	67.1	130
Sterkspruit 66/22kV	2013/04/13 16:59	500	RWB	58.8	50
Sterkspruit 66/22kV	2013/04/13 18:50	210	RWB	60.1	460
Sterkspruit 66/22kV	2013/04/13 19:18	310	RWB	60.3	460

VOLTAGE DIPS FOR MULTIPLE METERING POINTS					
NAME	DIP DATE	MILLISECOND	PHASES	MAX_DEPTH	MAX_DURATION
Sterkspruit 66/22kV	2013/04/13 19:29	740	RWB	59.9	460
Sterkspruit 66/22kV	2013/04/17 13:54	180	R	28.3	1160
Sterkspruit 66/22kV	2013/04/17 13:54	720	R	27.2	1190
Sterkspruit 66/22kV	2013/04/17 13:54	970	R	28.5	1180
Sterkspruit 66/22kV	2013/04/17 13:54	200	R	27.9	1170
Sterkspruit 66/22kV	2013/04/17 19:46	180	RWB	61.2	90
Sterkspruit 66/22kV	2013/04/17 21:03	500	WB	67.4	130
Sterkspruit 66/22kV	2013/04/17 21:04	320	WB	67.9	140
Sterkspruit 66/22kV	2013/04/17 21:09	180	WB	67.7	130
Sterkspruit 66/22kV	2013/04/17 21:09	360	WB	67.3	130
Sterkspruit 66/22kV	2013/04/20 06:04	680	RWB	56.9	160
Sterkspruit 66/22kV	2013/04/20 06:04	510	RW	56.9	170
Sterkspruit 66/22kV	2013/04/20 06:06	30	RWB	57	160
Sterkspruit 66/22kV	2013/04/20 06:08	840	RWB	57.2	160
Sterkspruit 66/22kV	2013/04/20 06:08	270	RWB	56.8	170
Sterkspruit 66/22kV	2013/04/20 06:09	480	RWB	57	160
Sterkspruit 66/22kV	2013/04/20 06:11	220	RWB	56.9	160
Sterkspruit 66/22kV	2013/04/20 06:13	970	RWB	57	170
Sterkspruit 66/22kV	2013/04/20 06:14	840	RWB	56.9	170
Sterkspruit 66/22kV	2013/04/20 06:15	610	RWB	56.8	170
Sterkspruit 66/22kV	2013/04/20 06:15	40	RWB	57.3	160
Sterkspruit 66/22kV	2013/04/25 02:26	700	RWB	76.8	90
Sterkspruit 66/22kV	2013/04/27 06:58	630	RWB	80.8	90
Sterkspruit 66/22kV	2013/04/28 00:49	530	RW	52.4	1000
Melkspruit 132/22kV	2013/04/28 00:49	490	RWB	95.9	1000
Sterkspruit 66/22kV	2013/04/30 07:16	400	RW	51.3	190
Sterkspruit 66/22kV	2013/04/30 08:41	230	RWB	67.1	140
Sterkspruit 66/22kV	2013/05/01 02:43	40	WB	49.3	110
Melkspruit 132/22kV	2013/05/01 02:43	0	RWB	50.7	110
Dreunberg 132kV	2013/05/01 02:45	860	W	68.6	80
Sterkspruit 66/22kV	2013/05/06 09:00	220	RB	30.1	50
Sterkspruit 66/22kV	2013/05/06 09:02	260	RW	33.8	250
Sterkspruit 66/22kV	2013/05/06 09:02	440	RW	33.6	260
Sterkspruit 66/22kV	2013/05/06 09:02	60	RW	33.5	210
Sterkspruit 66/22kV	2013/05/06 09:10	270	RWB	33.8	210
Sterkspruit 66/22kV	2013/05/06 10:01	800	RWB	34.1	210
Dreunberg 132kV	2013/05/08 00:10	400	W	31.2	70
Sterkspruit 66/22kV	2013/05/08 17:55	960	RB	48.3	90

Appendix F: Voltage Unbalance on the Aliwal North Power System

METERING POINT	LIMIT GROUP	LIMIT DATE	LIMIT	VALUE
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/26	1.4	1.5
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/27	1.4	1.6
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/28	1.4	1.6
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/29	1.4	1.7
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/30	1.4	1.7
Dreunberg 132kV	VOLTAGE UNBALANCE	2013/12/31	1.4	1.7
Dreunberg 132kV	VOLTAGE UNBALANCE	2014/01/01	1.4	1.7
Dreunberg 132kV	VOLTAGE UNBALANCE	2014/01/02	1.4	1.7
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/12	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/13	1.8	2.9
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/14	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/15	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/16	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/17	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/18	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/19	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/20	1.8	3.2
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/21	1.8	3.5
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/22	1.8	3.6
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/23	1.8	3.6
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/24	1.8	3.6
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/25	1.8	3.6
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/26	1.8	3.4
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/27	1.8	3.4
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/28	1.8	3.2
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/29	1.8	3
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/04/30	1.8	2.9
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/05/01	1.8	2.8
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/05/02	1.8	2.7
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/06/01	1.8	3.1
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/06/02	1.8	3.1
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/06/03	1.8	3.1
Sterkspruit 66/22kV	VOLTAGE UNBALANCE	2013/06/04	1.8	3.4

Appendix G: Eastern Cape Operating Unit Protection Equipment

Southern Region Scheme Type count as of April 2003					
NB: There is data inaccuracies of line equipment namely recloser, sectionalizer, regulators, etc					
Data extracted from Maintenance databases -					
Manufacturer	Scheme Description	Count Of Equipment Scheme **Aliwal North**	Count Of Equipment Scheme **Ducats**	Count Of Equipment Scheme **Uitenhage**	**TOTAL Count**
ABB	2BC0300	1	0	1	**2**
ABB	2TD20	2	0	1	**3**
ABB	Jerico	1	0	2	**3**
ABB	Paul van Zyl	2	1	0	**3**
ABB	Rv Recloser with seq.SE/F	2	1	1	**4**
ABB	2TA2101	1	0	0	**1**
ABB	2TC0100	10	5	4	**19**
ABB	2TC1000	1	1	6	**8**
ABB	2TM0100	8	6	2	**16**
ABB	2TM0400	1	1	1	**3**
ABB	3FZ23920	3	1	2	**6**
ABB	3LM3400	1	0	7	**8**
ABB	3RF3100	9	53	5	**67**
AEG	AEG	1	0	0	**1**
BBC	LZ32	5	16	12	**33**
Beckwith	3TC2300	2	8	1	**11**

Southern Region Scheme Type count as of April 2003					
NB: There is data inaccuracies of line equipment namely recloser, sectionalizer, regulators, etc					
Data extracted from Maintenance databases -					
Manufacturer	Scheme Description	Count Of Equipment Scheme **Aliwal North**	Count Of Equipment Scheme **Ducats**	Count Of Equipment Scheme **Uitenhage**	**TOTAL Count**
Cooper Power	Form 5	8	0	1	**9**
GEC	4B3	2	0	0	**2**
GEC	CDG 66	3	0	0	**3**
GEC	CDG16	1	4	0	**5**
GEC	CDG36	41	9	0	**50**
GEC	VTJC	4	0	0	**4**
GEC	YTG	4	0	0	**4**
Genwest,SEL	3FZ0500	2	1	0	**3**
Reyrolle	2RF0100	22	18	18	**58**
SEL	4TC2100	3	0	0	**3**
Siemens	2FZ23	3	2	4	**9**
Siemens	2TM1000	3	1	4	**8**
Siemens	2TM1001	1	0	5	**6**
Siemens	3TM2500	3	2	1	**6**
Siemens	4TM2100	2	0	0	**2**
	TOTAL	**142**	**302**	**206**	**650**

Appendix H: Conductor Parameters

Voltage kV	Conductor	Conductor dimension	Conductor	Conductor	Typical constant per km in ohms and pu on 100 MVA base at 35°C					Ampacity (Thermal rating) in MVA		Ampacity (Thermal rating) in AMPS	
Un	Code	Alu Area	Per	Type	R_1	X_1		B_1		TT 70°C		TT 70°C	
	Name	mm²	Phase		Ohm	Ohm	pu	micm	pu	Normal	Emergency	Normal	Emergency
11	SQUIRREL	20	1	ACSR	1.5500	0.4500	0.3719	2.8000	1.2810	2.6	3.5	138	183
	ACACIA	23.8	1	AAAC						2.8	3.7	145	194
	GOPHER	26	1	ACSR	1.0470	0.4500	0.3719	2.8000	0.8653	2.9	3.8	150	200
	FOX	37	1	ACSR	0.8600	0.4500	0.3719	2.8000	0.7107	3.7	4.9	196	258
	35	42	1	AAAC						4.0	5.2	209	275
	RABBIT	53	1	ACSR	0.6800	0.4450	0.3678	2.8500	0.5620	4.8	6.5	250	340
	MINK	63	1	ACSR	0.5000	0.4400	0.3636	2.9000	0.4132	5.1	6.9	270	361
	PINE	71.6	1	AAAC						5.6	7.3	293	385
	HARE	105	1	ACSR	0.3200	0.4100	0.3388	3.0000	0.2645	7.2	9.5	376	496
	OAK	119	1	AAAC						7.4	10.1	391	530
	WOLF	158	1	ACSR	0.1950	0.3240	0.2678	3.5500	0.1612	9.5	12.8	498	671
	CHICADEE	201	1	ACSR						10.7	14.5	559	761
	MAGPIE	10.6	1	ACSR						3.0	3.8	80	100
22	SQUIRREL	21	1	ACSR	1.5500	0.4500	0.0930	2.8000	0.3202	5.3	7.0	138	183
	ACACIA	23.8	1	AAAC						5.5	7.4	145	194
	GOPHER	26	1	ACSR	1.0470	0.4500	0.0930	2.8000	0.2163	5.7	7.6	150	200
	FOX	37	1	ACSR	0.8600	0.4500	0.0930	2.8000	0.1777	7.5	9.8	196	258
	35	42	1	AAAC						8.0	10.5	209	275
	RABBIT	53	1	ACSR	0.6800	0.4450	0.0919	2.8500	0.1405	9.5	13.0	250	340
	MINK	63	1	ACSR	0.5000	0.4400	0.0909	2.9000	0.1033	10.3	13.8	270	361
	PINE	71.6	1	AAAC						11.2	14.7	293	385
	HARE	105	1	ACSR	0.3200	0.4100	0.0847	3.0700	0.0661	14.3	18.9	376	496
	OAK	119	1	AAAC						14.9	20.2	391	530
	WOLF	158	1	ACSR	0.1950	0.3550	0.0733	3.2400	0.0403	19.0	25.6	498	671
	CHICADEE	201	1	ACSR	0.1450	0.3400		3.2600		21.3	29.0	559	761

Voltage kV	Conductor	Conductor dimension	Conductor	Conductor	Typical constant per km in ohms and pu on 100 MVA $_{base}$ at 35°C					Ampacity (Thermal rating) in MVA		Ampacity (Thermal rating) in AMPS	
	PANTHER	212	1	ACSR	0.1460	0.3440	0.0711	3.3000	0.0302	23.1	31.2	606	818
66	RABBIT	53	1	ACSR	0.6800	0.4870	0.011180	2.6280	0.015611	28.6	38.9	250	340
	MINK	63	1	ACSR	0.5000	0.4850	0.011134	2.6399	0.011478	30.9	41.3	270	361
	PINE	71.6	1	AAAC	0.4956	0.3916	0.008989	2.9705	0.011377	33.5	44.0	293	385
	RACCOON	78	1	ACSR	0.3633	0.4704	0.010799	2.7716	0.008340	35.4	45.7	310	400
	HARE	105	1	ACSR	0.3200	0.4530	0.010399	2.6530	0.007346	43.0	56.7	376	496
	OAK	119	1	AAAC	0.2810	0.4310	0.009894	2.6600	0.006451	44.7	60.6	391	530
	RABBIT	53	2	ACSR	0.3130	0.4300	0.009871	2.6850	0.007185	57.2	77.7	500	680
	RACCOON	78	2	ACSR	0.1870	0.3280	0.007530	2.9150	0.004293	70.9	91.5	620	800
	WOLF	158	1	ACSR	0.1880	0.4180	0.009596	2.7600	0.004316	56.9	76.7	498	671
	CHICADEE	201	1	ACSR	0.1466	0.4076	0.009356	2.8730	0.003365	63.9	87.0	559	761
	PANTHER	212	1	ACSR	0.1450	0.4100	0.009412	2.8190	0.003329	69.3	93.5	606	818
	BEAR	265	1	ACSR	0.1170	0.4000	0.009183	2.8690	0.002686	80.7	110.0	706	962
	ZEBRA	429	1	ACSR	0.0820	0.3960	0.009091	2.9380	0.001882	107.2	146.9	938	1285
132	FOX	37	2	ACSR	0.3912	0.2926	0.001679	3.8625	0.002245	89.6	118.0	392	516
	WOLF	158	1	ACSR	0.1880	0.4180	0.002399	2.7600	0.001079	113.9	153.4	498	671
	CHICADEE	201	1	ACSR	0.1464	0.4334	0.002487	2.6940	0.000840	127.8	174.0	559	761
	CHICADEE	201	1	ACSR	0.1549	0.4161	0.002388	2.7612	0.000889	127.8	174.0	559	761
	CHICADEE	201	1	ACSR	0.1455	0.3738	0.002146	3.0740	0.000835	127.8	174.0	559	761
	PANTHER	212	1	ACSR	0.1450	0.4100	0.002353	2.8100	0.000832	138.6	187.0	606	818
	BEAR	265	1	ACSR	0.1170	0.4030	0.002313	2.8690	0.000671	161.4	219.9	706	962
	HARE	105	2	ACSR	0.1386	0.3373	0.001936	3.6586	0.000795	171.9	226.8	752	992
	HARE	105	2	ACSR	0.1378	0.2799	0.001606	4.3480	0.000791	171.9	226.8	752	992
	ZEBRA	429	1	ACSR	0.0800	0.3960	0.002273	2.9370	0.000459	214.5	293.8	938	1285
	BEAR	265	2	ACSR	0.0590	0.3040	0.001745	3.8402	0.000339	322.8	439.9	1412	1924

Appendix I: Sequence of Events on the Melkspruit Substation outage

EASTERN CAPE OPERATING UNIT

Fault Management System

Printed on 19/08/2014 13:08:02

EVENT ID: 2001328757

CLEARED DATE: 21/07/2014 13:23:37 **CLEARED BY:** THOKOZANI DOLO

EVENT DATE: 20/07/2014 03:31:58

CLOSED DATE: 21/07/2014 13:42:53 **CLOSED BY:** THOKOZANI DOLO

EVENT TYPE: NOTIFIED **QA CLOSED BY:** MR S KLAAS

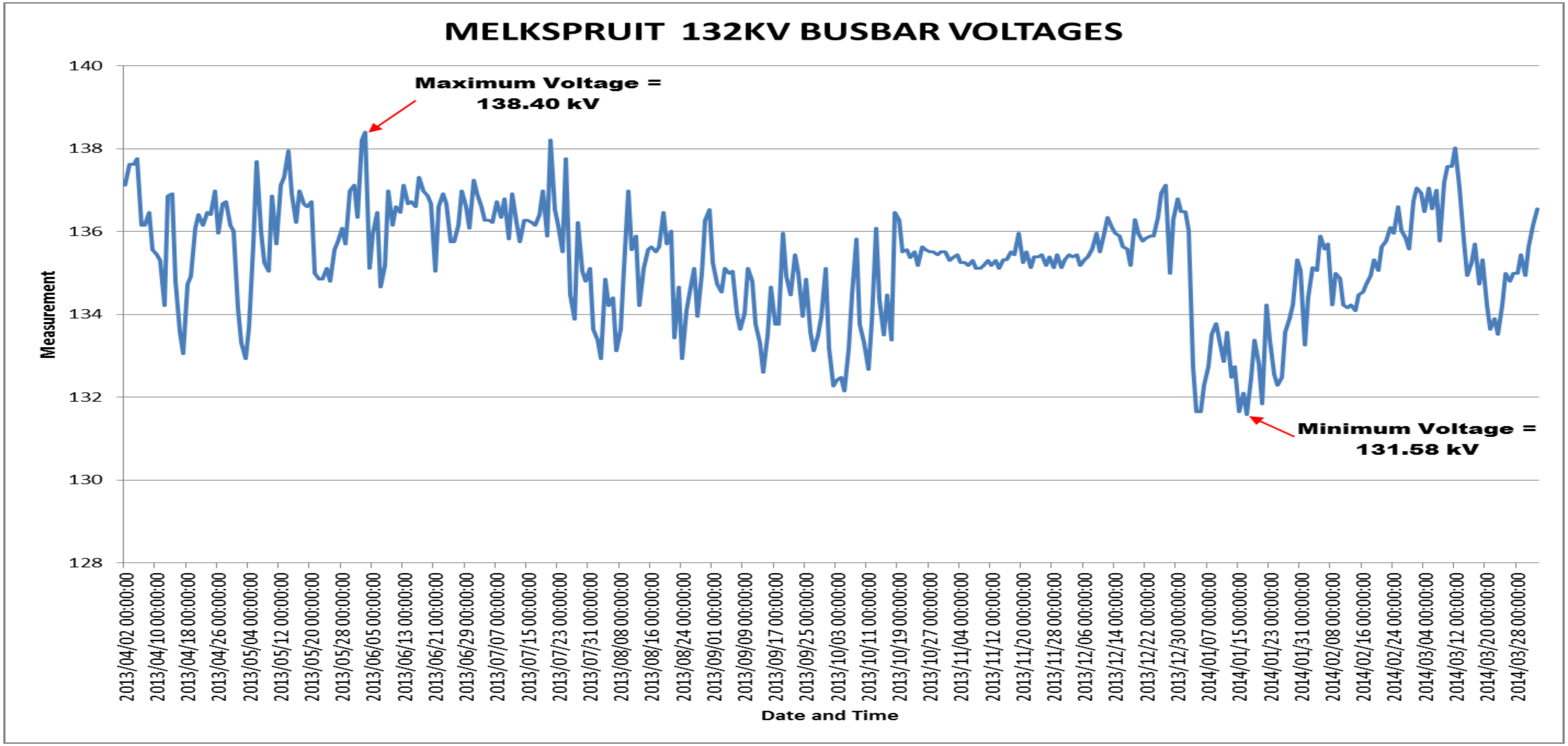
WEATHER: CLEAR

DESCRIPTION: Melkspruit S/Stn - Scheduled Work - Equipment Maintained

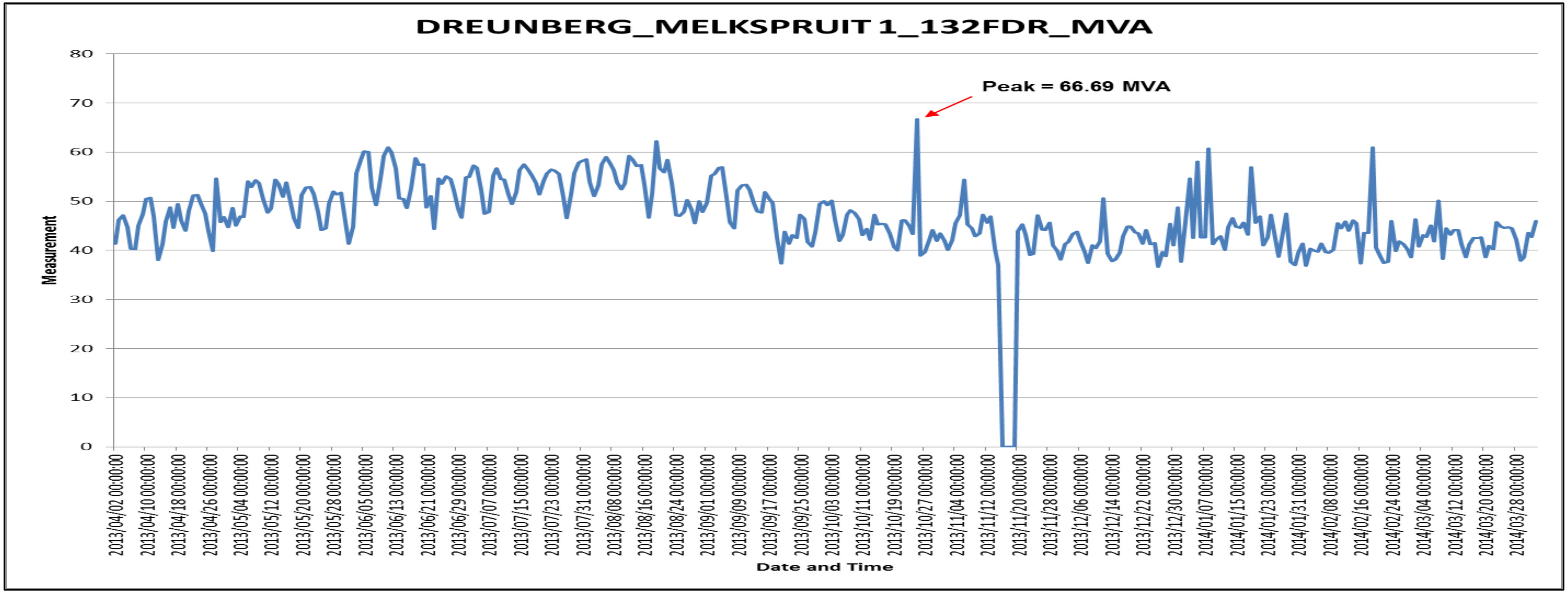
NOTES : Outage late because the 22KV B/S bkr @ Melkspruit failed to close because of a loose connection on trfr 3 22 KV bkr and also @ Dreuberg S/S the 132KV B/C bkr tripped cause of suspected inrush currents.
Then @ Sterkspruit S/S the Trfr 66 & 22 kv brkr s tripped due to the incorrect CT ratios that were applied,The trfr had to be taken out of service to adjust the CT ratios settings. The outage only came back at 04h06 this morning.

	START DATE	END DATE	LOCATION	OPERATION / CAUSE
	20/07/2014 21:11:59	20/07/2014 23:43:59	Melkspruit S/Stn	Defective Equipment-Jumpers-Jumper Failure-Burned Off
RC	20/07/2014 03:31:58	21/07/2014 13:25:39	Melkspruit S/Stn	Maintenance / Construction related-Equipment Related-Equipment Maintained
	21/07/2014 13:23:37	21/07/2014 13:23:37	Witkrans/Rhodes 1 22kV Line Isolator	Closed
	21/07/2014 13:23:11	21/07/2014 13:23:11	Witkrans/Rhodes 1 22kV Busbar 1 Isolator	Closed
	21/07/2014 13:17:56	21/07/2014 13:17:56	BAP-RD-L-14 22kV Solid Cutout	Open
	21/07/2014 13:17:29	21/07/2014 13:17:29	BAP-152 22kV Solid Cutout	Closed
	21/07/2014 12:43:48	21/07/2014 13:17:01	BAP-2 -- 22KV BKR 22kV Recloser	Open
	21/07/2014 12:42:59	21/07/2014 13:20:59	Witkrans/Rhodes 1 22kV Bkr	Open
	20/07/2014 21:11:59	20/07/2014 23:43:59	Dreunberg/Melkspruit 2 132kV Bkr	Tripped
	20/07/2014 12:27:15	20/07/2014 12:27:15	Dreunberg Trfr 11 132kV Bkr	Closed
	20/07/2014 12:23:04	20/07/2014 12:23:04	Dreunberg/Melkspruit 2 132kV Line Isolator	Closed
	20/07/2014 12:20:10	20/07/2014 12:20:13	Dreunberg/Melkspruit 2 132kV Busbar 2 Isolator	Open

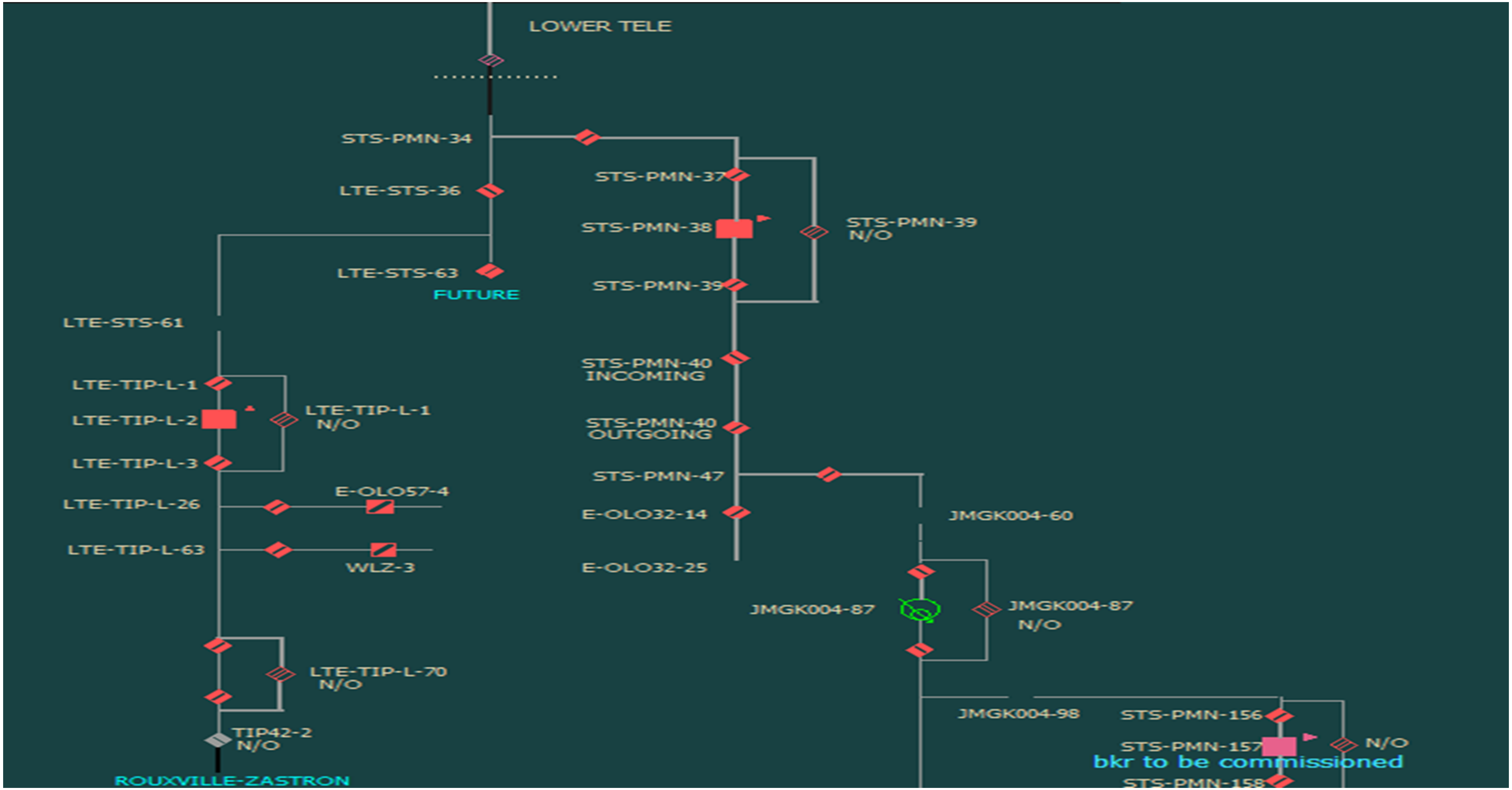
Appendix J: Busbar Voltages at Melkspruit Substation



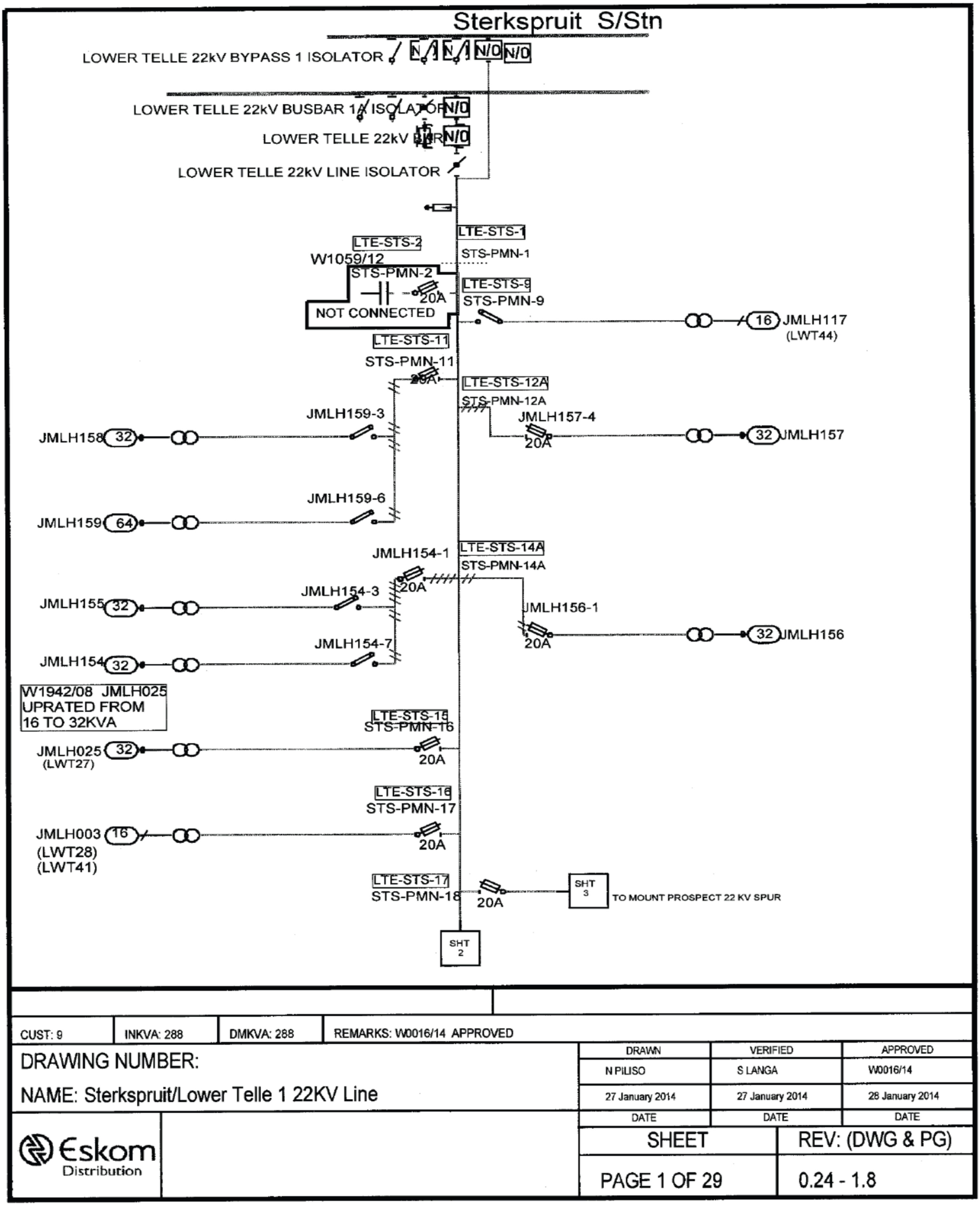
Appendix K: Maximum Demand of Dreunberg/Melkspruit 132 kV line



Appendix L: Medium Voltage Overview Diagram of Sterkspruit/Lower Telle 22 kV line



Appendix M: Single Line Diagram of Sterkspruit/Lower Telle 22 kV line



Appendix N: Sub-transmission line cost per km

Customer type	COUE rate (R/kWh)
Industrial	6.69
Mining	14.14
Commercial	102.90
Agricultural	20.16
Residential	20.83
Prepaid	5.22
Redistributors	29.53
Traction	111.90
Other	27.95

Analysis of the reliablity for the 132/66/22 kV Distribution nework within Eskom's Eastern Cape Operating Unit

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***Abstract* — a stable and reliable electrical power supply system is an inevitable pre-requisite for the technological and economic growth of any nation. Due to this, utilities must strive and ensure that the customer's reliability requirements are met and the regulators requirements satisfied at the lowest possible cost. It is known fact around the world that 90% of the customer service interruptions are caused due to failure in the distribution system [1]. Therefore, it is worth considering reliability worth assessments as it provides an opportunity to incorporate the cost or losses incurred by the utilities customer as a result of power failure and this must be considered in planning and operating practices.**

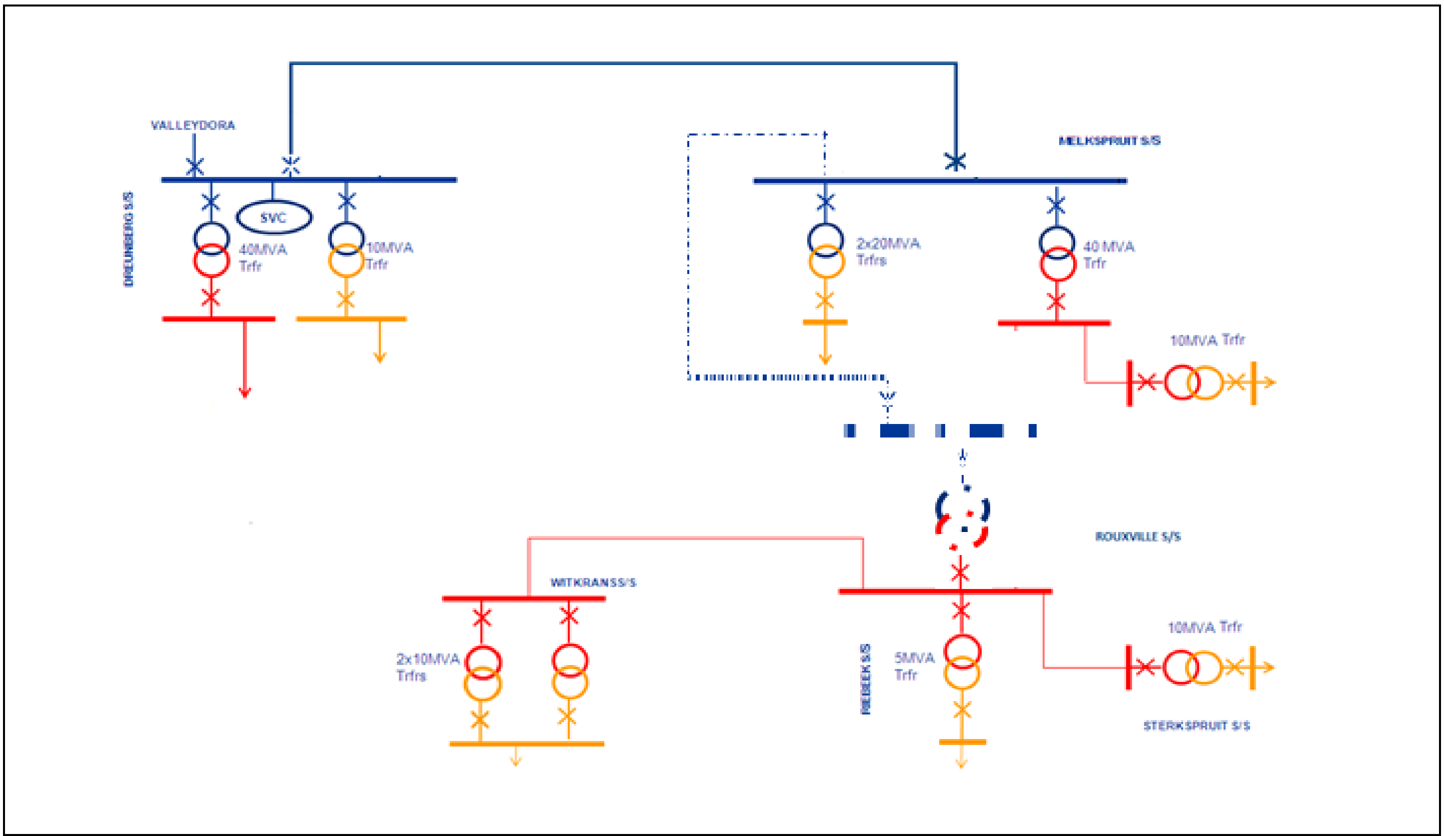
The system modelling and simulation study is carried out on one of the district's distribution system which consists of 132 kV, 66 kV and 22 kV network in Aliwal North Sector (Eastern Cape Operating Unit) ECOU. The reliability assessment is done on these levels 22, 66 and 132 kV system to assess the performance of the present system and also predictive reliability analysis for the future system considering load growth and system expansion. The alternative which gives low System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) and minimum breakeven costs are being assessed and considered. The reliability of 132 kV system could be further improved by constructing a new 132 kV line from a different source of supply and connecting with the line coming from another district (reserve) at reasonable cost.

Keywords-component; Eastern Cape Operating Unit (ECOU), Eskom, Reliability, Power Quality, Load Flow, Protection Coordination, SCADA, Aliwal North, Eskom, DigSilent (PowerFactory), Cost of Userved Energy (COUE)

I. Introduction

The term reliability constitutes a very wide broad meaning. In general, the term reliability means the capability of a system to perform its dedicated function, whereby the historical data assists to perform estimations of the future performance for that system. Electricity has been the basic need for economic institutions of the world and it furnishes day-to-day necessity for the growing population in the world. Due to the nature of electrical technology systems, the power demand at every specific moment needs to be met by consistent electricity supply to make sure of the continuous availability of the resources [8][1]. However, reliability of service has always been of primary importance to electric utility systems and there are many publications which describe various levels of activity and application [2]. Hierarchically, power systems comprise three distinct parts: Generation, Transmission and Distribution. Power systems have evolved over decades with the primary emphasis of providing a reliable and economic supply of electrical energy to their customers [1].

Figure 1: Aliwal North Power System Overview



II. Problem Statement

The planning phase of a power system network, reliability aspects are an important part of the decision making. Hence, to be able to assess and simulate, reliability analysis is needed in the planning process. It has been found that after planning decisions have been made, Aliwal North Sector (ANS) power system network can still be inadequate for operations and maintenance requirements, due to the fact that there are no other alternative sources of supply for faults, planned and unplanned outages on the Dreunberg-Melkspruit 132 kV line. This line is responsible for feeding five substations, which further affects the reliability indices of the distribution network in the area.

A. Sub-Problems

- *Sub-Problem 1*

Power System reliability improvement may further expand to other network challenges such as power system load flow. If the network apparatus such as busbars, conductors and transformer are not operating at nominal values it may have a huge impact on the life cycle and performance of these apparatus and that of the network.

- *Sub-Problem 2*

The inability of the system to respond to sudden network disturbances such as electrical and non-electrical faults that could results in damages in the utility's power system equipment conductors, breakers, power transformers, voltage regulators etc. and in turn damage customer appliances.

- *Sub-Problem 3*

Power quality is one of important components that are embedded within the reliability study; customers may experience quality of supply problems such as voltage flickers, voltage swells, voltage regulation, voltage dips, voltage unbalance and total harmonic distortion. These challenges might be present, during commissioning and after reliability improvement is completed.

III. PROPOSED SOLUTION

Figure: 2 show the proposed solution for Aliwal North Reliability Improvement [5].

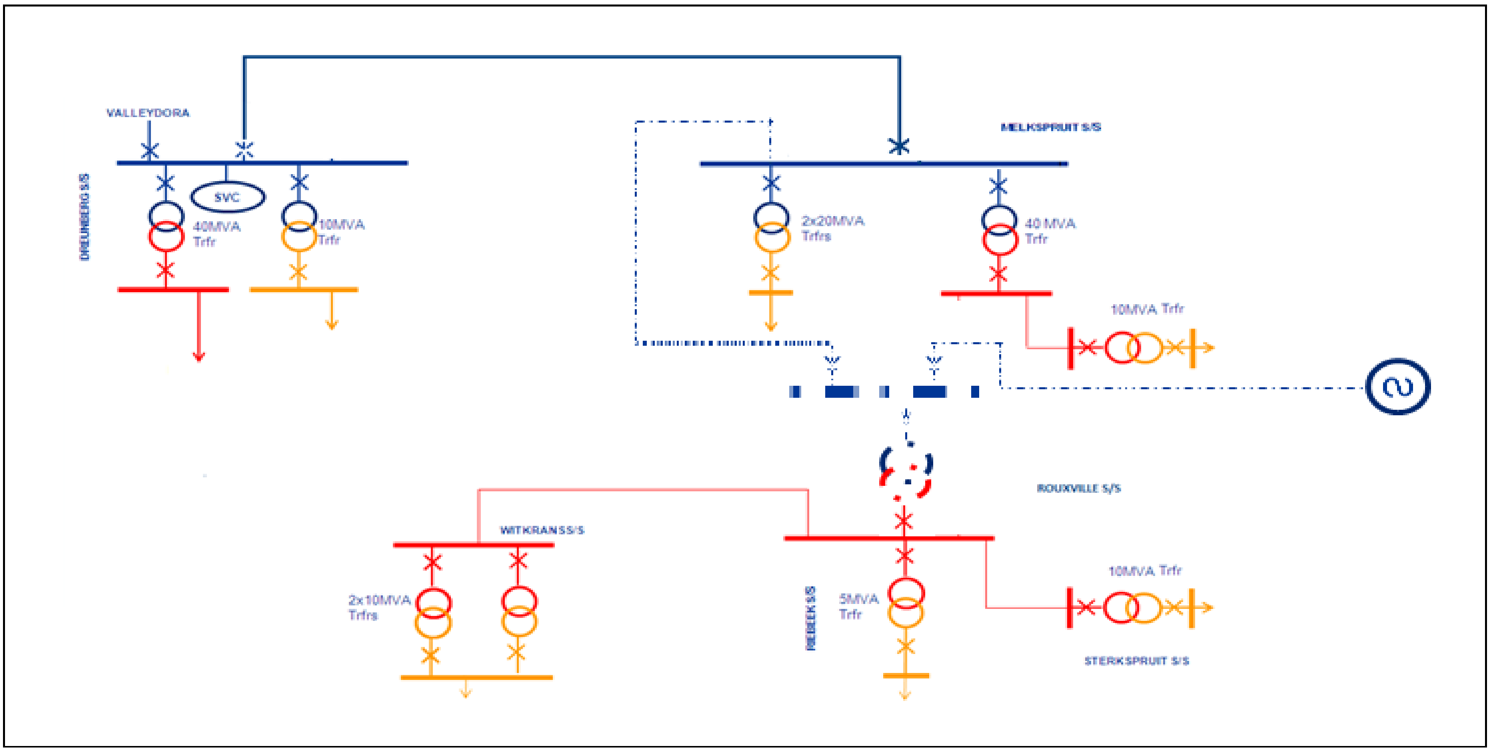


Figure 2: Proposed solution for Aliwal North power system reliability

To carry out a predictive reliability analysis and compute its indices by using present fault rates and durations of outages on the 132/66/22 kV Aliwal North Sector Network and recommend new 132 kV line from a different source of supply, making use of the already started construction of the 132 kV line of Melkspruit-Riebeek. This alternative will require a comprehensive analysis on the benefit to cost and cost of unserved energy (COUE). Thus, thereafter draw up a conclusion on which solution is the best. See figure 2 for the newly proposed 132 kV line which will be fed from the newly strengthened Elliot Substation which is 132/66/22 kV substation. This configuration will make ECOU power system distribution network to be firm and less vulnerable from reoccurring faults. This will also mean in terms of maintenance, that the network can follow its normal maintenance schedule without fearing the outages that will affect customer [10].

IV. DATA ANALYSIS

1. Reliability Evaluation

A. FMEA

Failure Mode and Effect Analysis (FMEA) [12] is used to evaluate the contingencies of the components failing and to see how this affects the load points. The failure mode is identified in such a way that component outages overlap to cause system outage. At this point only components failures are considered.

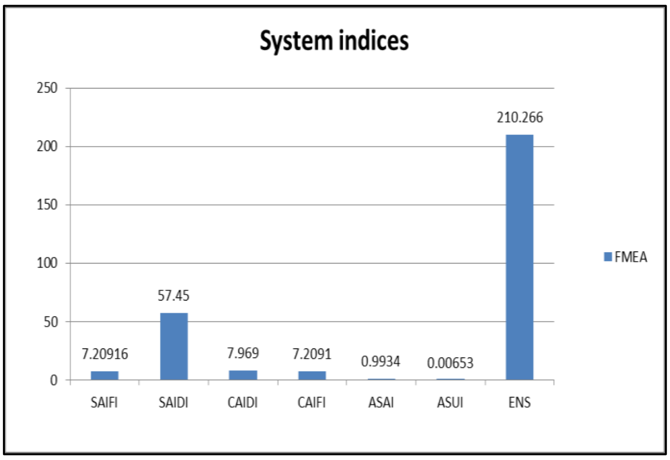


Figure 4: FMEA reliability indices assessment results [6]

B. DigSilent (PowerFactory)

Reliability analysis can be defined as an automation and probabilistic extension of contingency evaluation. In DigSilent the author is not required to pre-define outage events, but can optionally select that all possible outages are measured for analysis.. The following results are obtained from PowerFactory simulations for reliability assessment, load points are the substations affected when the Dreunberg/Melkspruit 132 kV line is out.

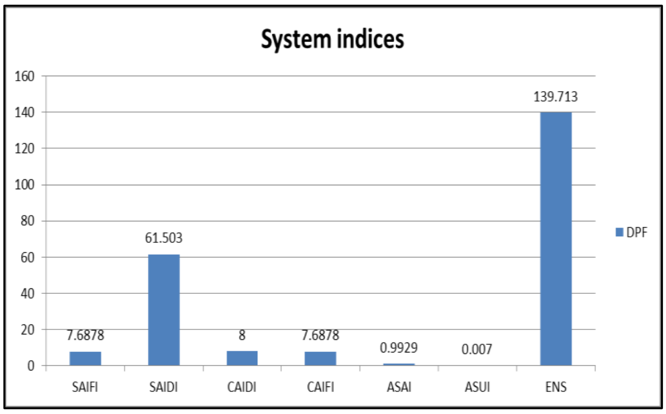


Figure 5: PowerFactory results

2. *Comparison of FMEA and DigSilent (PowerFactory) results.*

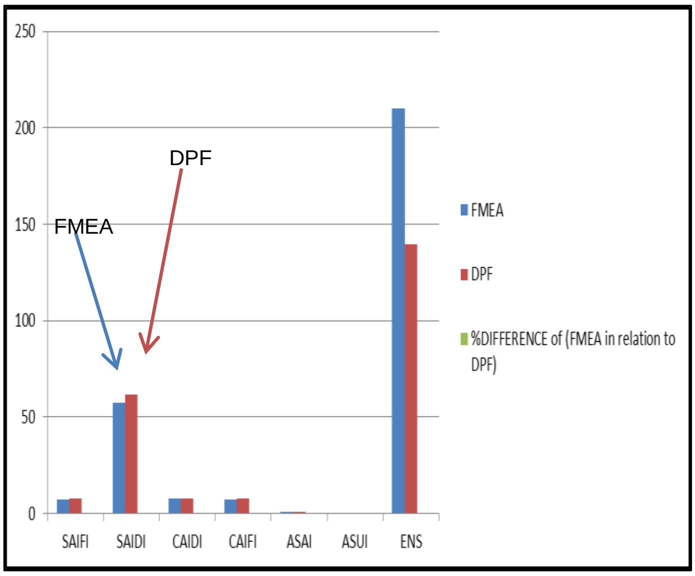


Figure 6: Comparison between FMEA and PowerFactory results

Table 1: Tabled comparison of FMEA and PowerFactory

INDICES	FMEA	DPF	%DIFFERENCE
SAIFI	5.9758	6.0629	1.46%
SAIDI	47.528	48.503	2.05%
CAIDI	7.953	8	0.59%
ASAI	0.995	0.99446	0.05%
ASUI	0.0054	0.00554	2.59%
ENS	174.01	111.313	36.03%

Based on table 1 the two methods have given results that are very close to a degree that the difference shown is less that 5%. A percentage difference of 36.03% is experienced for the ENS. This is due to the lack of sufficient data and therefore alternative formulae's and means were used to obtained results (the kVA is used instead of the number of customer interrupted). Although both methods show a high degree of accuracy, DIgSilent is still the number one choice due to many advantage that are linked with it. This includes the convenience of simulating larger networks, the accuracy of the software, the graphical representation of the obtained data etc.

Due to this significant difference between PowerFactory and FMEA on the ENS results in particular, the solution was that DIgSilent results are the most trustworthy, because DIgSilent incorporates all embedded conductor parameters that FMEA ignores or assumes a certain value to them. This was the conclusion that was reached after simulating all three scenarios.

3. Benefit to cost Analysis

If Dreunberg-Melkspruit 132 kV line (line 1) fails, 56 MVA will be lost to the entire substations supplied by this feeder. The equivalent (Cost of Unserved Energy) COUE rate of the load lost is:

$$\text{Equivalent COUE rate} = \frac{(56\text{ MVA}\times\text{R40/kWh})}{56\text{ MVA}}$$

$$= \text{R40 / kWh}$$

This is indicated by point “a” in Figure 7. A second line is therefore economically justified. Hence, based on the above analysis, additional redundancy is required to provide alternate supplies for the failure of lines 1. This justifies the reason to have an alternate source of supply to formulate a ring in this network [9].

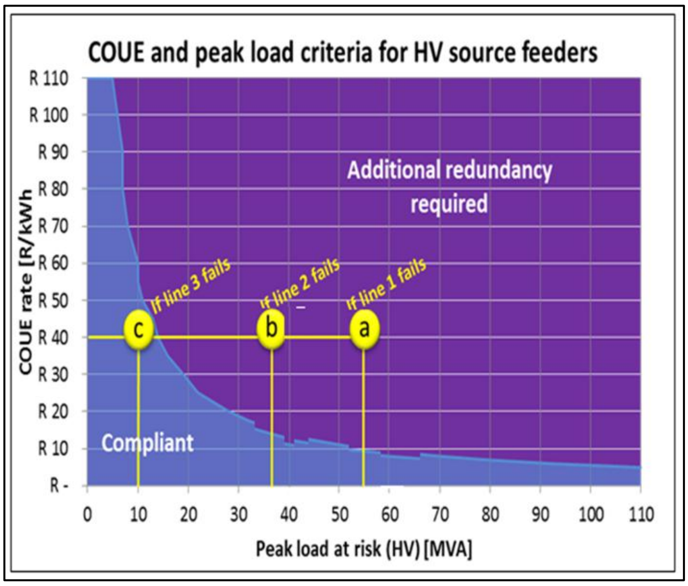


Figure 7: Calculating load at risk – radial network [3]

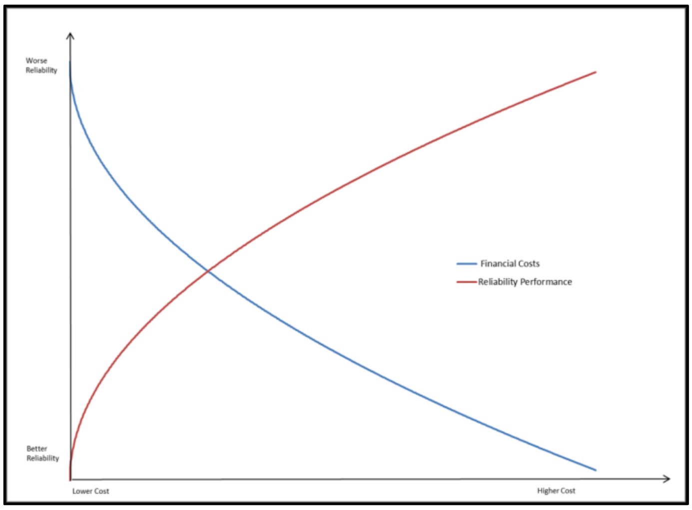


Figure 8: Solution to the reliability of Aliwal North Network [2]

From the review of the above drivers for improved network reliability it is clear that:

- Eskom is incentivised by, and needs to adhere to the MYPD rules set by NERSA, and by implication to the requirements of the Distribution Network Code, in order to recover its investments or other costs through the NERSA approved tariff.
- Investments have to be justified on the least life cycle economic costs basis as specified in the Distribution Network Code, meaning that the cost to Eskom and the economic or societal cost (COUE) have to be minimised.
- At the same time, there are strong drivers such as Eskom’s strategic intent to be a top 5 utility compared to international benchmarks, and internal SAIDI targets, to improve Distribution’s SAIDI in the long term.

Eskom Distribution planning circles as value-based planning) is illustrated in Figure 8.

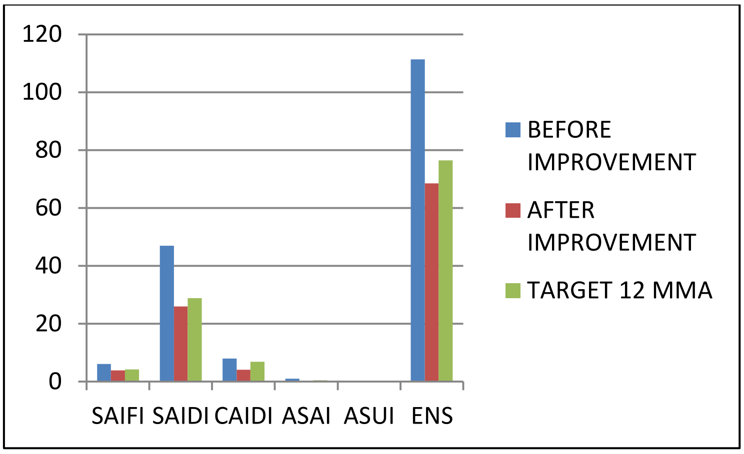


Figure8A: Aliwal reliability performance after network improvement all voltage levele i.e. 132/66/22 kV in average.

Figure 8A, shows the predictive DigSilent results considering the alternative source as the remedial strategy to the poor reliability performance of the Aliwal North sector. The above comparison was carried out using the Eskom ECOU target for the 2014/2015 financial year (12 Month Moving Average). The result were computed using the average reliability evaluation results for all the voltage levels i.e. 132/66/22 kV.

4. Power Quality

C. Voltage Unbalance

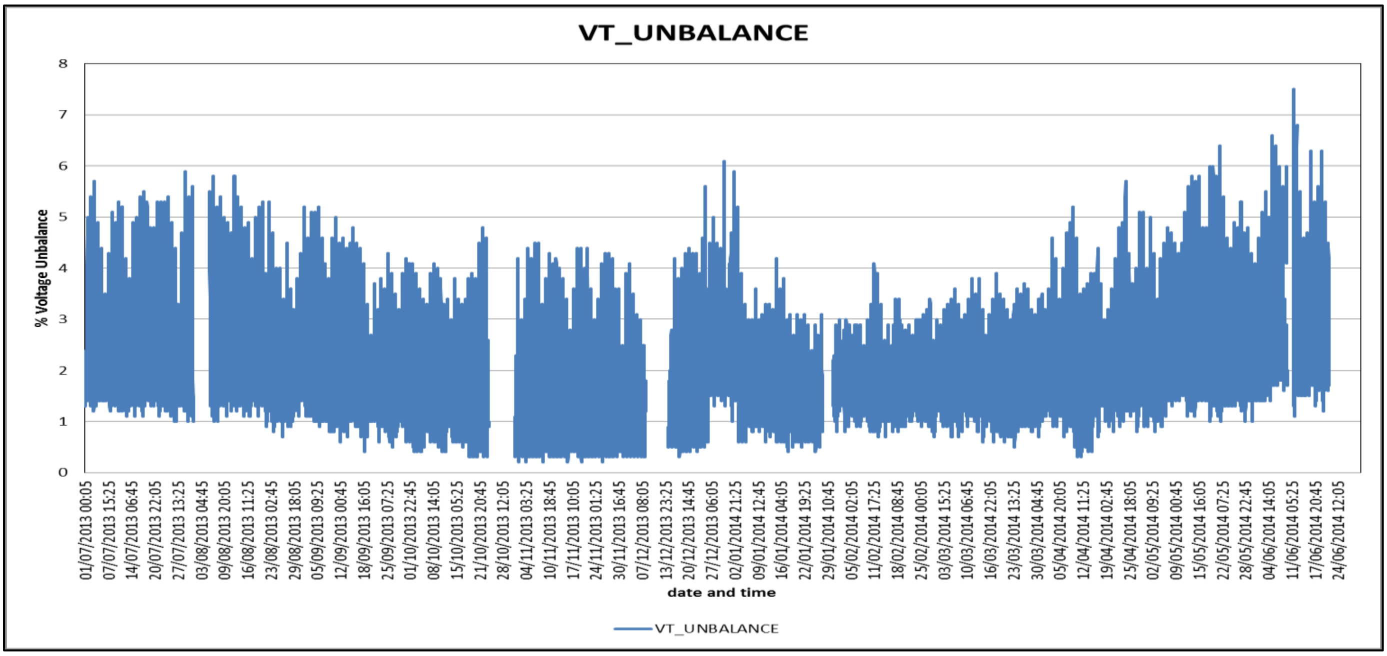


Figure 9: Voltage Profile for unbalanced

According to the voltage unbalance profile from figure 9, voltage unbalance on the Sterkspruit Substation 22 kV busbar mainly occurs on evening and morning peak periods. This unbalance was noticeably due to the fact that it exceeded the 2% voltage imbalance limit. Moreover the profile also shows that during winter period this voltage unbalance becomes worse in this area. DigSilent (PowerFactory) simulations in figure 10 shows that the phases A and B are the most unbalanced feeders.

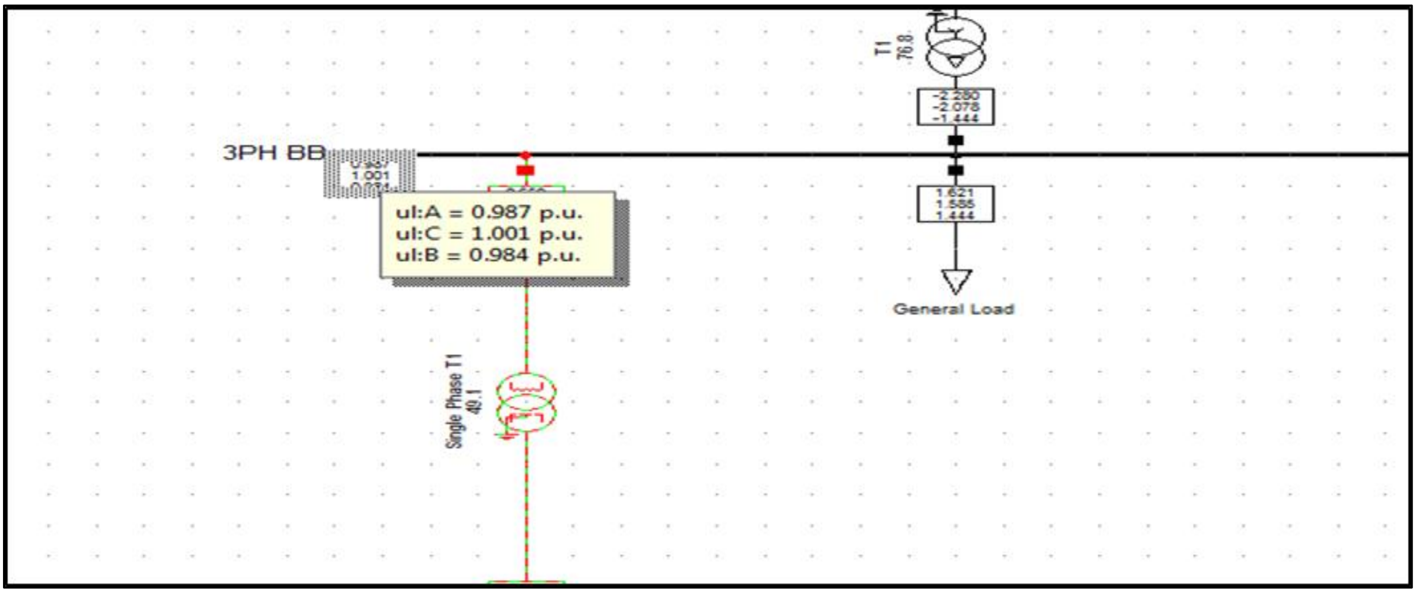


Figure 10: PowerFactory unbalanced results

D. Voltage Flicker

Dynamic voltage fluctuations are usually caused by the starting and stopping of motors. Here as per water demand, discharge pipe valve setting of an induction motors keeps on changing. Although a single induction motor alone may not generate flicker complaints, the cumulative effect of several motors starting randomly on a distribution feeder can generate objectionable flicker see figure 11.

A solution to control the severity of voltage flicker is by installing 800 kVar shunt capacitor bank. Capacitor bank can be connected series with induction motor loads in order to compensate voltage variations and to improve power factor of the network. See figure 12 for the corresponding arrangement of the shunt capacitor bank and motor loads.

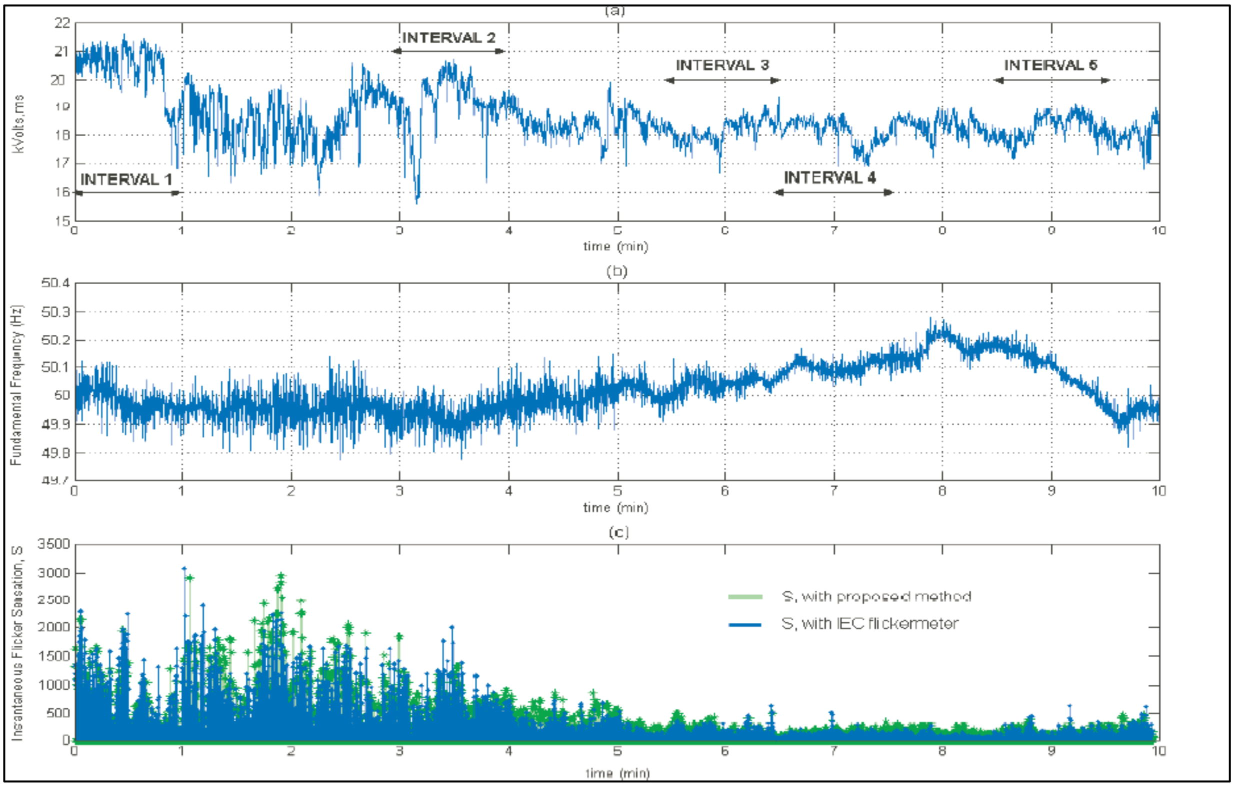


Figure 11: Measured values of Voltage, Reactive and Active power Variations when four induction motor operates at its full capacity Power System.

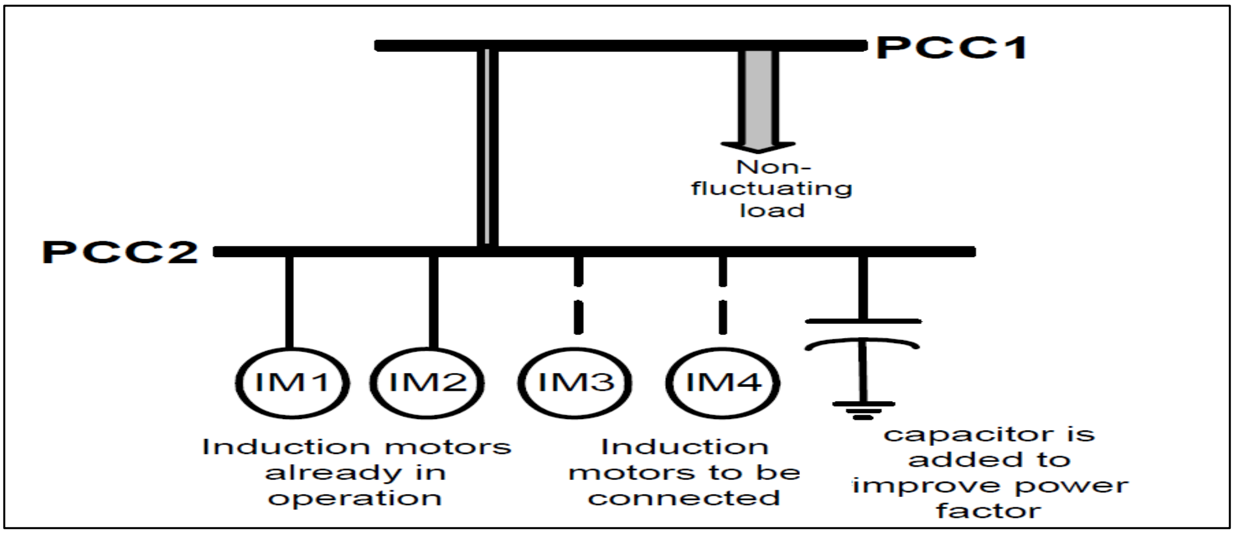


Figure 12 Shunt Capacitor Bank connected series with Motor Loads at PCC2.

E. Voltage Dips

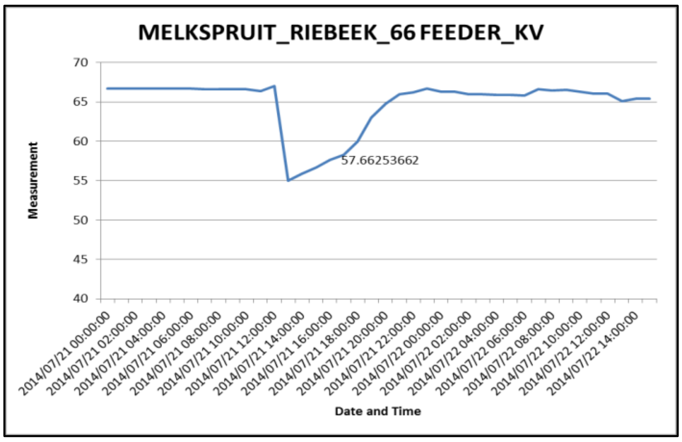


Figure 12: Voltage Profile with Voltage DIPS

The above scenario is regarded as voltage dip, due to the fact that it is less than 90% of the declared voltage. It is important to note that a voltage deep has huge impact on the Cost of Unserved Energy (COUE). COUE forms significant aspect of benefit to cost analysis [4].

F. Voltage Swells

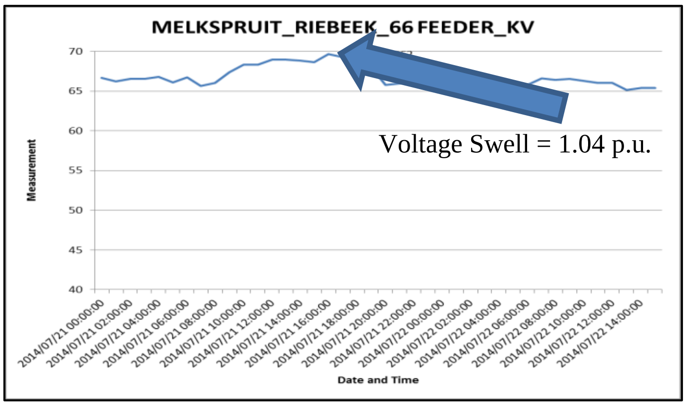


Figure 13: Voltage Swells incident

The probability of flashover can be reduced by applying surge arresters to divert current to ground. that is if voltage flashover becomes a problem in the within the Aliwal North network after future expansion has been completed.

At the moment the figure 13 shows that this network only experiences temporary voltage swells during stormy weather as the area is more inland which is exposed to lightning. In reference to NRS 048-2 standard, which say overvoltages must be above 5% of norminal voltage for a duration above 30 minutes. Most of all, Aliwal North power system network does not have major problems in voltage swells as they within the limits.

G. Harmonics Distortion Analysis

Harmonic distortion problems are increasing on the Sterkspruit Medium Voltage distribution networks, especially with the application of power factor correction capacitors that results in resonance close to the 3rd harmonic. Power systems analysts typically do not have L and C readily available, so they commonly compute the resonant harmonic, based on fundamental frequency impedances and ratings using the following equation:

$$h_r = \sqrt{\frac{MVA_{SC}}{Mvar_{cap}}} \qquad \dots \qquad 1$$

Where, $h_r = resonance\ harmonic$

$MVA_{SC} = system\ short - circuit\ MVA$

$Mvar_{cap} = Mvar\ rating\ of\ capacitor\ bank$

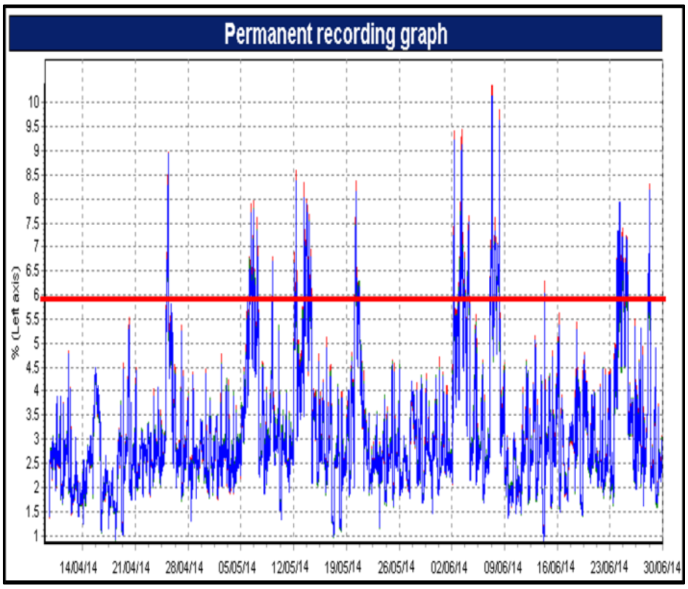


Figure 14: 3rd Harmonic in MV busbar 2.

As shown in the Figures above, the values of the 3rd harmonics frequently exceeded the limits (6%) defined in standard NRS048. From the equation (1) and for the first profile, the resonant harmonic is approximately 4.80, close to the 3rd harmonic voltage. The HV/MV (66/22 kV) Sterkspruit substation topology is illustrated in figure 14.

This can be rectified by introducing filters that will divert harmonic currents away from the system (using passive filters) or inject phase-shifted harmonic components [11].

The second is to reduce the system impedance of the Sterkspruit 66 and 22 kV power network, by increasing the system fault levels and avoiding system resonance condition at harmonic frequencies. Eskom ECOU can achieve this by introducing a second 66 kV line between Riebeek and Sterkspruit Substation. This will not only solve harmonics problem as it will solution to reliability and improves system voltages. However, also to move one of the shunt capacitor banks to the downstream of the line, thus maintaining the VAR support but alleviating the THD problem at Sterkspruit Substation, as shown in figure 14.

H. Voltage Regulation Analysis

Voltage regulator such as powerPerfector (pP) and MicroPlanet has the advantage of being able to connect further down the feeder to address the voltage regulation issues for any heavy loaded feeder. When the feeder has many customers, this could lead to high voltage level during the daytime with low demand, and low voltage level at period of maximum demand. The voltage regulator would be able to step down the voltage level during and boost the voltage during peak period.

However unlike other control options such as energy storage, it does not generate additional energy. For this reason installation of voltage regulators is the best solution to achieve voltage regulation in a feeder as it boosts voltages up to almost 1.03 p.u, see figure 15, from retic master simulation tool.

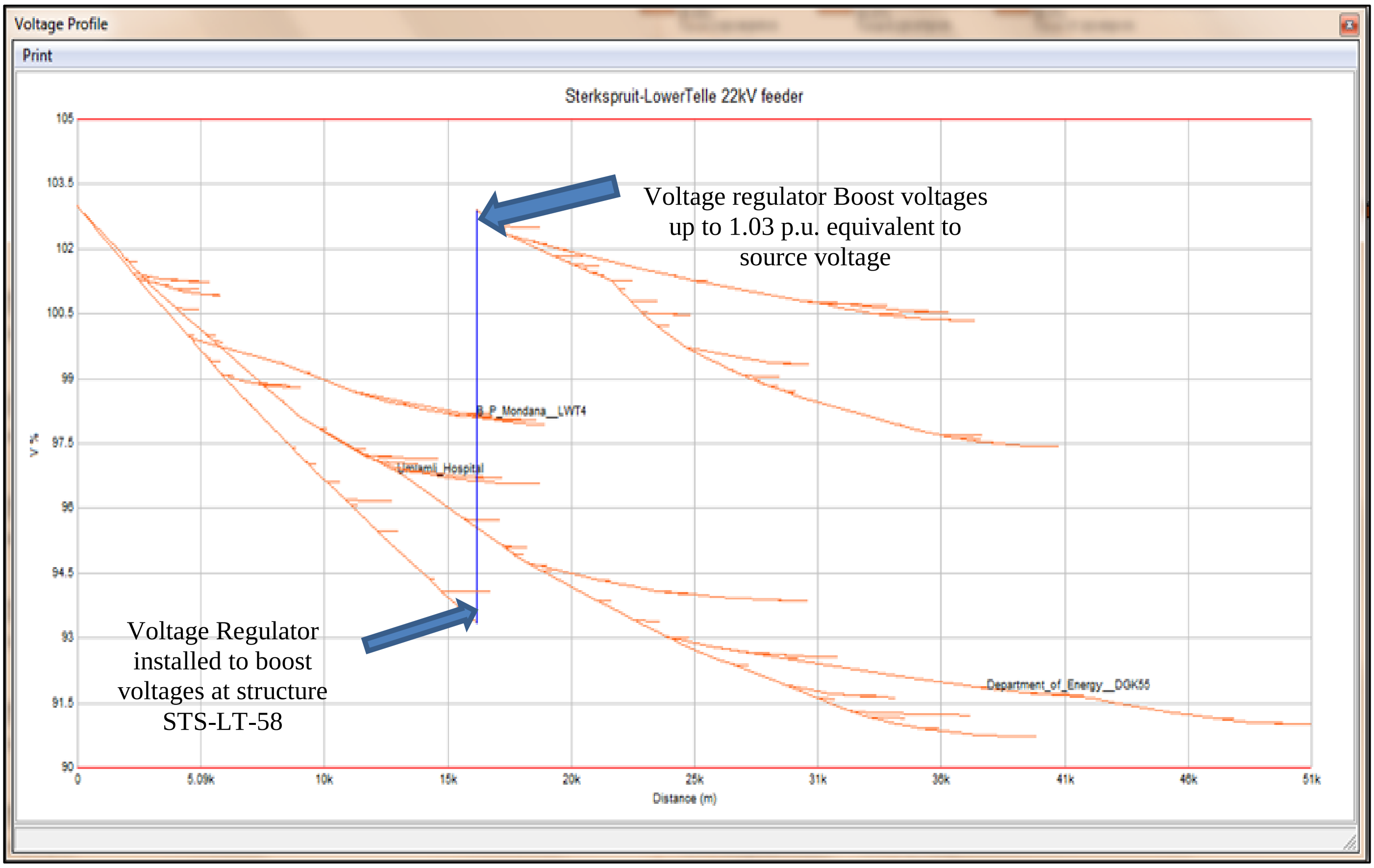


Figure 15: Voltage Profile Improvement using Voltage Regulator.

5. Protection and Coordination

For short circuit analysis we consider three phase short circuit as it is the most severe fault amongst all the faults. We are going to assume three phase short circuit on various locations from 400V to 22kV level. The impedances of transformers, cables and motors are contributing to the change in fault level at different locations. Formulae used for calculations of short circuit analysis.

I. 3 phase Short Circuit Analysis

$$Zpu = \%Z\ x\ \frac{Base\ MVA}{Transformer\ Rating} \quad \ldots\ 2$$

$$Fault\ MVA = \frac{Base\ MVA}{Z_{(pu)T}} \quad \ldots\ 3$$

$$Fault\ Current = \frac{Fault\ MVA}{\sqrt{3}\ x\ Voltage} \quad \ldots\ 4$$

Base MVA = 20 MVA

Base Voltage = 22kV

For Sterkspruit Substation 66/22 kV:

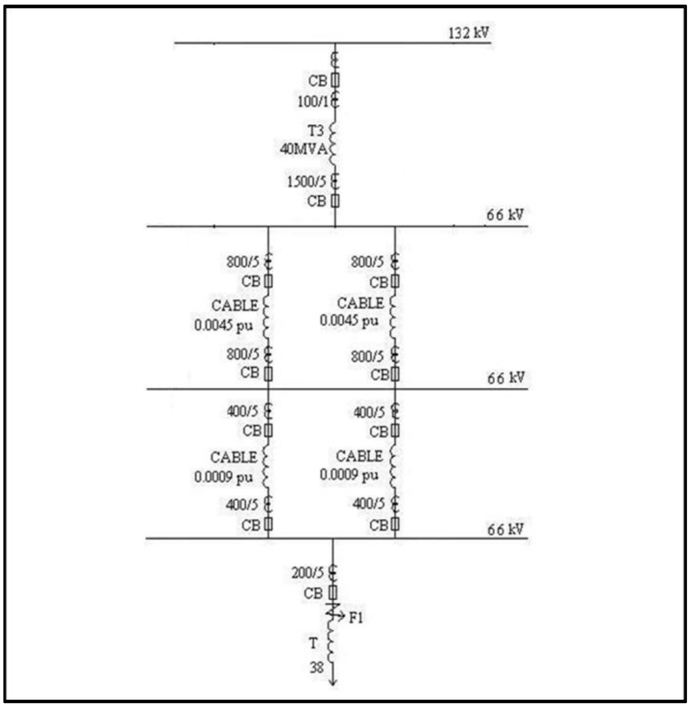


Figure 16: Impedance Diagram for Faults on 22 kV bus on Sterkspruit Substation

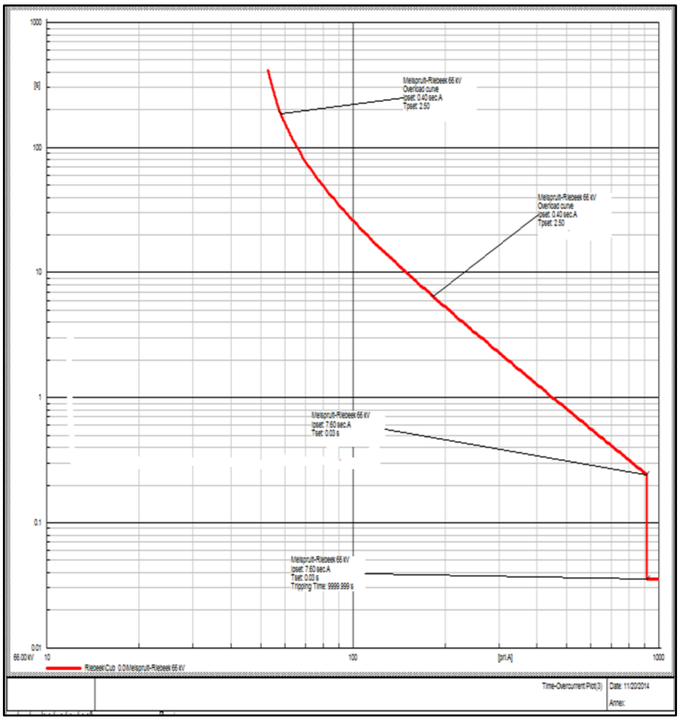


Figure 17: Relay Co-ordination for Melkspruit Substation

The relay current and time settings for all other relays in the system are shown in the relay report for all the voltage levels. The earth fault settings for the relays is generally 20 -30% of the rated current of the system. The time interval that must be allowed between the operation of two adjacent relays in order to achieve correct discrimination between them is called the grading margin. If a grading margin is not provided, or is insufficient, more than one relay will operate for a fault, leading to difficulties in determining the location of the fault and unnecessary loss of supply to some consumers, which contributes severely in unreliable network.

J. Phase to Phase Short Circuit Analysis

The results in this section are provided to demonstrate the performance of the individual relays for faults in their primary and backup protection zones. The performance is analyzed by looking at the grading margin, operating time for primary zone fault and operating time for backup zone fault for each algorithm.

Figures 18 show the coordination curves for the selected relay coordination pair using Siemens and Reyrole algorithms. The main relay for the selected pair is Relay 12 and the backup relay is Relay 6. For this relay pair, a phase to phase fault was simulated in front of Relay 12. This fault is in the primary zone of protection for relay 12 and in the backup zone of protection for Relay 6.For this fault Relay 12 measures 12674 A and Relay 6 measures 1854A. Relay 12 operates in 0.521 seconds and Relay 6 operates in 1.043 seconds. The relays operated properly with the grading margin of 0.522 seconds which is above the coordination time interval of 0.3 seconds. Relay 12 operates in 0.499 seconds and Relay 6 operates in 0.920 seconds. Using the Reyrole relays operated correctly with the grading margin of 0.422 seconds which is above the coordination time interval of 0.3 seconds.

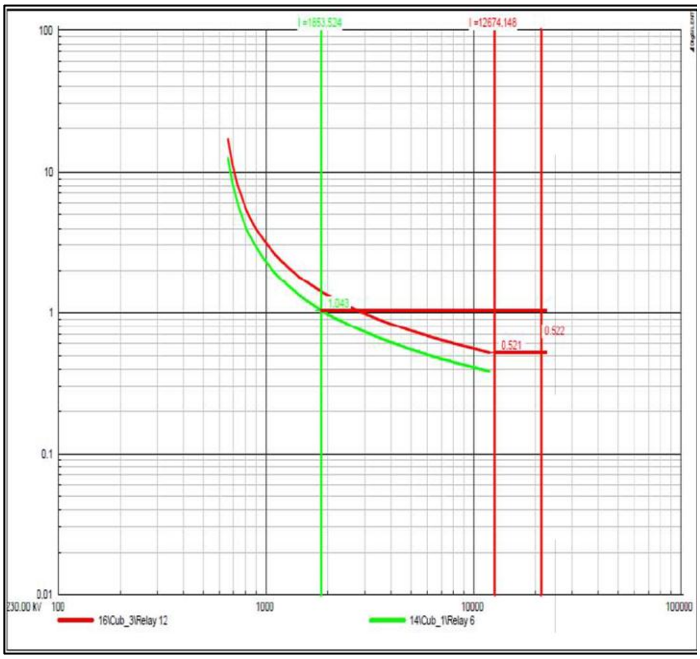


Figure 18: Performance of Relay Coordination at Riebeek Substation

V. CONCLUSIONS

The primary goal of this paper was to carry out power system reliability evaluation, to see if the Aliwal North network operations satisfy customer requirements.

Aliwal North network was used as the case study in this paper to do reliability evaluation. It was therefore found that the network is vulnerable to system faults, planned and unplanned outages. However, the application of predictive approach reliability analysis on DigSilent in conjunction with the alternative source of supply solution, in figure 8A shows that the reliability indices will improve, and will be below the 12 MMA average Eskom ECOU reliability indices targets for the 2014/2015 financial year.

It is imperative to consider power quality challenges when implementing reliability improvement in the network. The paper also looked at power quality issues such as voltage; dips, swell, flickers, unbalance & regulation, and harmonics.

Voltage unbalanced analysis was carried out using the historical data from the vectograph see figure 9, however DigSilent simulations in figure 10 shows that phase A and B are the most unbalanced phases.

During voltage flicker analysis it was observed that the large currents drawn by the motors gave rise to voltage changes when switched on and it was resulting to voltage flicker see figure 12. The remedial strategy to the problem was to install a shunt capacitor bank rated at 800 kVar in series with the four motors to improve power factor control and compensate for voltage variations see figure 12.

Voltage dip analysis proved that Melkspruit/Riebeek 66 kV network fed from Drerunberg/Melkspruit 132 kV line experiences voltage severe dips due to the lightning strike in the area, which has a huge impact on COUE. The solution to this is to have an alternative source of supply to the Aliwal North network.

Due to large number of customers and line length, Sterkspruit/LowerTelle 22 kV feeder 22 kV feeder experiences low voltage further down the line and it resulted to non-conformance in this feeder. However, simulations from retic master suggest that installation of voltage regulator is the best solution as it boost the voltage up to 1.03 p.u. see figure 15.

Relay coordination analysis was done on DigSilent considering three phase and phase to phase faults see figure 17 and 18 respectively for results. Moreover, manual calculations were also carried out on the three phase circuit in figure 16. The results shows that current existing protection coordination on the Aliwal North network requires no adjustment or improvement as the relay setting and tripping times are operating as expected.

Benefit to cost analysis based on the alternative source of supply as the best solution, shows that the network performance will improve severely in the Aliwal North sector see figure 8A, all indices do not exceed the target. Most of all, this solution is very economical to Eskom as it improve load flow, and power quality without affecting network protection.

VI. RECOMMENDATIONS

In order to achieve better results for reliability analysis, to determine the present performance and to improve the reliability in the Aliwal North power system network the following recommendations are presented below.

- Focused research need to be conducted by Eskom regarding Eskom specific environment and equipment failure rates and performance. This will serve the dual purpose for reliability modelling as well as provide information required in support of asset management strategies and implementation.
- The present data recording system should be upgraded from manual to computer aided system. All the events should be specific and the step restorations made should be recorded accordingly so that true reliability indices are obtained. The failure of individual components in the system should be maintained so the probability of failure represents its true system. Its repair time and sectionalizing time should be separated since it has high impact on the reliability indices during predictive analysis.
- Reliability of 22kV system could be further improved by installing Voltage Regulator at structure LTE-STS-36 of Sterkspruit-LowerTelle 22 kV line
- The failure rates of all components in a network should be taken into account when evaluating the reliability of a network. Assuming components are always operable in a system is nonsensical and should not be done.
- With adequate time for future expansion of this thesis, I will strongly recommend a full protection analysis in this topic e.g. phase to earth and phase to phase analysis.

VII. REFERENCES

[1] Wang Saiyi: "An Effective and Applied Method on Evaluation of Distribution Network Planning". China International Conference on Electricity Distribution 20 – 23 Sep. 2010.

[2] Jin Yi-xiong, Li Hong-zhong, Duan Jian-min: "Algorithm Improvement for complex Distribution Network Reliability Evaluation and its programming", 2010.

[3] M Schwan, A Ettinger, S Gunaltay: "Probabilistic Reliability Assessment in Distribution Network Master Plan Development and in Distribution Automation Implementation", 2012.

[4] José A. Rosendo, Antonio Gómez-Exposito, Gabriel Tevar, and Manuel Rodriguez: "Evaluation and Improvement of Supply Reliability Indices for Distribution Networks": 2009.

[5] Navan M. Pindoriya: "Power System reliability Analysis": - 201.

[6] M. Al-Muhaini, G.T. Heydt, A. Huyn: "The Reliability of Power System of Power Distribution System as calculated using system theoretic concepts". In Proc, IEEE Conf. Power and Energy Society General Meeting, USA 2010.

[7] L. Goel, R. Billinton: "Determination of Reliability Worth for Distribution System Planning. IEEE Transactions on Power Delivery.

[8] R. Billinton, RN, Alan: "Reliability Assessment of Large Electric Power System. Springer, 1st edition – 1998.

[9] M.A. Van Harte: "Network Planning Reliability Guidelines Eskom", August 2010.

[10] S.R.L. Goel, P. Wang: "Modelling Station-originated outages in composite system using duration sampling simulation approach computers & electrical engineering, vol. 27 2009.

[11] R.U. Nighot: "Incorporating Substation and Switching Station related Outages in Composite System Reliability Evaluation", 2008.

[12] G. Pulcini: "Modelling the failure data of repairable equipment with bathtub type failure intensity", 2009.