Improving the reliability performance of medium voltage networks

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Dissertation presented for the degree of Master of Science in Engineering in the Department of Electrical Engineering University of Cape Town

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DECLARATIONS

I declare that this dissertation, entitled*, “**Improving the reliability performance of Medium Voltage networks**”* is my own unaided work. “I know the meaning of plagiarism and declare that all of the work in the document, save for that which is properly acknowledged, is my own” Materials used from other authors have been duly referenced. This dissertation has neither, in part nor entirety, been submitted to any other universities for any other degree. This dissertation is being submitted in fulfilment of the academic requirements for the degree of Master of Science in Electrical Engineering in the Faculty of Engineering and the Built Environment at the University of Cape Town.

Signed: Signed by candidate Signature Removed Date: 20 July 2015

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ABSTRACT

The aim of this dissertation is to investigate alternative, more reliable and cost effective ways of improving the reliability performance of medium voltage networks. Customers are mainly affected by faults on the distribution MV network, to which, consequently, we have to pay particular attention. A major requirement on electricity supply systems is high supply reliability for the customer which is mainly determined by the distribution networks. Power system reliability is an essential factor in the quality of supply and is directly related to the number and duration of outages. By analysing the power system properly, the weaknesses will then be identified and improvements can be introduced to minimise the occurrence of outages. A decrease in the outage rate will result in an improvement in reliability and quality of supply of the distribution MV network.

The dissertation focuses on improving the network management by increasing the level of network automation and control which improves the operating efficiency of medium voltage distribution networks. Steps are shown how to equip the network according to progressive investment capability, from Fault Path Indicators (FPIs) and remote control Pulseclosing technologies to automatic FuseSavers and Tripsavers used in a feeder automation scheme to minimise the number of disturbances and the outage durations experienced when they occur.

The results of a study analysing the impact of different intelligent automation solutions on the reliability performance of Medium Voltage distribution networks are presented in the dissertation. The respective system topologies are modelled and the resulting system reliability performance is determined by reliability calculations such as the SAIDI and SAIFI values. The results show that the distribution automation technologies can have a very significant impact on both the SAIDI and SAIFI performance of the systems. Further, selected details related to the implementation of such intelligent automation schemes are presented in this dissertation.

The dissertation begins with a brief introduction about power systems, followed by a review of the literature pertaining to the topic. The dissertation then describes how to carry out reliability evaluation of a real distribution network using DIgSILENT PowerFactory and compare the results with the analytical method, the historical data method and results obtained from the field after the installation of the new innovative technologies. Thereafter a cost analysis for the distribution system reliability enhancement solution implementation was performed.

It was concluded based on the results that the use of different distribution automation technologies improved reliability performance by reducing the duration of interruptions but not the frequency of interruption i.e. it improves the SAIDI but not SAIFI. It appears clear that implementation of automatic technologies, remote control and fault detection are the key solutions to improving network reliability.

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LIST OF ACRONYMS

CAIDI -	Customer Average Interruption Duration Index
CAIFI -	Customer Average Interruption Frequency Index
CC -	Contact Centre
CNC -	Customer Network Centre
DA -	Distribution automation
DAS -	Distribution automation system
DAS -	Distribution Automation System
DNP -	Distributed Network Protocol
DSLI -	Distribution Supply Loss Index
E/F -	Earth-fault
EDNO -	Electricity Delivery Network Optimisation
ENS -	Engineering Network Schematic
FALLS -	Faults Analysis and Lightning Location Systems (Server, to indicate where lightning strikes)
FLISR -	Fault Location, Isolation, and Service Restoration
FMEA -	Failure Mode Effect Analysis Method
FPI -	Fault Path Indicator
IBR -	Incentive Based Regulation
IEEE -	Institute of Electrical and Electronic Engineers
KPI -	Key Performance Indices
LBS -	Load Breaker Switch
LPU -	Large Power Users
LV -	Low Voltage
MAIFI -	Momentary Average Interruption Frequency Index
Mink Conductor -	10,98mm, (Aluminium Conductor Steel Reinforced)
MV -	Medium Voltage (1 kV ≤ MV ≤ 22 kV)
NEC -	Neutral Earth Compensator
NEPS -	Network and Equipment Performance Management System
NEPS QA -	Network and Equipment Performance Management System Quality Assurance
NIP -	Network Interruption Performances

NOPs -	Normally Open Points
O/C -	Over-current
OMS -	Outage Management System
PPU -	Pre- Paid Users
QOS -	Quality of Supply
RSLI -	MV Supply Loss Index
RTU -	Remote Terminal Unit
RTU -	Remote Terminal Unit
S/S -	Substation
SAIDI -	System average interruption duration index
SAIFI -	System average interruption frequency index
SCADA -	Supervisory Control and Data Acquisition
SE/F -	Sensitive earth-fault
SEL -	Schweitzer Engineering Laboratories
SF -	Section Fuse
SL -	Section Link
SLD -	Single Line Diagram
SPU -	Small Power Users
Squirrel Conductor -	6,33mm, (Aluminium Conductor Steel Reinforced strikes)
SWER -	Single Wire Earth Return
TSC -	Technical Service Centre
UFLS -	Under - Frequency Load Shedding
WMC -	Work Management Centre

LISTS OF DEFINITIONS

AUXILIARY TRANSFORMER - Any transformer that has been installed and supplied from a supply transformer with the purposes of supplying auxiliary equipment or supply points.

ARC- AUTO-RECLOSE - Operation when the network breaker opens its contacts for a set period of time allowing the fault current on the line to be removed and then closes the contacts, restoring voltage supply to the line [3].

BULK LOADS / POINTS - It refers to a customer's supply point (metering points), where the customer's supply voltage is >1 kV i.e. the transformer supplying the customer is not an Eskom asset, but the customer's.

CAUSE (ROOT) - The source factor or root cause resulting in a network event or loss of supply to a customer.

CUSTOMER - A person or legal entity who has an electricity supply agreement with the relevant distribution licensee (Eskom Group) [3].

CUSTOMER (NEPS) - This is the outage classification for faults caused directly by the customer or network outages requested by the customer for the maintenance of their own plant, up-rating of equipment or the refurbishment of the networks.

DIgSILENT PowerFactory - The calculation program PowerFactory, as written by DIgSILENT, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to an electrical power system and control analysis in order to achieve the main objectives of planning and operation optimisation [25].

DISTRIBUTION NETWORK OPTIMISATION - Process by which the protection equipment philosophies and positioning are optimised so as to improve the overall network performance.

DISTRIBUTION SYSTEM - That portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer.

DURATION INTERRUPTION -	The period (measured in seconds, or minutes, or hours, or days) from the initiation of an interruption to a customer or other facility until service has been restored to that customer or facility. An interruption may require step-restoration tracking to provide reliable index calculation. It may be desirable to record the duration of each interruption.
EMERGENCY-	A condition that poses an immediate and direct threat to life or could possibly cause severe damage to the plant of the distribution licensee or the customer [3].
EVENT -	An incident on the network that may or may not have caused losses or an event affecting the customer.
FAULT -	Those outages due to network fault (transient or permanent) conditions or an unplanned interruption of supply due to protection mal-operation or switching errors.
FMS -	Fault Management System. An application used in the Network Management Centre to record network faults.
FREQUENCY -	The frequency of alternating voltage generated by power system generators (50Hz in South Africa) [3].
INTERRUPTION -	The event that occurs when one or more phases of a supply to a single customer or group of customers are disconnected for a period exceeding three seconds [4].
INTERRUPTING RATING -	The interrupting rating of a circuit breaker is a critical factor concerning protection and safety. The interrupting rating of a circuit breaker is the maximum fault current the breaker has been tested to interrupt in accordance with the testing laboratory standards.
I^2t (AMPERES SQUARED SECONDS) -	An expression related to the circuit energy as a result of current flow. With respect to circuit breakers, the I^2t [A^2s] is expressed for the current flow between the initiation of the fault current and the clearing of the circuit [20].
LATERAL LINES -	Spur lines or T-offs.
LIVE WORK -	Live work conducted on a network or plant using standard accepted techniques where the supply to the customer was not lost [3].
LOSSES -	Supply losses energy not supplied as a result of the network interruption of supply. Losses are measured in MVA hours [3].

MAJOR EVENT - A disastrous event that exceeds design limits of the electric power system and is characterized by the following (as defined by the utility):

a) Extensive damage to the electric power system;
b) More than a specified percentage of customers simultaneously out of service;
c) Service restoration times longer than specified.

MOMENTARY INTERRUPTION - Interruption of supply with a duration < 2 minutes.

NETWORK BACKBONE - The section of a network from the source to the principal load or normal open point considered to be the main line.

NMC - Network Management Centre is where the network is safely and efficiently managed and operated.

PARETO NETWORK - The network that has a major contribution (80%) to network performance KPIs.

PERMANENT FAULT - Assumes that the line has experienced permanent damage and the fault cannot be cleared by a momentary interruption to supply. A line crew must physically repair the damage before re-energising the line [19].

PLANNED INTERRUPTION - An interruption that occurs when a component is deliberately taken out of service by the utility at a selected time, usually for the purposes of construction, preventative maintenance or repair [4].

QA - An application (Quality Assurance), used to audit, edit and verify network event related data (FMS data).

ROGUE FEEDER Worst performing feeder.

RSLI (MV Supply Loss Index) - RSLI is the measure of the MV supply unavailability (MV/LV transformers and bulk loads) caused by sustained interruptions. RSLI is expressed as hours per month.

SCADA - Supervisory control and data acquisition - This provides the monitoring and control of the distribution system in real-time.

SINGLE - PHASE SUPPLIES (≤ 16 kVA) -

- Dual-phase SPU supplies (≤ 128 kVA)
- Three-phase SPU supplies (≤ 100 kVA)
- Three-phase LPU supplies (≥ 100 kVA and ≤ 500 kVA)
- Three-phase LPU supplies (> 500 kVA)

SMALLWORLD - Is the brand name of a portfolio of GIS software provided by GE Energy, a division of General Electric. Smallworld technology supports application products for telecommunications, utilities, and public systems organizations. A database technology called Version Managed Data Store (VMDS) that has been designed and optimized for storing and analysing complex spatial and topological data. The native Smallworld data store can be stored in an Oracle Database. This allows the use of Oracle facilities for backups and recovery.

SUSTAINED INTERRUPTION - Interruption of supply with a duration ≥ 2 minutes

TRANSIENT FAULT - Means that the electricity supply is turned off momentarily and that the fault will be gone when the line is re-energized [19].

TRANSIENT INSENSITIVE - An ability to withstand temporary over-current conditions without being damaged or destroyed [6].

UNPLANNED INTERRUPTION - Interruption of supply due to network transient or permanent conditions, protection, mal-operation, or switching error by the distribution licensee [4].

Chapter 1: Introduction

The performance and reliability study in power systems is very important to the utilities as well as to the country as it could be used for many decisions making in the development of the system and increasing the end user satisfaction. Improving quality of supply in a demanding and competitive business environment is one of the most challenging tasks for power utilities today. Reducing the number and duration of power outages and limiting the number of affected customers are important steps toward this goal.

The dissertation is about the improvement of reliability performance of medium voltage networks using new techniques, technologies, applications and simulations.

1.1. Background to the Problem

The reliability of electric distribution systems is critically important for both utilities and customers. Electric reliability affects public health and safety, economic growth and development, and societal well-being. Many utilities estimate the value of electric services to consumers to assess the benefits of investments to improve reliability.

Most power outages are caused by weather related damage to overhead power lines. High winds, ice, and snow can cause trees to touch power lines and sometimes can cause lines and poles to break. Animal contact, vehicle accidents, equipment failure, and human error also contribute to power outages.

Power outages in electric distribution systems are documented and classified by the number of customers affected and the length of time that power is out. The Institute of Electrical and Electronic Engineers (IEEE) specifies three types of outages [1], [2]:

- **Major Events** are those that exceed the reasonable design and/or operational limits of the electric power system and affect a large percentage of the customers served by the utility.

- **Sustained Interruptions** include outages not classified as momentary events and that last for more than two minutes.

- **Momentary Interruptions** involve the brief loss of power to one or more customers caused by opening and closing of interruption devices.

The reliability of the electricity supply depends on the number of disturbances in the network and the time it takes to restore supply to the customers. Challenges regarding reliability concern the reduction of the number of outages, the minimisation of the number of affected customers and the reduction of the outage duration.

The reliability evaluation study of the electricity networks in South Africa is seldom carried out. Moreover in areas where this is carried out, it is limited to the calculation of System Average Interruption Frequency Index (SAIFI); System Average Interruption Duration Index (SAIDI) by means of using the failure data. This is not enough to evaluate and improve the reliability levels of the network. The failures of Medium Voltage (MV) lines and equipment result in revenue losses to the utilities as well as to consumers. In South Africa, the utilities are concerned about the collection of revenue but not much about reliability issues.

Medium Voltage networks have the highest impact on reliability in electricity distribution because more than 90 % of the customer experienced outages occur on MV networks. A challenge with the MV network is that it is usually very large, and the line length of a single feeder may be even more than 100 km. Thus, improving the distribution reliability in these areas poses a considerable challenge, because it is too expensive to install a lot of cables underground. Network automation provides a good opportunity to reduce the effects of outages [1], [2].

The reliability indices SAIFI, SAIDI and Momentary Average Interruption Frequency Index (MAIFI) [1] have been traditionally used to provide statistical information to evaluate the state of the distribution network and the demand for new investments. These are the standard indices used by the electric power industry and provide a uniform methodology for data collection and analysis. The indices have also played a key role in the valuation of investment options, which may not be feasible in the present operational environment because the valuation of interruptions is not taken into account in the economic regulation [2]. Therefore, interruptions have a real effect on the allowed profit, and the level of outage costs is an important indicator of reliability and a significant driver in investment decisions. The traditional reliability indices SAIFI and SAIDI include information about the number and duration of faults, which form the basis for outage costs [2].

MV distribution networks constitute the backbone of power distribution systems and for this reason utilities justifiably strive to improve their performance. Distribution Automation provides a means of enhancing feeder performance in the event of a fault by automatically restoring supply, after the fault has been cleared by a circuit breaker, to as many customers as possible, whilst isolating the faulted section of the line or cable.

1.1.1 Why Distribution Automation? [5]

Distribution businesses and utilities are improving their business performance both technically and financially by implementing distribution automation (DA). DA has improved their businesses in the areas of reliability and quality of supply to customers by minimising downtime, improving efficiencies of restoration times technically including the inherent benefit of improving the safety to operating personnel [5].
The distribution industry in the distant past did not readily accept DA because it was expensive and at it did not make good investment sense at the time however recently with the rise of new cost efficient control systems and deregulation within the industry it has been increasingly adopted by distribution businesses globally.
Automation is usually implemented upstream in the network. Since a loss of supply affects more customers upstream and downstream closer to the customers site it is only implemented if it makes economic sense or if there are stiff financial penalties. For example, if a utility like Eskom should be unable to supply a large power user like a mine or aluminium smelter for a long period of time or rather greater than the period of time stipulated in the large power user contract. The benefits demonstrated through automating substations are now being extended outside the substation to devices along the feeders and even down to the meter. The key areas of benefits down the control hierarchy are described below and summarised in Table 1 [5].

Table 1.1: Key Automation Benefit Classifications by Control Hierarchy Layer [5]

Control Hierarchy Layer	Reduce O&M	Capacity Project Deferrals	Improved Reliability	New Customer Services	Power Quality	Better Info for Engr. & Planning
1. Utility	√			√		√
2. Network	√	√	√		√	√
3. Substation	√	√	√		√	√
4. Distribution	√	√	√		√	√
5. Customer	√	√	√	√	√	√

a) Reduced Operation and Maintenance (O&M) Costs

Automation reduces operational costs in various ways. At high voltage level rapid response times are needed to restore the service after faults however high voltage lines are usually very long and if a fault is located on a line it will take a long time to locate and the height of high voltage overhead lines makes the task of finding a fault like insulator breakdown very hard. Night time visibility is also a factor which operators struggle with when trying to restore the service after faults. At the substation and distribution layers, fast fault location substantially reduces crew travel times, because crews can be dispatched directly to the faulted area of the network. Time consuming traditional fault location practices using line patrols in combination with field operation of manual switches and the feeder circuit breaker in the primary substation are eliminated. The same issues are of course true for long MV lines and requires a large number of operating staff to do manual switching sectionalising to identify fault location.

In contrast, the benefits of DA to a distribution business is obvious that by automatically isolating fault locations on the network and implementing the predefined contingency switching plan would completely or significantly reduce the number of customers affected by faults or power outages.

Issues of quality of supply can also be monitored to protect equipment from overvoltage or overcurrent including monitoring frequency which affects network security. Condition monitoring systems can also be implemented. A hypothetical example would be to have an instrument which monitors a transmission transformer temperature and oil properties to measure trending of transformer condition and automatically flag when the data indicates there may be a problem and requires human inspection [5].

b) Capacity Project Deferrals

Optimum substation transformer loadings can be achieved by monitoring transformer loading in real-time and transfer excessive short-term loading from one transformer to another transformer located at another substation by switching open points automatically.

This will extend the lifetime of the substation transformers by always optimally loading them and keeping their thermal limits well below the transformers manufactures maximum thermal limits [5].

c) Improved Reliability

Reliability in distribution business is usually improved by introducing equipment like reclosers, load break switches and communicating fault path indicators which are linked remotely to the

control room management system so that control room personnel can direct field operators to the location of the fault. Automation provides the fastest way to reduce outage duration. Installation of this reliability improving equipment can reduce average outage durations by as much as 20-30% annually for a reasonably well maintained overhead feeder. It can even reduce the number of outages if an outage is recorded as an outage only if it is sustained beyond a certain interval. This improvement is made on the basis that momentary interruptions due to autorecloser operation are acceptable.
Autoreclosers are mainly responsible for these types of reliability improvements since they automatically reclose for nuisance tripping events which prevents unnecessary disruption to the supply of customers [5].

d) Power Quality

With the proliferation of electronic consumer goods/loads, the power quality received by these sensitive devices needs to be of high quality to prevent these electronic devices from being damaged for example high voltages, sags, swells and harmful harmonics. Although many albeit usually the more expensive electronic equipment such as laptops and expensive medical instrumentation usually have embedded protection circuits or passive elements like fuses which protect these devices from a low quality power supply. Therefore, this is another area where DA can improve utility performance with respect to quality of supply by complying with regulations such as NRS 048-2:2007 with respect to power quality. Automation also enables the dynamic control of voltage regulation through remote control of capacitor banks and voltage regulators [5].

e) Improved Information for Engineering and Planning

The increase in real-time data availability resulting from DA provides more visibility to planners and operators of the network. The optimisation of the communications infrastructure is an important aspect of the automation implementation that will deliver the required data to the appropriate application. This data is fundamental to better planning and asset management under business objectives, forcing lower operating and capital investments [5].

1.2. Motivation for the Dissertation Topic

With dependence on electricity increasing, driven by load growth, unpredictable weather conditions, aging distribution equipment, and other factors, the need for reducing the frequency, duration and severity of interruptions is vital. Hence, a research in this field of study was chosen.

1.3. Research Objectives and Questions

1.3.1 Research Objective

The main objective of this research is to improve the reliability performance of a medium voltage system using new technologies which will provide the fastest way to reduce outage durations.

The specific objectives of this research include the following to:

1. *Improve the level of reliability and performance of a distribution network using distribution automation.*

2. *Improve the level of quality of supply to the customers.*

3. *Carry out reliability evaluation of distribution networks using DIgSILENT PowerFactory software*

4. *Model an existing real network using DIgSILENT PowerFactory software (version 15.0) and compare the results obtained to that of the analytical method FMEA, historical data analysis method and the pilot project field work data.*

5. *Perform cost benefit analysis for the tested distribution system*

6. *Draw conclusions based on the results obtained from the field, DIgSILENT PowerFactory software evaluation, FMEA and the Historical data method.*

1.3.2 Research Questions

The main research question associated with this research project is:

"To what extent will the installation of IntelliRupter PulseCloser, Tripsaver and the FuseSaver Breakers improve the reliability performance of Medium Voltage Rogue Feeders?"

This question will be addressed through detailed consideration of each of the following secondary research questions:

- How often does the average customer experience an interruption? When a service interruption occurs, how long does it take to restore power on average?
- What techniques best improve the reliability performance of MV networks?
- How will the MV overhead feeder automation technology such as the IntelliRupter PulseCloser, Tripsaver and the FuseSaver Breakers improve the SAIDI and SAIFI of a rogue feeder?
- How will Eskom benefit with regards to the implementation of the IntelliRupter PulseCloser, Tripsaver and FuseSaver Breakers?
- How will the collection and analysis of different data be used to monitor/ improve the reliability performance of MV networks?
- What is the expected network performance and how does it vary from the actual performance?
- What is the cost saving benefits and the percentage performance improvement?
- The ultimate goal of applying reliability analysis is to help answer questions such as:
    - Is the system reliable enough?
    - Which scheme is more reliable and fails less frequently? and

- Where can the next rand be best spent in order to improve the particular network?

1.4. Limitations and Scope of the Study

The scope of the dissertation is to accurately locate the Distribution Automation (DA) devices in an electric power distribution network that can help engineers quickly identify and repair faulted components, reduce outage time, speed up system restoration, and, thus, greatly improve the reliability performance of the medium voltage system.

Although there are a number of methods that are used in improving the reliability of the distribution feeders, this dissertation report focuses mainly on the use of DA on one of the worst performing feeders in the Western Cape in South Africa.

The Neutral Earth Compensator (NEC) minimum earth fault current value was limited to either 360 A or 960 A on the Eskom network, which in turn limited the installation of Intellirupter [IR] Pulsecloser. The Intellirupter pulseclosing fault-detection threshold minimum is 400 A, and applies to both phase-earth and phase-phase faults. The IR will trip in response to fault currents less than 400 A (if configured to do so), but upon testing for the continued presence of the fault that caused the initial trip, its pulseclosing technology will not be able to determine if the fault is still present unless the resulting pulseclosing data indicates a current of 400 A or greater. The consequence of not determining if a fault (with a projected current of < 400 A) is still present, simply results in an automated reclosing operation, albeit pole-by-pole, and at or near a voltage peak.The Waterkloof substation was installed with a 960 A NEC which was ideal for the correct operation of Intellirupter Pulsecloser.

1.5. Plan of Development

The dissertation contains twelve chapters that explain the perceptions, developments and the results of the research.

The layout of this dissertation is as described below

Chapter 1: provides a general introduction to the topic of the dissertation. The chapter gives a brief outline and overview of the whole dissertation and its scope.

Chapter 2: briefly presents the dissertation literature review including power system overview, the importance of reliability in distribution systems, causes of interruptions and the introduction to the analytical method using load point reliability indices such as failure mode effect analysis (FMEA).

Chapter 3: describes the electricity quality regulation, utility cost and promoting continuity of supply. It also introduces the reward and penalty plot for incentive scheme.

Chapter 4: is a continuation of the literature review, it focuses mainly on the MV Overhead Feeder Automation. The chapter includes the following: Benefits of Distribution Automation System Implementation and Distribution Automation Technologies - An enabling technology for the smart grid.

Chapter 5: describes the reliability evaluation of the Waterkloof Farmers 1 11 kV Feeder distribution network before installation of equipment using Historical Data, FMEA and DIgSILENT.

Chapter 6: is devoted to protection coordination and grading. It focuses on the method of selective coordination to avoid blackouts on the tested feeder. It includes the TCC curves for Intellirupter Pulsecloser, Modelling and Simulation of Protection Time/Current Characteristics of Waterkloof Farmers 1 11 kV Feeder using DIgSilent PowerFactory Software, protection settings and protection functionality for the innovative new technologies.

Chapter 7: Laboratory work and field work is presented. It focuses on the methodology of the dissertation. It describes field trial of the innovative new technologies which includes the practical and field installation methods used for each technology.

Chapter 8: describes the load point and system indices calculations of Waterkloof Farmers 1 11 kV Feeder after installation of equipment.

Chapter 9: is the continuation of the results describing the cost assessment of the reliability improvement in distribution networks by means of distribution automation systems using DIgSILENT PowerFactory software. It also describes the different configurations tested i.e. cost benefits analysis before and after the installation of the equipment.

Chapter 10: focuses on the results and analysis of field data.

Chapter 11: draws conclusions based on the findings of this research.

Chapter 12: Some recommendations are made as to how the system should be implemented and future development works that should be carried out.

Chapter 2: Power System Reliability

2.1. Power System Overview

The general outline of the power system is shown in Figure 2.1. The electricity delivered to residential and industrial or commercial customers is generated in large power plants. The electricity is then transmitted from the power plants via high voltage transmission lines, which are interconnected in a network configuration to distribution substations. From these substations, the power is then distributed via low voltage distribution feeders to different load points (customers) through transformers located at close proximity to the load points. The distribution feeders are made up of overhead and underground cables. The voltage is stepped up or down by transformers appropriately along the transmission and distribution networks [15].

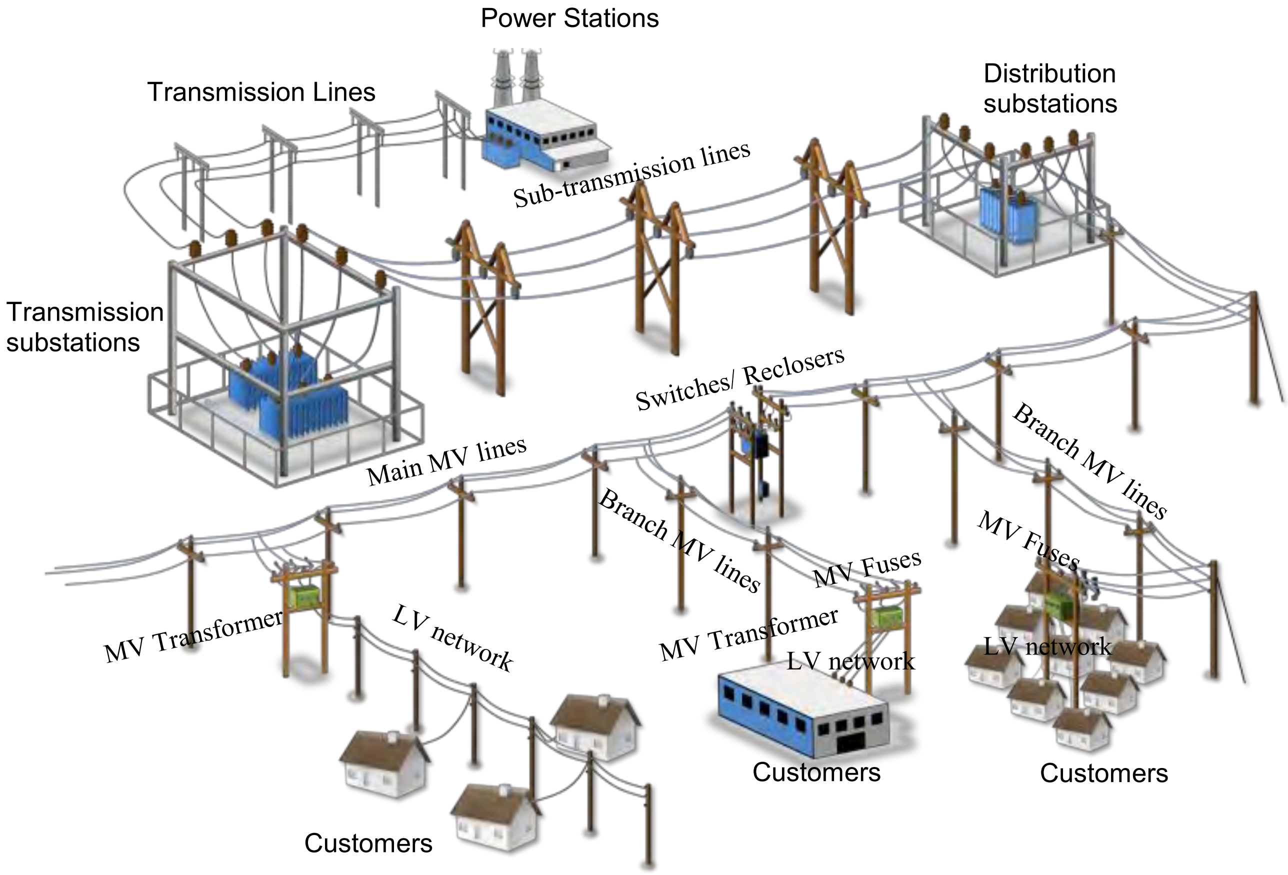


Figure 2.1: **Key Network Elements – Focusing on Medium Voltage Networks [15]**

2.1.1 Power Generation

The generator is a machine that converts mechanical energy into electric power. The main movers such as engines and turbines convert thermal or hydraulic energy into mechanical power. Thermal energy is derived from the fission of nuclear fuel or the burning of common fuels such as oil, gas, or coal. The alternating current generating units of electric power utilities generally consist of steam turbine generators, gas combustion turbine generators, hydro (water) generators, and internal-combustion engine generators [14].

2.1.2 Alternating Current Power Transmission System

The transmission system transfers power between the power generation station and the distribution station from which power is carried to the customer delivery point. It includes step-up and step-down transformers at the generating and distribution stations, respectively. Power transmission systems may include sub-transmission stages to supply intermediate voltage levels. Sub-transmission stages are used to enable a more practical or economical transition between transmission and distribution systems [14].

Transmission Lines

Transmission lines supply distribution substations equipped with transformers which step the high voltages down to lower levels e.g. 132 kV to 11 kV. The transmission of large quantities of power over long distances is more economical at higher voltages. Power transmission at high voltage can be accomplished with lower currents which lower the I^2R power losses and reduce the voltage drop. The consequent use of smaller conductors requires a lower investment. Standard power transmission systems are 3-phase, 3-conductor, overhead lines with or without a ground conductor. Transmission lines are classed as unregulated because the voltage at the generating station is controlled only to keep the lines operating within normal voltage limits and to facilitate power flow [15].

2.1.3 Primary Distribution Systems

The distribution system is commonly broken down into three components: distribution substation, distribution primary and secondary. The transmission system voltage is stepped down to lower levels by distribution substation transformers. The primary distribution system is that portion of the power network between the distribution substation and the utilisation transformers. The primary distribution system consists of circuits, referred to as primary or distribution feeders that originate at the secondary bus of the distribution substation. The distribution substation is usually the delivery point of electric power in large industrial or commercial applications. A typical South African primary distribution system voltage range can be anywhere from 132 kV down to 11 kV [15].

2.1.4 Distribution Substations

Distribution substations supply MV power to the distribution system. The substation contains one or more power transformers, voltage and current regulating equipment, bus bars and switchgear. A simple substation arrangement consists of one incoming line and one transformer. A more complicated substation arrangement results when there are two or more incoming lines, two or more power transformers, or a complex bus bar network [15].

2.1.5 Distribution Feeders

The most common equipment found on primary distribution feeders are fuses, distribution transformers, reclosers, load break switches, tri-switches and voltage regulators. Most common distribution feeder configurations include feeder splitting, loop, radial and parallel. These configurations may be implemented closer to the substation side or downstream depending on what constraints are present when designing the feeder to meet customers' needs and embedding the required level of reliability.

Tie Feeder

The main function of a tie feeder is to connect two sources. It may join two substation buses in parallel to provide service continuity for the load supplied from each bus.

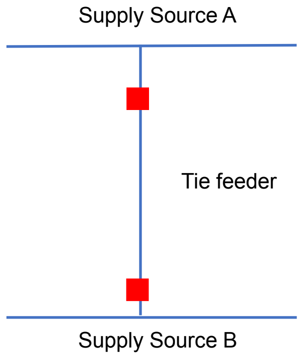


Figure 2.2: **Tie Feeder**

Loop Feeder

A loop feeder has its ends connected to a source (usually a single source), but its main function is to supply two or more load points in between. Each load point can be supplied from either direction; so it is possible to remove any section of the loop from service without causing an outage at other load points. The loop can be operated normally closed or normally open. Most loop systems are, however, operated normally open at some point by means of a switch. The operation is very similar to that of two radial feeders [15].

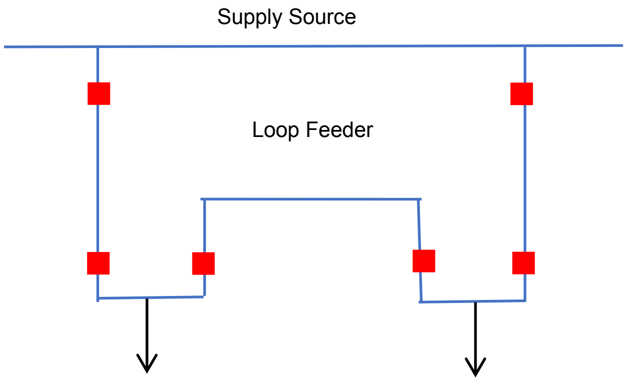


Figure 2.3: **Loop Feeder**

Radial Feeder

A radial feeder connects between a source and a load point, and it may supply one or more additional load points between the two. Each load point can be supplied from one direction only. Radial feeders are most widely used by Eskom because the circuits are simple, easy to protect, and low in cost [15].

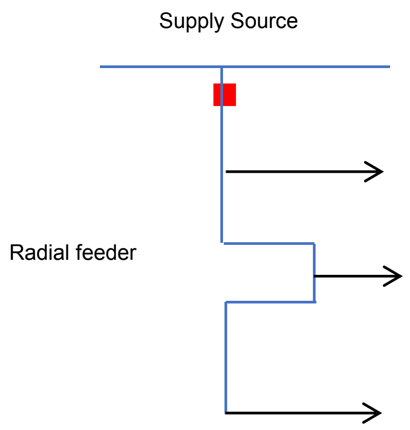


Figure 2.4: **Radial Feeder**

Parallel Feeder

Parallel feeders join the source and a load which provides the capability of supplying power to the load through one or any number of the parallel feeders. Parallel feeders provide for maintenance of feeders without interrupting service to loads and quick restoration of service when one of the feeders fails [15].

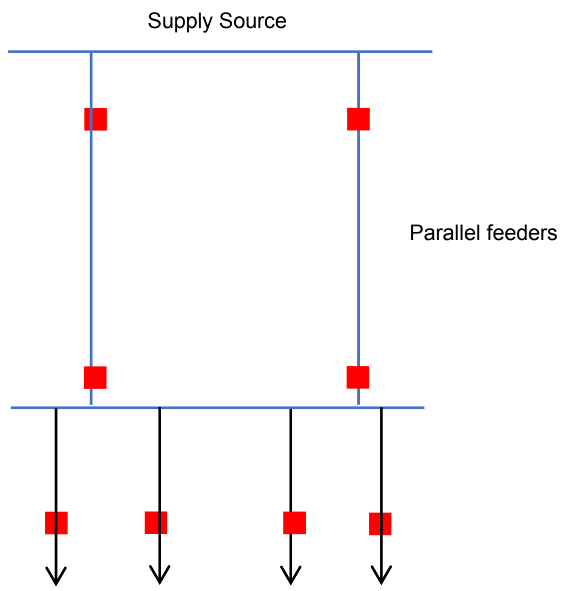


Figure 2.5: **Parallel Feeder**

2.1.6 Secondary Distribution Systems

The secondary distribution system is that section of the network between the primary feeders and utilisation equipment. The secondary system consists of step-down transformers and secondary circuits at utilisation voltage levels. Residential secondary systems are mainly single-phase, but commercial and industrial systems generally use three-phase power. The voltage levels for a particular secondary system are determined by the loads to be served. The utilisation voltages are generally in the range of 230 V to 400 V.

2.2. Power Quality, Reliability, and Availability

Power quality problem from a customer perspective might be defined as any electric supply condition that causes appliances to malfunction or stops their use. Power quality problem from a utility perspective might be perceived as nonfulfillment of various standards such as RMS voltage or harmonics. Power is equivalent to the instantaneous product of current and voltage, and formulating a meaningful definition of power quality is difficult. The best a utility can do is to supply customers with a perfect sinusoidal voltage source with constant frequency and amplitude [7]. Less than perfect power quality occurs when a voltage waveform is distorted by transients or harmonics, changes its amplitude, or deviates in frequency [7]. Customer interruptions are power quality concerns since they are a reduction in voltage magnitude to zero.

Reliability is primarily concerned with customer interruptions and is, therefore, a subsection of power quality [7]. Sustained interruptions have continuously been categorised as a reliability issue, but many utilities have categorised momentary interruptions as a power quality issue [7]. Momentary interruptions are an important customer issue and most distribution engineers consider them a reliability issue. Therefore, reliability is all aspects of customer interruptions, together with momentary interruptions.

Availability is defined as the proportion of time a voltage source is uninterrupted. Its complement, unavailability, is the fraction of time a voltage source is interrupted. Since availability and unavailability deal strictly with interruptions, they are classified as a subsection of reliability. The grading of power quality, reliability, and availability is shown in Figure 2.6 [7].

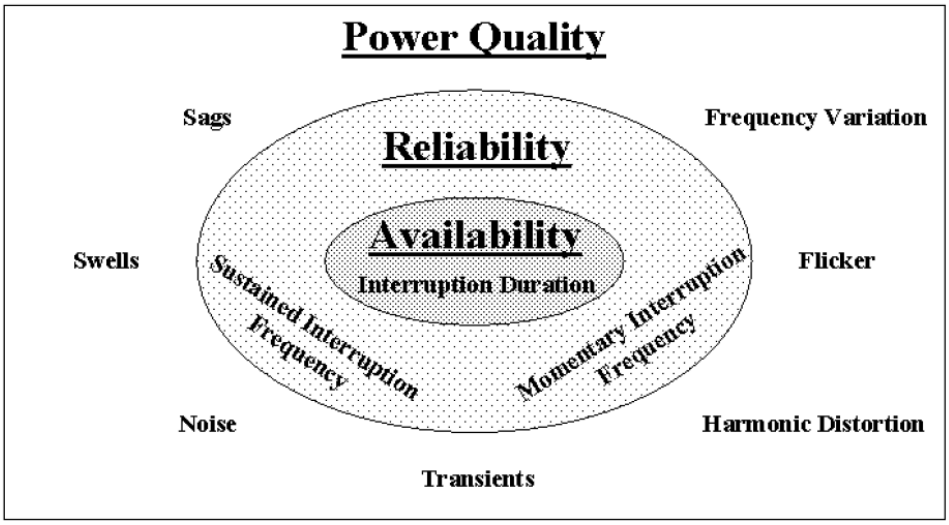


Figure 2.6**: Grading of Power Quality, Reliability, and Availability [7]**

2.3. Causes of Interruptions

The supply of power or electricity to the customers (loads) can be interrupted for many reasons. The factors are classified or arranged into different categories namely, equipment failure, natural events, theft and vandalism, operational failure, third party and unknown.

The different categories are discussed herewith [12]:

2.3.1 Equipment Failure

Equipment failure occurs when any component at the substation or on the feeder results in loss of supply. The equipment which failed will be located visually if the defect is obvious or by a process of elimination if the fault is not obvious like when a recloser trips on SEF or when an insulator has failed. The consequence of equipment failure depends on how far from the end of the feeder the equipment has failed, although this is not always a reliable proxy to determine how much revenue loss may be incurred since LPU's may be located at the end of a feeder. However in general if an equipment fails at or near substation location on a feeder resulting in loss of supply, many customers are affected and the revenue loss is usually substantial including the cost of restoration which includes paying personnel, repairing or replacing defective equipment. Other overheads include transportation of staff, equipment and tools. Power utilities may implement capital projects like reliability centred maintenance, preventative maintenance and condition monitoring systems strategies to reduce equipment failure rates to sustainable economic levels.

Equipment failure includes the following [12]:

- Failure of cable circuit (including any terminations to lines, joints, ferrules and lugs)
- Failure of overhead line (including associated equipment, but excluding transformers)
- Failure of a transformer (including tap-changers and voltage regulators, auxiliary, current, distribution, grounding, potential or voltage, power, rectifying, step-down/conversion, and voltage regulating transformers)
- Failure of reactive control devices (capacitors, reactors)
- Failure of switchgear
- Failure of terminal equipment and sundry substation plant (busbars, lightning arresters and instrument transformers, etc.)
- Protection system failure (fuse failure)
- Control system failure (SCADA)

2.3.2 Natural Events

Natural events can be classified as any act of nature outside the control of human beings which may disrupt power supply which includes adverse weather conditions, animals and vegetation becoming in contact with live apparatus.

2.3.3 Theft and Vandalism

Theft and vandalism of distribution system equipment is one of the factors that cause interruptions. Vandalism of power equipment is prevalent in South Africa, and incidents targeting power equipment have escalated in the recent past to unprecedented levels. Transformer oil, copper and aluminium are the main targets of the vandals. In the past problem of vandalism has been related to socio-economic conditions. However, this has now changed and vandalism is now largely driven by the soaring values of copper and aluminium in the international metals market due to increased world market demand fuelled by China and India's growth in industrialisation [17]. Unfortunately, it is impossible for utilities to protect all the components of the distribution system from human interference [17].

2.4. The Importance of Reliability in Distribution Systems

Distribution reliability primarily relates to equipment outages and customer interruptions. In normal operating conditions, all equipment (except standby) are energised and all customers are energised. Scheduled and unscheduled events disrupt normal operating conditions and can lead to outages and interruptions.

The objectives of evaluating, planning and improving reliability in distribution systems are therefore to:

- Maintain continuous supply of electricity to customers.
- Reduce the frequency and duration of interruptions.
- Minimise the severity of interruptions.
- Determine the causes of interruptions in order to take corrective action to reduce interruptions in view of its enormous cost to customers.
- Ensure compliance with standards.
- Analyse and improve system performance.

2.5. System Reliability Indices

The performance of the electricity distribution networks can be evaluated by several different indices. These indices are a measure of the reliability and availability of supply of the network and of the interruptions experienced by the customers. The performance reliability indices quantify the loss of supply in terms of the frequency, duration, the amount of installed plant (transformers) affected and the number of customers affected by the events occurring on the network.

The formulas and equations defined for each index are given below:

2.5.1 Sustained Interruption Indices (≥ 2 minutes window)

The following KPI all refer to sustained interruptions (≥ 2 minute window). The indices are all customer based (number of customers effected) KPIs and installed load based (KVA) [3].

SAIFI (System Average Interruption Frequency Index)

The SAIFI of a network indicates how often the average customer connected would experience a sustained interruption per annum excluding re-interruptions [3]. It can be mathematically expressed as [3]:

$$\text{SAIFI} = \frac{Total\ number\ of\ customer\ interruptions\ p.a}{Total\ number\ of\ customers\ served}$$

“SAIFI is a measure of how many sustained interruptions an average customer will experience annually. For a fixed number of customers, the only way to improve SAIFI is to decrease the number of sustained interruptions experienced by customers [7]”.

SAIDI (System Average Interruption Duration Index)

The SAIDI of a network indicates the duration of a sustained interruption the average customer would experience over the course of a year excluding re-interruptions. It is usually measured in customer minutes or customer hours of interruption [3]. Mathematically SAIDI can be expressed as [3]:

$$\text{SAIDI} = \frac{\sum customer\ interruption\ durations\ p.a.}{Total\ number\ of\ customers\ served}$$

For a fixed number of customers, SAIDI can be improved by decreasing the number of interruptions or by decreasing the duration of these interruptions. Since both of these reflect reliability improvements, a drop in SAIDI indicates an improvement in reliability [7].

CAIDI (Customer Average Interruption Duration Index)

The CAIDI of a network shows the average duration of a sustained interruption that only the customers affected would experience annually. This excludes re-interruptions. It is normally measured in customer minutes or customer hours of interruption [3]. This index differs from SAIDI in that only the number of affected customers interrupted is used in the denominator and not the total number of customers served. CAIDI is also the ratio of SAIDI and SAIFI and can be mathematically expressed as [3]:

$$\text{CAIDI} = \frac{\sum customer\ interruption\ durations\ p.a.}{Total\ number\ of\ customers\ interrupted}$$

or expressed as:

$$\text{CAIDI} = \frac{SAIDI}{SAIFI}$$

The general case is for CAIDI ≥ SAIDI, as CAIDI only takes into account the number of affected customers. CAIDI is also the index used to measure the average customer restoration times.

CAIDI is a measure of how long an average interruption lasts, and is used as a measure of utility response time to system contingencies. CAIDI can be improved by decreasing the length of interruptions, but can also be reduced by increasing the number of short interruptions. Consequently, a drop in CAIDI does not necessarily reflect an improvement in reliability [7].

CAIFI (Customer Average Interruption Frequency Index)

The CAIFI of a network indicates how often (frequency) on average only the customers affected by an interruption experience a sustained interruption per annum. The customer is counted only once in this calculation regardless of the number of times interrupted [3]. This index differs from SAIFI in that only the number of customers interrupted is used in the denominator and not all the customers connected. Mathematically CAIFI can be expressed as [3]:

$$\text{CAIFI} = \frac{Total\ number\ of\ customer\ interruptions\ p.a.}{Total\ number\ of\ customers\ interrupted}$$

Average System Interruption Frequency Index (ASIFI)

ASIFI is similar to SAIFI, but instead of a number of customers interrupted, the load affected is considered [7].

$$\text{ASIFI} = \frac{Load\ interrupted}{total\ load\ connected} = \frac{\sum \lambda i Li}{\sum Li}(int/kW)$$

where, Li is the load interrupted at load point i.

Average System Interruption Duration Index (ASIDI)

ASIDI is a measure of duration of the load interrupted rather than interruption duration experienced by the number of customers [7].

$$\text{ASIDI} = \frac{duration\ of\ Load\ interrupted}{total\ load\ connected} = \frac{\sum UiLi}{\sum Li}(hr/kW)$$

where, Li is the load interrupted at load point i.

Average Service Availability (Unavailability) Index ASAI (ASUI)

The ASAI represents the fraction of time (often expressed as a percentage) that a customer has received supply during one year. ASAI is a useful KPI for measuring the availability of customers with firm supplies [3]. Mathematically ASAI can be expressed as [3]:

$$\text{ASAI} = \frac{Customer\ hours\ service\ availability\ p.a}{Customer\ hours\ service\ demand\ p.a.}$$

Note: There are 8760 hours in a non-leap year and 8784 hours in a leap year.

Alternatively ASAI can be expressed as:

$$\text{ASAI} = 1 - \frac{\text{SAIDI}}{8760}$$

$$\text{ASUI} = 1 - \text{ASAI}$$

Energy not supplied index, ENS [7]

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

where $L_{a(i)}$ is the average load connected to load point i and U_i is the annual outage time [7]

DSLI (Distribution Supply Loss Index)

The DSLI of a network is the measure of the HV supply unavailability (HV/MV transformers and bulk loads) caused by sustained interruptions [3]. DSLI is expressed as minutes per month (also expressed in hours per month). The index offers a KPI to measure network performance due to distribution interruptions only (HV supply) [3]. Mathematically DSLI can be expressed as [3]:

$$\text{DSLI} = \frac{\sum MVA.Hours.lost(\text{"O"}+\text{"E"}+\text{"F"})\ per\ month}{Installed\ HV\ Transformer\ MVA\ base + Bulk\ load\ MVA\ base}$$

Where

"O" – Notified Outage
"E" – Unplanned Emergency Outage
"F" – Unplanned Fault

RSLI (MV Supply Loss Index)

RSLI is the measure of the MV supply unavailability (MV/LV transformers and bulk loads) caused by sustained interruptions [3]. RSLI is expressed as hours per month [3]. Mathematically RSLI can be expressed as [3]:

$$\text{RSLI} = \frac{\sum MVA.Hours.lost(\text{"O"}+\text{"E"}+\text{"F"})\ per\ month}{Installed\ MV\ MVA\ base + Bulk\ load\ MVA\ base}$$

Where

"O" – Notified Outage
"E" – Unplanned Emergency Outage
"F" – Unplanned Fault

Faults/100km (Sum of sustained interruptions per 100km)

The Faults/100km of a network shows the average number of sustained interruptions experienced normalised per 100km of line length per annum. It is usually measured as a number of faults. Mathematically Faults/100km can be expressed as [3]:

$$\text{Faults/100km} = \frac{\sum Total\ number\ of\ sustained\ interruptions\ p.a.\ \text{x}\ 100}{Total\ line\ length\ (km)}$$

2.5.2 Momentary Indices (< 2 minutes)

The following KPI refer to momentary interruptions (< 2 minutes) on all networks where the supply voltage is ≥ 1 kV. The indices are a measure of the transient interruption performance of a network.

MAIFI (Momentary Average Interruption Frequency Index)

The MAIFI of a network shows how often on (frequency) average the customers served would experience a momentary interruption per annum. Mathematically MAIFI can be expressed as [3]:

$$\text{MAIFI} = \frac{Total\ number\ of\ customer\ momentary\ \ interruptions\ p.a.}{Total\ number\ of\ customers\ served}$$

MAIFI is attractive to utilities because it can be easily calculated from breaker and recloser counters [7].

2.6. Load Point Reliability Indices

2.6.1 The three basic load point reliability indices (failure rate (*λ*), outage time (*r*) and annual unavailability (*U*))

Failure Rates, *λ*

Distribution feeders are radial systems consisting of a set of series components. A feeder includes lines, cables, interruption devices, fuses, reclosers, etc. Each component of the series system has its failure rate *λ,* which is defined as [11]:

$$\lambda = \frac{Number\ of\ failures\ per\ unit\ time}{Number\ of\ components\ exposed\ to\ failure}$$

For distribution feeders, this failure rate *λ* is directly related to the constructive aspects and the physical environment where the component is placed. This means that for improving the failure rate *(λ)* it is necessary to use more reliable components (lower *λ)* or modify the physical environment where the feeder is found, which is the equivalent to changing the line.

There is a design (acceptable) number of faults that one can expect on a network. It depends on the following [29]:

- The count of components (line length, structure count, transformer count etc.)
- Acceptable failure rate per component for that specific network
    - Environment (condition)
    - Equipment specification, quality (manufacture) and application
    - Quality of construction
    - Quality of maintenance

Failure rate changes throughout the life of a component as shown below.

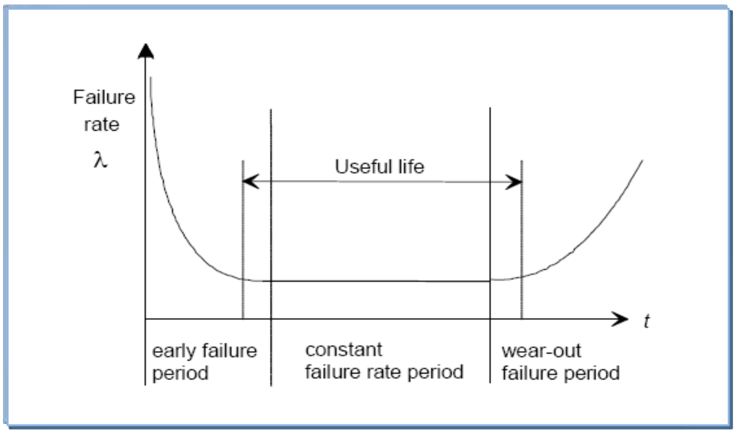


Figure 2.7**: The Bathtub Curve [29]**

Component failures can be characterised as teething failures, random failures or ageing failures relating to the well-known bathtub curve. Teething failures are normally found by onsite test and handled when the components are first connected to the system [29]. Random failures are caused by external factors such as weather conditions or excavator work. The random failure rate is constant over time. The operational age of the component has an obvious influence on the component reliability. Ageing failures are caused by electrical, thermal, mechanical, environmental stress and manufacturing. The ageing failure rate increases over time [29]. We are interested in the failure rate over the useful life i.e. failure rate is constant.

Mean Repair Time (*r*)

Another important index of distribution system reliability is the Mean Repair Time (*r*) of a component. This index is directly related to the duration of supply interruptions and, therefore, to how the distribution firm is to face failures in the network. This means that, in order to decrease the duration of an interruption, it is necessary to be better prepared for restoring such interruptions.

Unavailability

The final and also important index of distribution system reliability is unavailability. Availability is the probability of something being energised. It is the most basic aspect of reliability and is typically measured in percent or per-unit. The complement of availability is unavailability [7].

Availability — the probability of being energised.
Unavailability — the probability of not being energised [7]

2.7. Analysis of Reliability

2.7.1 Using Load Point Reliability Indices

The analytical approach calculates the average reliability indices using a set of mathematical equations hence the procedure is relatively simple and requires a reasonably small amount of computer time. The analytical approach is based on assumptions relating to the statistical distributions of failure rates and repair times [38]. The most well-known evaluation techniques, using a set of approximate equations, are failure mode analysis or minimum cut set analysis. The main focus on the analytical methods is on the index calculations.

The analytical method looks at how the load points would be affected if a specific component fails. The average values of the three fundamental load point indices for load point *i* can be calculated from the load point up-down operating history using the following formulae [26]:

$$\lambda s = \sum \lambda i \quad (2.1)$$

$$r_s = \frac{Us}{\lambda s} = \frac{\sum \lambda i \ ri}{\sum \lambda i} \quad (2.2)$$

$$Us = \sum \lambda i r i \quad (2.3)$$

Reliability indices such as SAIFI and SAIDI can be calculated using equations given below [37]. These indices relate to either frequency or duration of the service interruption and provide a relative measure for a group of load points or for the entire distribution system.

$$SAIFI = \frac{\sum \lambda iNi}{\sum Ni} \tag{2.4}$$

$$SAIDI = \frac{\sum UiNi}{\sum Ni} \tag{2.5}$$

$$\text{CAIDI} = \frac{SAIDI}{SAIFI} = \frac{\sum UiNi}{\sum \lambda iNi} \tag{2.6}$$

Where λi is the failure rate, Ui is the unavailability and Ni are the number of customers at load points i.

2.7.2 Failure Mode Effect Analysis (FMEA)

An FMEA is often the first step of a distribution system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. For each electrical component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. This method is one of the simplest approaches for estimating reliability. It is based on failure mode of components in a distribution system affected by a loss of power supply due to a specified load. FMEA classifies the single component failure state that occurs independently and is repaired before another occurs. It can be used in other techniques such as cut set and fault tree analysis to evaluate the failure behaviour of the components. The failure states can be tabulated in terms of the number of components affected and duration of the event [46].
The disadvantage of FMEA is that it is difficult to examine multiple failures, although it has an advantage of providing a full detailed description of the system failure behaviour, while evaluating the consequence of failure modes of all the components [46].

Chapter 3: Electricity Quality Regulation

3.1. Introduction

The utilities are responsible for the local distribution of electricity to homes and businesses, transporting electricity along overhead power lines and through underground cables. They have a responsibility to ensure that their customers have a reliable supply of electricity and must restore customer's electricity supply promptly in the event of an interruption, hence fulfilling the Electricity Regulation Act is essential.

The objects of this Electricity Quality Regulation Act are to [63]:

(a) achieve the efficient, effective, sustainable and orderly development and operation of electricity supply infrastructure in South Africa;

(b) ensure that the interests and needs of present and future electricity customers and end users are safeguarded and met, having regard to the governance, efficiency, effectiveness and long-term sustainability of the electricity supply industry within the broader context of economic energy regulation;

(c) facilitate investment in the electricity supply industry;

(d) facilitate universal access to electricity;

(e) promote the use of diverse energy sources and energy efficiency;

(f) promote competitiveness and customer and end user choice; and

(g) facilitate a fair balance between the interests of customers and end users, licensees, investors in the electricity supply industry and the public [63].

3.2. Utility Cost

In evaluating the benefit to cost ratio for any investment in automation, the utility computes its margin based on standard cost accounting practices for operating costs (burdened man-hour rates, maintenance costs, energy cost, etc.) and capital costs, all on a yearly basis. The cost of energy can vary from an average purchase price to the utility or as an opportunity cost of the selling price to the end user in the situation where the distribution entity still retains the supply business. The cost of losses is a direct cost, being a combination of the energy cost with a capacity investment component necessary to cover the network capacity to accommodate the losses. It is usual for most utilities to have set an energy value policy as part of their cost of service pricing for delivering the energy. In reality, the economic value of energy not delivered, by itself, using this type of evaluation is seldom sufficient to justify any network performance improvement measures in contrast to a penalty based environment [5].
In several countries where deregulation has been implemented as well as in South Africa, the regulator is designing incentives in the form of penalties, and in some cases rewards, to directly encourage utilities to improve their performance. These are output focused, and any performance improvement project can be compared with a specific economic penalty value. Under a penalty regime, the benefit to cost calculation is dominated by the resulting value of energy not supplied because the regulator tends to set the value closer to the customer's cost for loss of supply than that of the utilities. The major standards relate to interruptions to supply without notice and are typically either a number of interruption based or interruption duration based, or possible combinations of the two [5].

Today many regulatory bodies are using reliability indices in order to give electricity distribution companies the economic signs to improve reliability. The sign is given in the form of an economic penalty or compensation that must be paid to the affected customers. To avoid being given a penalty or paying compensation, distribution companies must improve the reliability by investing the optimal amount of money so that they can maximise their profits.

The basic function of a power distribution system is to provide electric power to its customers at the lowest cost with an acceptable level of reliability [5].

3.3. Promoting Continuity of Supply

Most regulators have taken a step to introduce methodologies that will motivate companies to increase the reliability of the network and maintain continuity of supply. There are four basic instruments that the regulator might use to ensure secure and desirable levels of quality of supply, service rendered and promote continuity of supply. Figure 3.1 below shows four basic instruments used towards insuring desirable levels and promoting performance.

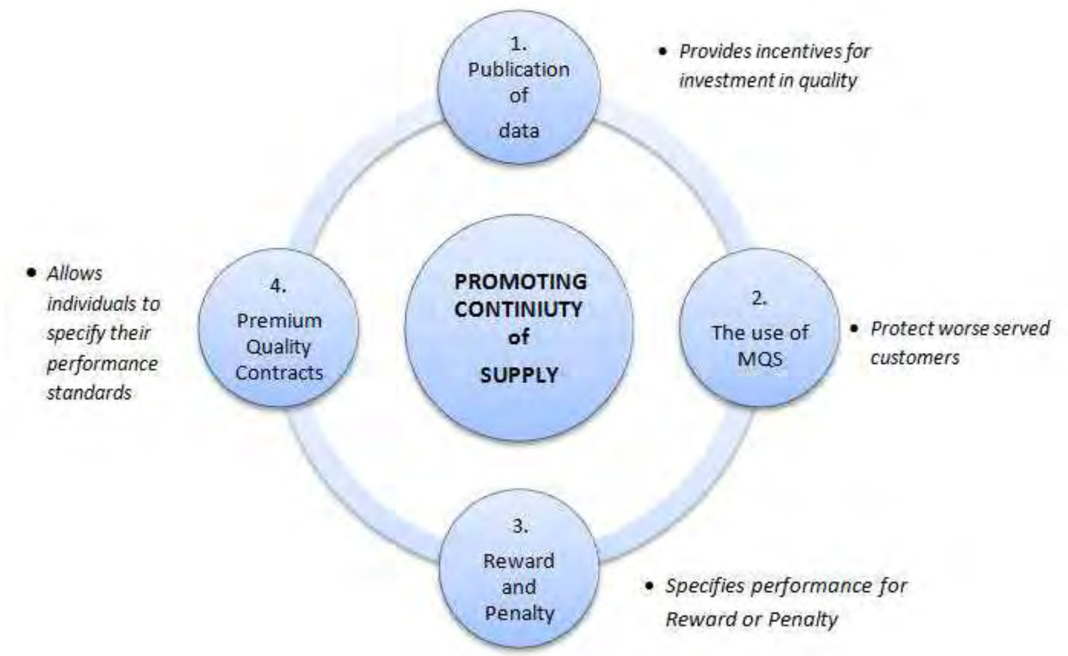


Figure 3.1: **Instruments for Promoting Quality Regulations [53]**

The instruments and incentives used by regulators to maintain and promote high levels of quality of supply, to increase reliability and hence maintain good standard of continuity of supply are as follow:

- Publication of company's performance data - provides incentives for investment in quality.

- Setting Minimum Quality Standards (MQS) - The MQS that are placed are the minimum level of performance which the company is not supposed to operate below, non-compliance with the MQS could lead to penalties. This may include KPI's and compliance with stipulations outlined in documents like NRS048-2:2007.The motivation behind MQS is to protect customers from a poor quality of supply. Therefore, companies which do not comply with set MQS are penalised.

- Reward and Penalty Schemes - This involves rewarding companies for exceeding MQS and KPI and penalising them for the converse scenario.

- Premium Quality Contracts - This entails the customer negotiating their performance standards with the power utility to provide a unique quality of supply and reliability levels usually at higher tariff to this individual customer.

Overall these incentives provide adequate push and pull levers to coerce the power utility to provide good quality of supply and reliability levels to customers. This section of the dissertation only focuses on MQS and the reward and penalty scheme as they motivate the company to focus on improving reliability and, on the other hand, protecting customers which receive poor quality. Even though the reward and penalty schemes are considered complex to design, they have delivered positive results on the regulated quality indicators [49].

3.4. Continuity Standards

In the promotion of continuity of supply, the regulators need to make sure that all the customers are supplied at minimally acceptable levels. Using MQS, they specify the minimal level of performance which the utility is not supposed to breach. Non-compliance with those minimal standards can lead to penalties in the form of payment. Figure 3.2 below shows penalty which can be incurred when MQS are breached in the incentive plot used by different countries.

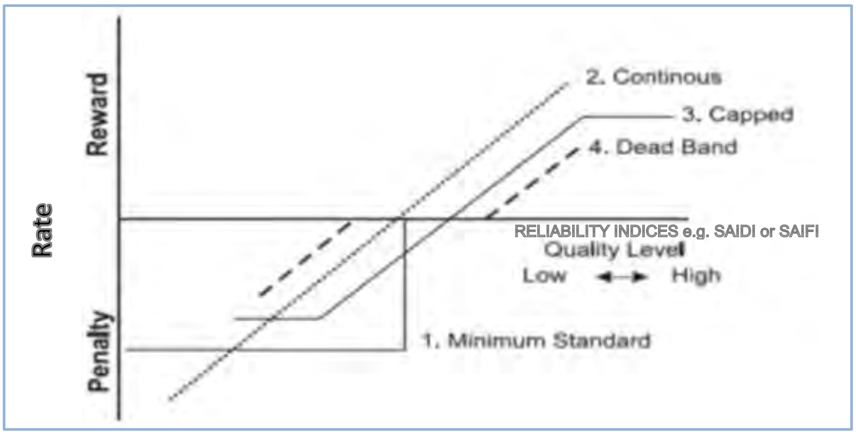


Figure 3.2: **Reward and Penalty Plot for Incentive Scheme [2]**

There are often different types of regulated indicators which are used to set minimum continuity standards, the indicators setting standards of continuity which are reported from [2] are:

- Annual number of long unplanned interruptions
- Annual number interruptions (short and long)
- Duration of a single long unplanned interruption
- Cumulative annual duration of long unplanned interruptions

In the setting of penalties for deviations from standards of continuity, there are exemptions which regulators might apply for certain exceptional events. The exceptional events mostly include interruption resulting from *force majeure* (a disaster from an act of God), this is from the fact that those acts are beyond the company’s control. The charges increase as a function of distance from the place of minimal standards.

3.5. Reward and Penalty Scheme

Reward and penalty scheme is the incentive scheme which regulates the revenue of utilities in accordance to its reliability performance. Better performance leading to reward and poor performance leading to a penalty. When designing the reward and penalty scheme there are a number of factors that the regulator has to consider including types of interruption that the scheme will be based on. Either planned or unplanned interruptions can be considered, unplanned and planned interruptions are given different weights of charges [50] and also the performance index to be used.

Other characteristics that are considered in the design of incentive/penalty schemes include baseline standards, a form of financial incentive and consideration of the effectiveness of the scheme. In the design of incentive/penalty scheme, the regulator should always keep in mind that the utilities will deliver the level of quality depending on the choices made by the regulators of the level of financial incentive and performance standards [49].

Indicators that are regulated in Incentive Scheme

Incentive schemes focus on indicators derived from the recording of long interruptions events; this is due to the fact that long interruptions determine to a major extent the level of customer satisfaction with the quality of services. The indicators that are used in different countries around the world that apply to incentive scheme include:

- SAIDI
- SAIFI
- ENS

Performance is usually based on average customer interruption measures such as SAIDI and SAIFI. A common method of implementing a Performance Based Rate (PBR) is to have a “dead zone” without bonuses or penalties. If reliability is worse than the upper dead zone threshold, a penalty is assessed. Penalties rise as the performance gets worse and are capped when a maximum penalty is reached. Rewards for good reliability can be applied in a similar manner. If reliability is better than the lower dead zone threshold, a bonus is given. The bonus grows as reliability improves and is capped at a maximum value. Bonuses are far less common than penalties since regulatory agencies do not have sources of revenue. A graph of a PBR based on SAIDI is shown in Figure 3.3. Regulatory agencies can simulate bonuses and rewards by yearly adjusting rates based on reliability performance. Rates are improved if reliability targets are exceeded and are reduced if reliability targets are not met. The optimal solution occurs when the marginal cost of increasing reliability is equal to the marginal increase in performance penalties [7].

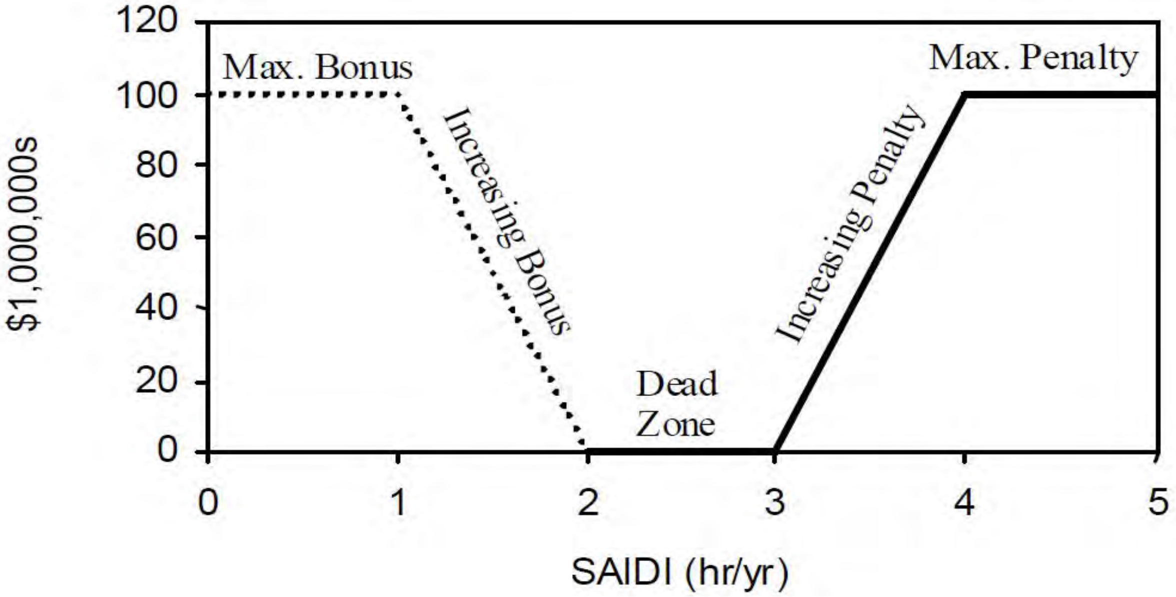


Figure 3.3: **A Typical Performance-Based Rate Structure [7]**

An example of a Swedish plot is shown below in Figure 3.4 how the compensation (reduction of tariffs) to customers increases annually as a function of interruptions length. As the hours of interruptions rises, the compensation towards the customers also rises, meaning the company is being penalised more when interruption length increases.

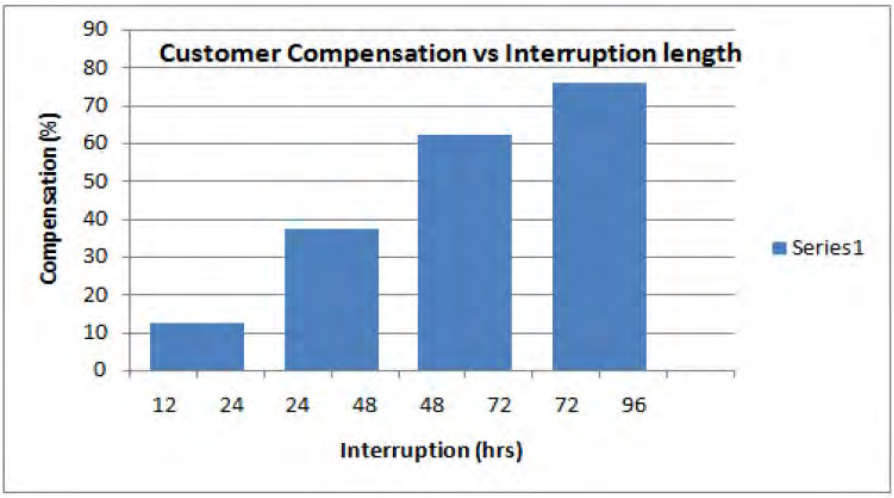


Figure 3.4: **Sweden Customer Compensation versus Performance Standards (Data from [14])**

Chapter 4: MV Overhead Feeder Automation

4.1. Introduction

"Distribution Automation Systems have been defined by the Institute of Electrical and Electronic Engineers (IEEE) as systems that enable an electric utility to monitor, coordinate, and operate distribution components in a real time mode from remote locations [18]. An electric power distribution system is an important part of electrical power systems in the delivery of electricity to consumers. Automation in the distribution field allows utilities to implement flexible control of distribution systems, which can be used to enhance efficiency, reliability, and quality of electric service [18]".

The word Automation means doing the specific task automatically in a sequence with faster operation rate. Application of automation within power distribution system entails automatically monitoring and switching apparatus to restore continuity of supply or isolate faulty part of a network with the distinct objective of keeping as many customers connected as possible without delay in real time. This automation allows network loading to be monitored in real time and implement predefined contingency switching plans based on current fault locations and feeder loadings. This process may not entirely provide fully automated process but depends on how many contingency switching levels has been pre-programmed in its automation functionality. Therefore, it simply reduces outage time for distribution systems by isolating fault locations and restoring power supply to customers where an alternative power source is available. Operators and responsible persons still have to drive out and fix or replace faulty apparatus when needed. Hence, automation does not just replace manual procedures; it permits the power system to operate in the best optimal way, based on accurate information provided in a timely manner to the decision-making applications and devices [5].

Distribution automation has to address enhancements in efficiency as well as reliability and quality of power distribution. Utilities are motivated to invest in Distribution automation systems which will enhance their efficiency, reliability of supply and quality of supply to prevent incurring penalties and maximising profits by exceeding MQS targets. This also encourages the customer to negotiate premium quality contracts with the power utility, hence improving and strengthening extra revenue streams for the utility [5].

4.2. Benefits of Distribution Automation System Implementation

The benefits of distribution automation system implementation can be classified in three major areas as follows:

4.2.1 Operational & Maintenance Benefits [5]

- Improved reliability by reducing outage duration using auto restoration scheme.
- Improved voltage control by means of automatic VAR control.
- Reduced man hours and man power.
- Accurate and useful planning and operational data information.
- Better fault detection and diagnostic analysis.
- Better management of system and component loading.

4.2.2 Financial Benefits

- Increased revenue due to quick restoration.
- Improved utilisation of system capacity.
- Customer retention for improved quality of supply.

4.2.3 Customer Related Benefits

- Better service reliability.
- Reduce interruption cost for Industrial and Commercial customers.
- Better quality of supply.

4.3. Distribution Automation Technologies - An enabling technology for the smart grid

4.3.1 Automatic Reclosers

The majority of faults on a distribution network can be considered temporary in nature meaning that they do not re-occur if the power is returned to the network soon after a trip. Automatic reclosing devices are therefore specifically designed to trip and clear transient fault conditions. Automatic reclosers are hydraulically or electrically operated devices that can sense over-current (O/C), earth-fault (E/F) or sensitive earth-fault (SE/F) conditions. Under these conditions the recloser will, subject to pre-determined settings, trip and after a time delay reclose automatically. If the fault is not cleared the recloser will go through a fixed sequence of a trip and reclose cycles after which it will lockout. When the recloser is in the lockout mode the faulted section will be isolated from the supply and human involvement is required to close the recloser. Most reclosers have 4 trips to lockout, typically set to 2 fast, 2 delays or 1 fast, 2 delays [6].

Pole/Pad-Mounted Recloser

The influence of the pole/pad-mounted recloser (circuit recloser) is comparable to the circuit breaker located at the primary substation. It detects and separates the faulted lines that are located after the recloser. The operation of the recloser is similar to that of a circuit breaker when the fault is momentary. This protects the customers before the recloser against the faults occurring after the recloser. However, a circuit recloser provides a good means to improve the reliability of the feeder. See Figures 4.1 and 4.2 below for a typical recloser structure.

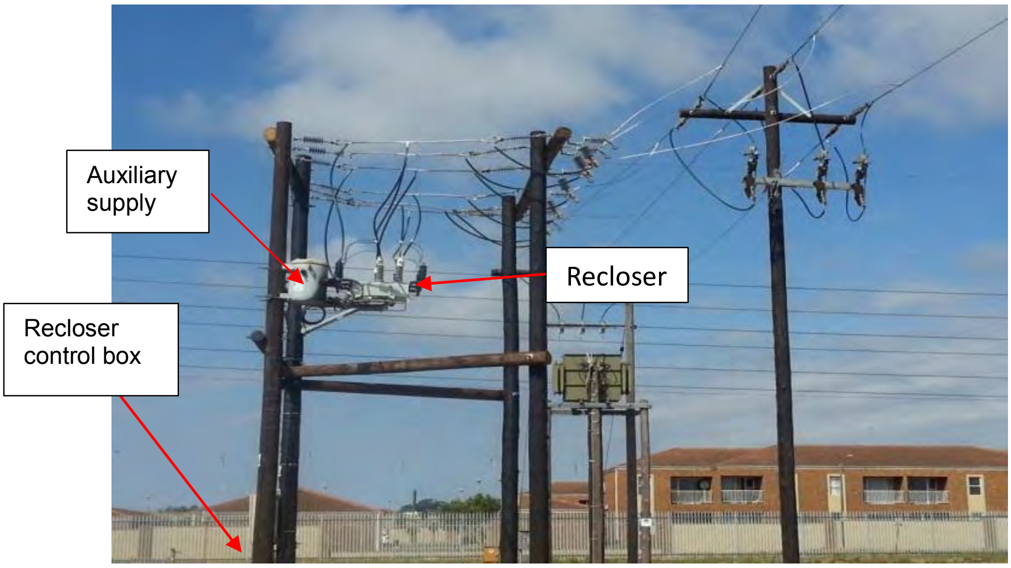


Figure 4.1: **Typical Recloser Structure used on the Utility Network**

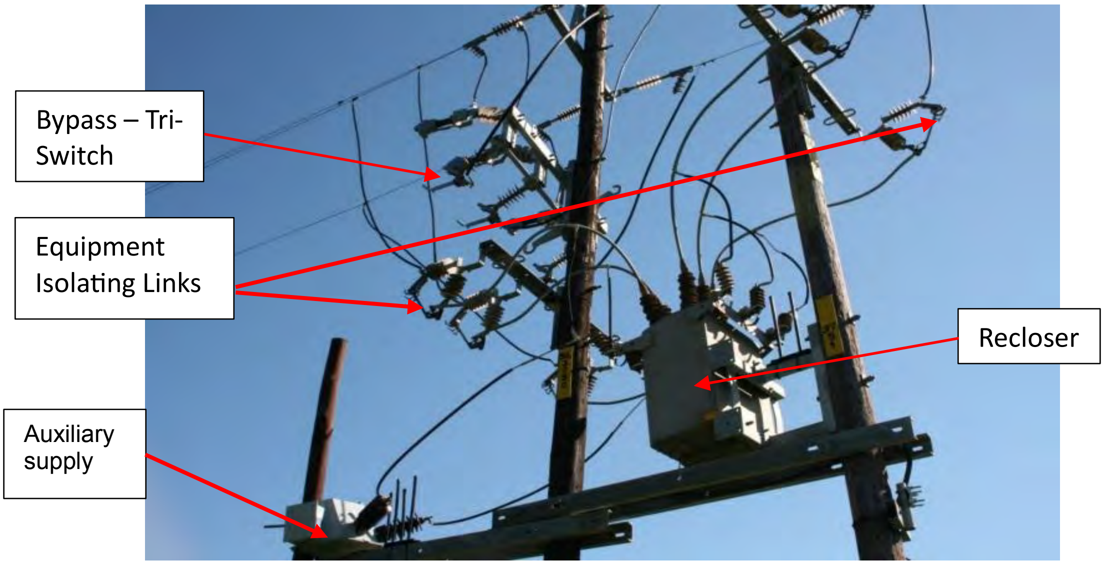


Figure 4.2: **Components of a MV Recloser Structure**

4.3.2 Automatic Sectionalising Devices

Sectionalisers are hydraulically or electronically operated devices that are used in conjunction with an upstream recloser to isolate a fault. These devices do not have fault breaking capability and rely on the upstream recloser to detect and open for a downstream fault. The device isolates the faulted section before the recloser finishes a sequence of automatic reclosing cycles (ARCs) and locks out. Sectionalisers can be current operated, voltage operated or a combination of both [6].
Sectionalisers simplify the job of restoring service after a fault has been removed since they do not require replaceable elements such as fuse links and they may be reclosed with a simple hook stick.

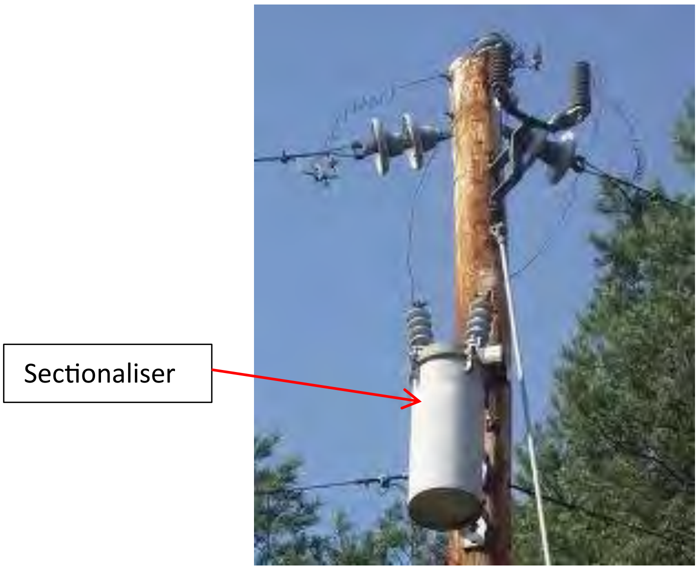


Figure 4.3: **Single or Three Phase Electronic Sectionaliser**

4.3.3 Fuses

The Expulsion fuses, installed in a fuse cut-out base, are used extensively in many utilities throughout the world. These fuses provide a fairly low cost, yet effective, method for clearing fault current. Expulsion fuses are defined by their type and rating. The type i.e. K, T or D defines the gradient of the fuse on the current (I) versus time (T) curve. (A table showing Standard Fuse ratings can be found in Appendix A) This curve is commonly referred to as the Time Current Characteristic (TCC) of the fuse. The rating of a fuse refers to the continuous load current that the fuse can carry safely. It is, in other words, the highest current that can flow through the fuse, for an unlimited period, without damaging or melting the fuse. There is, however, a 'safety factor' of 2.25 included in the fuse rating because the fuse will in fact only start to melt at 2.25 times its rating [6].
A fuse should however not be selected purely on its current rating, the TCC of the fuse must be used to ensure proper coordination with up and down stream protection devices. Two TCC's are defined for each fuse rating:

- Minimum Melting TCC - The time at which the fuse will start to melt for a certain current [6].
- Total Clearing TCC - The total time that it will take before the fuse clears a certain current [6].

(Graphs showing the Time Current Characteristics (TCC) can be found in the Appendix B and Appendix C)

Some utilities standardise on a range of only seven different expulsion fuses in order to rationalise stock holdings and simplify application. Only the standard ranges of fuses will be considered acceptable for use on distribution networks (see Appendix A for details).

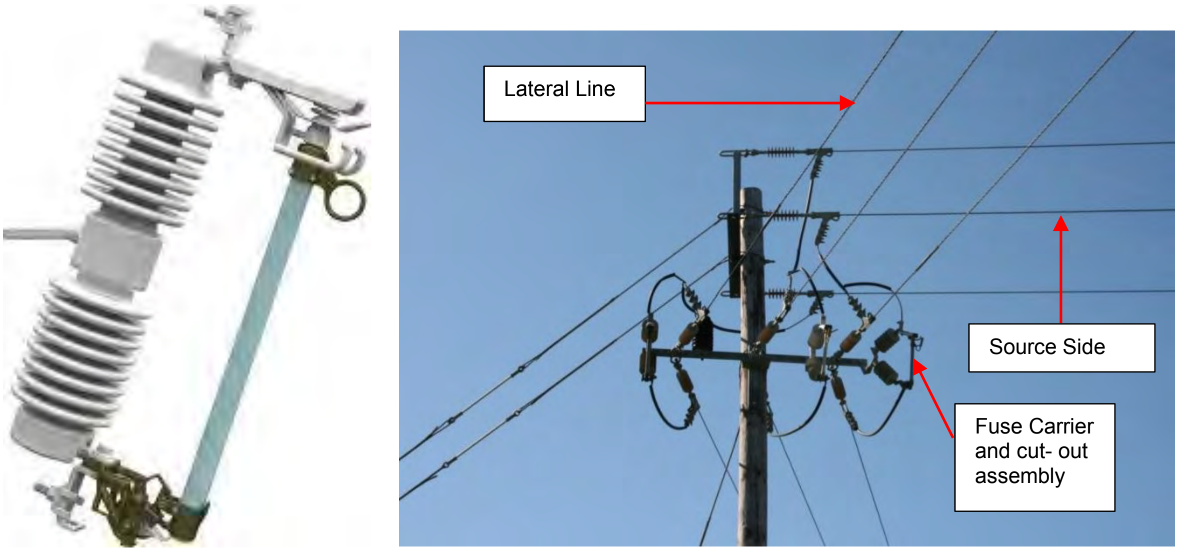


Figure 4.4: **A Traditional MV Drop-Out Fuse and Fuse Holder**

Most rural medium voltage networks are configured with the primary feeder protected by a circuit breaker or recloser, whilst a fuse protects the lateral line as shown in Figure 4.4 above.

When a fault occurs on the lateral line the fuse operates to clear the fault. When the fuse protection is graded correctly with the upstream recloser, the recloser will never need to operate on a lateral line fault. This means only the customers on the faulted lateral line experience an outage. The problem with this configuration is that the fuse blows on all faults, both permanent and transient, causing downstream customers to always experience a sustained outage and always requiring a line crew to replace the fuse incurring significant operating costs for the network owner. In most cases, this sustained outage is unnecessary as the fault is transient.

A fuse that has blown will drop down and provide a visual indication to passing line crews as to the faulted line. When in the dropped down position the fuse provides a genuine electrical isolation due to the large air gap. Whilst fuses possess a low capital cost, up to 80% of fuses blow unnecessarily [22]. Although fuses are quick and easy to install on site, a line man or crew, in an average rural environment may take hours to travel, patrol the line for potential fault, search for and repair the blown fuse, costing the utility lots of money for a single fuse operation [22].

A fuse has no electronics or intelligence and, therefore, no capability to record historical data about fault events or reliability data. Without communication functionality, it cannot communicate device status remotely. It makes no contribution to the formation of an intelligent grid.

When applying fuses to a network, it is imperative that the following points are considered:

a) A fuse is not placed in the network to protect the device connected downstream from it, e.g. distribution transformer. It rather protects the rest of the network against the effects caused by the failure of that device, i.e. it disconnects the failed unit from the healthy network [6].

b) Fuses are susceptible to transient damage, e.g. lightning current. The risk of lateral line fuse operations increases the lower the fuse rating. Fuses rated at 15 amperes and higher are generally considered to be transient insensitive [6].

c) Fuses cannot operate fast enough to clear lightning surges, travelling at roughly half the speed of light [6].

d) Application of fuses is prone to human error (incorrect rating replacement etc.).

e) Fuses tend to degrade with time.

f) Fuses introduce a 'weak link' on the system which can blow from inrush current, etc. if not applied correctly.

g) Fuses do not protect equipment from low value overload conditions, they only operate for fault conditions [6].

h) Low fault levels are not conducive to the use of fuses. Coordination problems between fuses and SE/F and E/F settings are experienced, especially with larger rated fuses [6].

i) High fuse ratings (20 K to 50 K) on 'weak' systems (end of line fault level < 200 A) cause dips [6].

4.3.4 Fault Path Indicators

A Fault Path Indicator (FPI) is a device that provides a visible indication that fault current passed through the location at which the FPI is installed. It is thus a very useful fault finding device. FPIs installed on distribution networks are usually pole mounted at between 1.8 m and 2 m below the lowest conductor or phase segregated units installed on the conductor [41].

Figure 4.5: **Line Tracker Conductor Mounted Sensor - Fault Path Indicator (FPI)**

The FPIs should be installed:

a) On rogue feeders (performance related)
b) Important sectionalising points
c) Major lateral take offs
d) On solid networks

4.3.5 IntelliRupter PulseCloser

IntelliRupter PulseCloser is a breakthrough in overhead distribution system protection. The IntelliRupter features ground breaking PulseClosing technology with a unique means for verifying that the line is clear of faults before initiating a close operation. Pulseclosing is superior to conventional reclosing. After a conventional recloser or relayed circuit breaker opens to interrupt a fault, it typically recloses into the fault several times to determine if the fault is still present. Pulseclosing, on the other hand, tests fault persistence without causing feeder stress due to high current surges. The Pulsecloser very quickly closes and re-opens its contacts at an exact point on the waveform to send a very short low current pulse down the line, then analyses the pulse to determine the course of action. If the pulse indicates a persistent fault, the Pulsecloser will keep the contacts open, wait for a user configurable interval, and pulse again. This process can repeat several times until the Pulsecloser determines that the line is no longer faulted; it then closes to restore service. If the fault persists for the duration of the test sequence, however, the Pulsecloser will lock out [9].

The IntelliRupter PulseCloser greatly reduces stress on system components, as well as voltage sags experienced by customers upstream of the fault. It provides full live switching performance under all ice conditions; circuit making, circuit breaking, and Pulseclosing are accomplished within the interrupters. The component's life is extended, eliminating costly replacement. Pulseclosing dramatically reduces through faults which are a leading cause of premature aging of substation transformers and power quality is improved since Pulseclosing doesn't disturb source side customers with irritating voltage sags and blinks [8]. Its rapid self-healing feature accomplishes restoration in seconds and minimises the number of customers experiencing an extended power interruption, tremendously improving the System Average Interruption Duration Index.

Features and Uses of PulseClosing

Conventional reclosers trip to clear an initial fault, but then reclose several times to determine if the fault has disappeared or if it still remains. If the fault was only temporary, then one of the reclosing attempts will hold closed, and service is restored to the line. If the fault still exists at the end of the reclosing sequence, the recloser locks out, indicating that there is a permanent fault on the line that needs to be removed by a line crew. The problem with conventional reclosing is that each reclose attempt re-establishes full magnitude fault current until a tripping condition is reached according to the Time Current Characteristic (TCC) curve that has been configured for each operation. Depending on the fault current magnitude and the selected TCC curve, the fault current may flow for anywhere from many cycles to a few seconds. Each conventional reclose attempt reignites arcing at the fault location, potentially causing more damage to power system equipment and nearby surroundings. The bus voltage sags, affecting customers on the faulted feeder and possibly those on nearby feeders as well [8].

Fault currents create thermal and mechanical stress on all distribution system equipment that carry the fault current, so removing the fault as quickly as possible is critical. Nothing is more sensitive to through faults than the substation transformer. Each surge of fault current reduces the life of the transformer, so a method of reducing the size and quantity of these surges can result in an economic benefit in terms of asset life extension [9].

PulseCloser Features [8]

Utilities have standardised on the IntelliRupter with Pulseclosing technology as the fault interrupting device on 11 kV systems. One reason is that it includes many standard items that simplify installation:

• Completely integrated construction - installation is accomplished with a single lift.

• Integrated control and communications modules protect the electronics from vandalism, severe weather and electrical surges. WiFi connectivity from work vehicles enhances worker safety and comfort.

• Three built-in Rogowski coil current sensors and six voltage sensors eliminate the clutter and complexity of adding separate high accuracy sensors in the field.

Another factor in selecting the IntelliRupter as the standard equipment is that a single device can be used for many different types of applications. Additional features can be enabled as needed for the application:

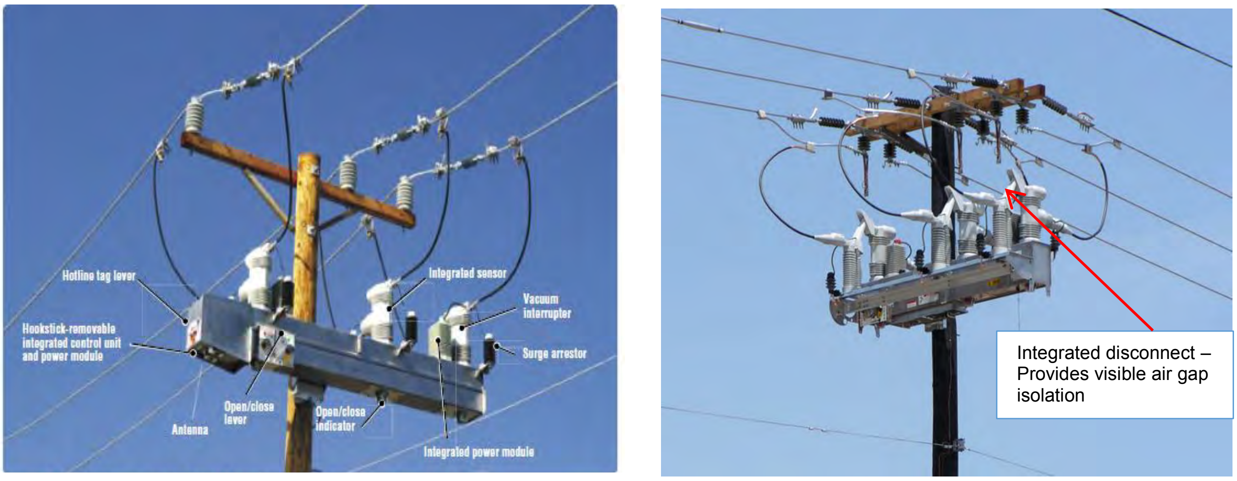
• Single-phase tripping is useful in reducing momentary outages by approximately two-thirds

• Intelligent Fuse Savings automatically determines if a fuse saving "fast" trip should be used based on the fault current magnitude. At high fault currents, a mechanical device cannot trip faster than a fuse will operate, so Intelligent Fuse Savings will avoid using the fast trip, thereby reducing momentary outages.

• Multiple pulse closers can be installed in series with identical protection settings if proper Time Current Characteristic coordination becomes difficult. By simply checking the PulseFinding option for each pulse closer, the devices will properly sectionalise the faulted section. Communications are not needed for this feature.

• IntelliRupter allows for simultaneous bi-directional overcurrent protection and has multiple protection profiles to allow for quickly switching between applications.

The Figures 4.6 (a) and (b) below show the IntelliRupter in the upright cross arm and compact cross arm mounting configuration, with or without an integral, hookstick operated disconnect for visible air gap isolation of switched open circuits. All components are mounted to the Intellirupter base – for one lift mounting and easy installation.



(a) **(b)**

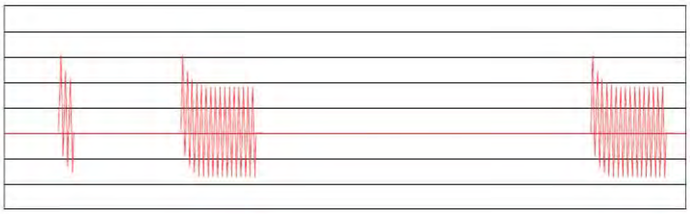
Figure 4.6: **Different Components of the Intellirupter Pulsecloser - (a) without integrated disconnectors, (b) with visible air gap isolators**

Fault Testing with an IntelliRupter PulseCloser

Every time conventional reclosers reclose into a fault, they stress the circuit with fault current. But after the IntelliRupter interrupts a fault, it pulsecloses to intelligently test for fault current before closing.

The oscillograms in Figure 4.7 show the significant difference in current versus time during fault testing with a conventional recloser and IntelliRupter Pulsecloser [8]. Figure 4.7 shows the fault current that exists when a recloser or breaker is closed into a permanent fault and the impact on the unfaulted phases when this is done. This clearly shows the improvement when Pulseclosing technology is used to test a permanent fault.

Current versus Time – Conventional Recloser – Fault from Phase Wire to Grounded Neutral



Current versus Time – IntelliRupter PulseCloser – Fault from Phase Wire to Grounded Neutral

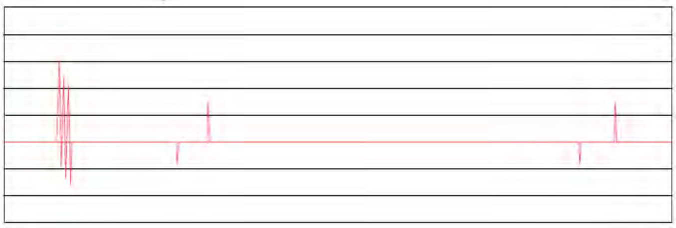


Figure 4.7: **Current versus time graph [8]**

The relative let through energy, in I^2t, of a Pulseclosing operation is typically less than 2 % of a conventional reclosing operation, as shown in Figure 4.8 [8].
Low-current Pulseclosing Technology as seen in Figure 4.8 below can safely test as many times as required to determine if a fault is permanent. It also will improve conductor life, conductor accessory life, and transformer life compared to the hard reclose used by a conventional recloser for fault-persistency testing.

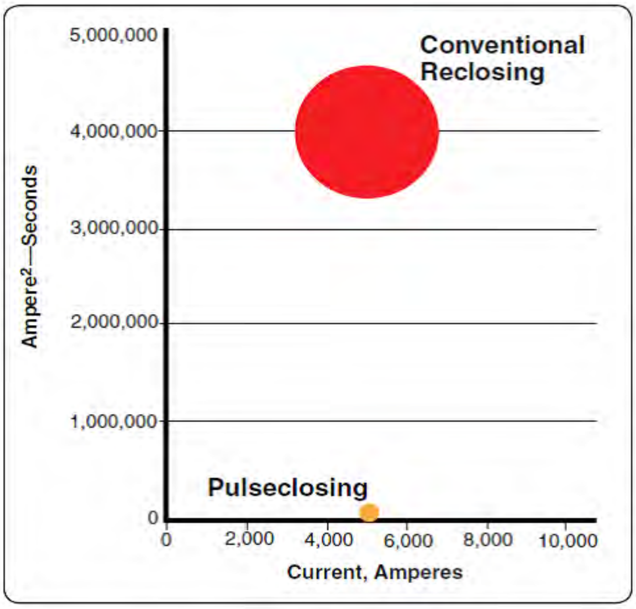


Figure 4.8: **Relative let-through energy for a typical 5 kA fault [8]**

An example of a 5,000 ampere fault is displayed graphically in Figure 4.8. To calculate the conventional reclosing energy, a common delayed TCC is used, and it will allow a 5,000 ampere fault to remain on the system for 0.160 seconds. The equivalent I^2t is approximately 4,000,000 A^2s. Pulse closing does not use a TCC curve for testing. Instead, a pulse of current lasts for approximately 5 ms, and due to precision point-on-wave closing, the RMS equivalent fault current is limited to approximately half that of the symmetrical fault current experienced with conventional reclosing. So, the I^2t for a pulse is approximately 30,000 A^2s. Using an IntelliRupter dampens the forces experienced by overhead line equipment by a factor of 0.75% since it does not reclose under fault conditions [8].

Figure 4.9 shows how a conventional recloser operates in response to a permanent single phase to ground fault. The uncontrolled closing often results in asymmetric fault current, significantly increasing peak energy into the fault [8].

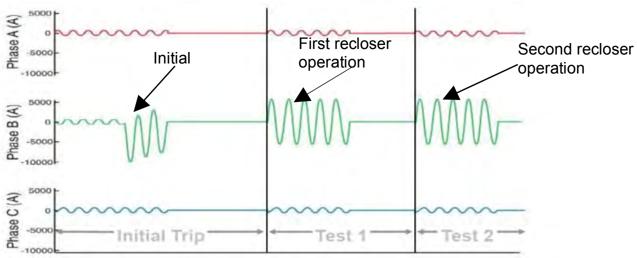


Figure 4.9: **Conventional reclosing in response to a Permanent fault [8]**

After the IntelliRupter clears a fault, it will test for the continued presence of the fault using an advanced PulseClosing technology to intelligently close at a precise point on the voltage wave. Figure 4.10 shows how the IntelliRupter operates in response to a permanent single-phase-to-ground fault, with a typical current pulse of just 5 milliseconds. The IntelliRupter causes the system to only experience overcurrent stress from the initial fault and not from every reclosing operation. The opposite polarity pulse detects magnetising inrush current; if the transformer is not faulted the IntelliRupter will be automatically instructed to close [8].

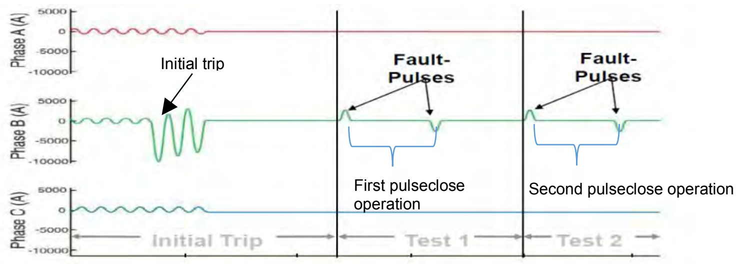


Figure 4.10: **Pulseclosing in response to a Permanent fault [8]**

The figures below show the Pulsecloser clearing a temporary fault on the B - Phase and A to B Phase Permanent Fault

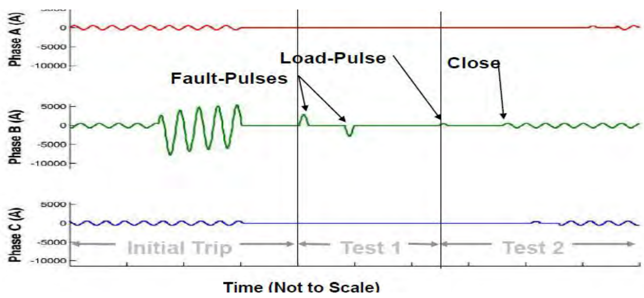


Figure 4.11: **Pulseclosing, B-Phase Temporary Fault [8]**

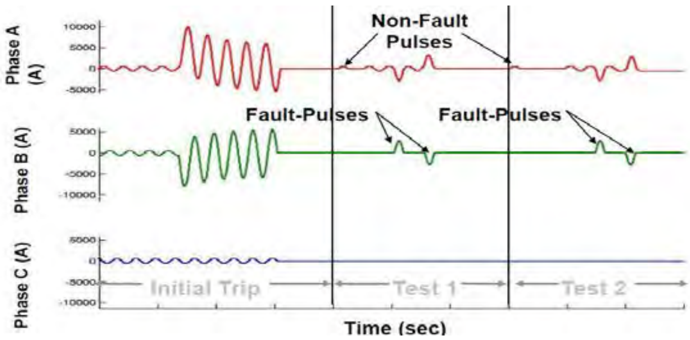


Figure 4.12: **Pulseclosing, A-to-B Phase Permanent Fault [8]**

Installation of IntelliRupter PulseCloser using Different Network Configurations

Loop Restoration Applications

Loop automation uses time, voltage, power flow, and some simple rules to isolate the fault and reconfigure the network, without any communications or operator assistance. In a loop automation network, the following actions will take place when a fault occurs [41]:

- The recloser immediately upstream of the fault automatically trips, recloses to lockout, and remains open.

- Reclosers downstream of the fault automatically change the protection settings in the anticipation of power flowing in the opposite direction.

- The normally open tie recloser closes automatically.

Due to the fault still being present, the recloser immediately downstream of the fault trips, and locks out without reclosing. This will automatically restore power to the healthy parts of the network. An operator can now despatch line crews to the faulted segment [41].

The IntelliRupter can boost the performance of loop restoration schemes using conventional reclosers, by eliminating the need to subject the alternate circuit in the loop to a fault when closing the tie. To take advantage of PulseClosing Technology, the conventional recloser in the tie position is replaced with an IntelliRupter. Where all protective points are using the IntelliRupter Pulsecloser, an even superior benefit can be achieved in loop schemes. “Its fast interrupters and accurate sensing and control enable significant reductions in protection margins. With the negligible effect Pulseclosing has on source side customers, the system can be segmented as needed without sacrificing protection [8]”. With the IntelliRupter protecting the loop, customers won’t experience voltage sags on their good circuit during testing of a faulted circuit [8].

Pulse Finding Application - Radial Circuit Protection Applications

The IntelliRupter enhances reliability on radial circuits by overcoming the limits of conventional coordination methods. Series connected IntelliRupters can be configured so that after one unit opens to isolate a fault, those downstream, with the same settings, also open. When power returns, each IntelliRupter starting at the source pulsecloses, in turn, to verify that its line segment is unfaulted then closes to restore service. It will never close into a fault. Cold load inrush is alleviated because only one line segment is energised with each closing. No communication system is required to take advantage of this enhanced coordination and inrush mitigation.

Only a limited number of series connected reclosers or relayed breakers can be coordinated. The ability to detect a faulted line section without relying on a Time Current Characteristic curve allows a virtually unlimited number of series connected Pulseclosers to be coordinated, even when proper TCC curve coordination cannot be achieved [8].

Point-on-Wave Closing

Pulseclosing utilises very fast, about one or two milliseconds, closing and the opening of the main switchgear vacuum interrupter contacts, introduced at a pre-determined point-on-wave after a voltage wave peak. This controlled point on wave closing is important because it limits peak pulse current to approximately half the expected symmetrical fault current occurring with a hard close into the fault [8].

Pulseclosing is accomplished by a sub-cycle close-open of the switchgear contacts. The contacts are closed for less than 2 ms. Current flow is established as the contacts close, but the contacts open before the first current zero crossing, at which time the current flow is extinguished. Another important part of the technology is the ability to close the interrupter contacts at a specified point on the voltage wave. The ideal point-on-wave closing angle must generate enough current to measure and analyse while still keeping the energy let through into the fault as low as possible. The target range for point-on-wave closing is shown in Figures 4.13 - 4.15. The interrupter contacts are closed after the voltage peak with the intention of creating an asymmetrical current, but with the first loop being a minor loop. Since the contacts part before the zero crossing, only the first minor loop of current is allowed to flow. Therefore, the peak magnitude of the current is reduced and the duration is limited to 3 – 8 ms. This minor loop of fault current is the pulse used for testing the line [8].

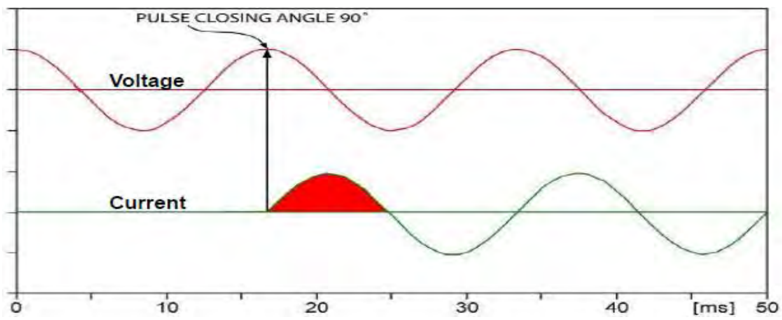


Figure 4.13: **Symmetrical fault current - Closing angle = 90° (voltage peak) [8]**

Pulseclosing uses fault asymmetry to its advantage, such that the first current loop is the much smaller minor loop; it then interrupts the current before the major loop occurs. Current flows from contact touch until the next current zero, typically resulting in a pulse current of approximately 5ms duration. This very fast mechanism hits the point-on-wave closing target and then quickly reverses momentum to open the contacts. The magnetic actuators used in the Pulsecloser employ real-time feedback to ensure that each pulse is highly accurate, regardless of fault current magnitude, environmental conditions, and contact wear [8].

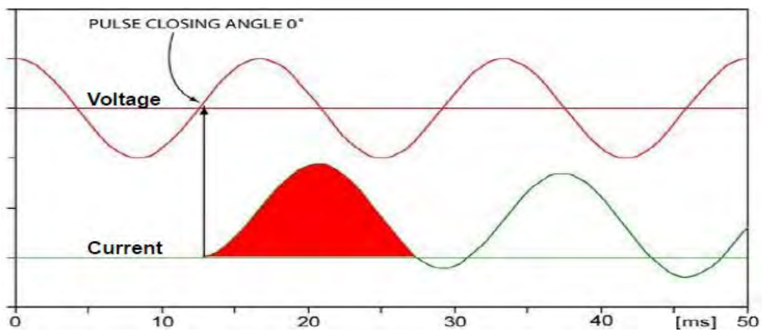


Figure 4.14: **Fully asymmetrical fault current - Closing angle = 0° (voltage zero) [8]**

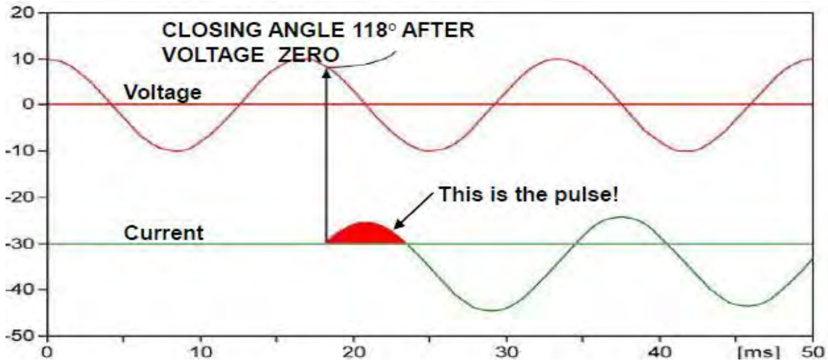


Figure 4.15: **The closing angle of 118° after a voltage zero yields initial minor loop and opens the contacts before the major loop [8]**

4.3.6 FuseSaver

The partner fuse protects the lateral line from permanent faults and the FuseSaver protects the partner fuse from being blown by transient faults. The FuseSaver is a self-powered, electronically controlled, single-phase fault interrupting device that works in partnership with a fuse to protect a lateral or lateral line from both transient and permanent faults. The FuseSaver is capable of detecting, opening and clearing a fault in a half cycle which in most cases is less time than it takes for the fuse to melt. The FuseSaver is primarily targeted at providing protection and automation of low fault level lines. By installing FuseSavers, the utility will gain the benefits of improved network availability and reduced maintenance callouts because the FuseSaver will prevent transient faults from blowing fuses [19].

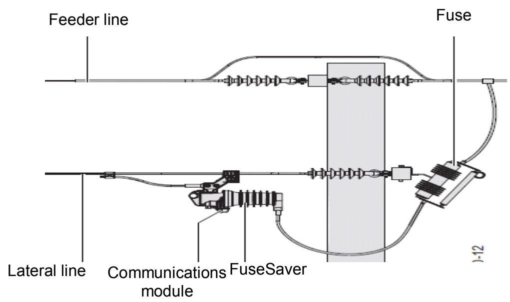


Figure 4.16: **FuseSaver Principle [19]**

Also shown in Figure 4.16 is a communications module plugged into the underside of the FuseSaver. The communications module connects directly to the electronics module in the FuseSaver and has a short range wireless communications capability so that the FuseSaver can be configured, interrogated and controlled from ground level. The communications module is needed to install and commission a FuseSaver but is optional thereafter. The communications module can only communicate with other control devices such as a computer loaded with the Siemens Connect software and fitted with the USB antenna or the remote control cubicle. When the communications module is left permanently fitted this allows FuseSavers on two or three phase lines to be operated in a ganged mode [19].

In most network configurations as shown in Figure 4.17 below, both the fuse and FuseSaver must be in series on the lateral line. From this arrangement a number of points are relevant: It does not matter whether the fuse or the FuseSaver is neighbouring to the feeder line, either configuration is acceptable. Although it is preferable for the fuse and FuseSaver to be located as close together as is practical, mounting the FuseSaver on a different pole is acceptable. The only risk is if a transient fault occurs between the fuse and the FuseSaver then if the FuseSaver is the downstream device it will not be able to save the fuse [19].

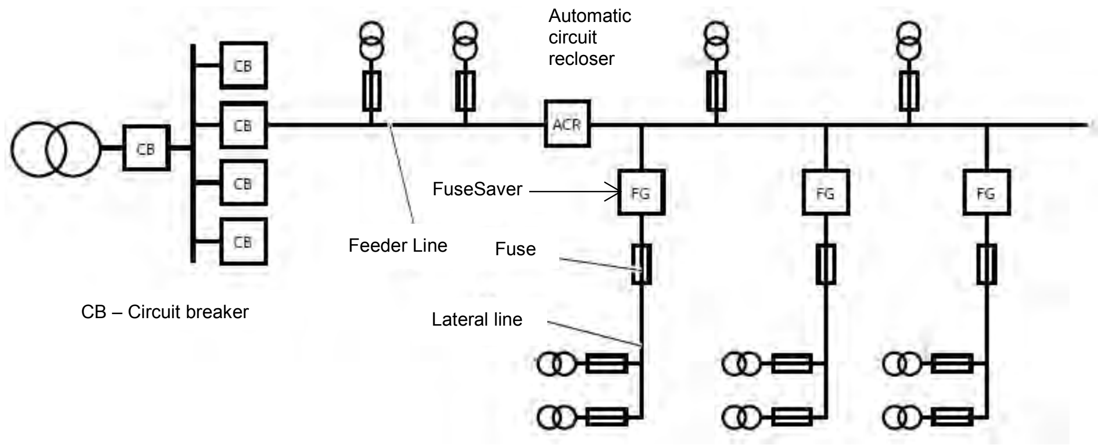


Figure 4.17: **Location of FuseSaver on a Typical Rural Network [19]**

FuseSaver Components

The FuseSaver is attached on the dead end of the lateral line by line clamp assembly. Status indicator, protection-OFF lever and bird saver are installed on the FuseSaver. See Figure 4.18 below.

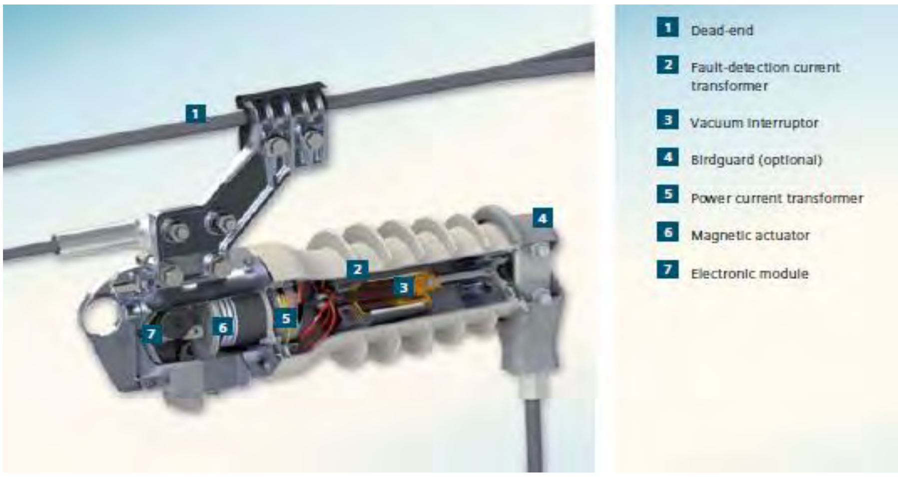


Figure 4.18: **FuseSaver with bird saver and line clamp assembly [19]**

Status Indicator

An indicator of the OPEN/CLOSE contact status of the vacuum interrupter is visible by a transparent window from ground level. The indicator is directly coupled to the magnetic actuator and has highly reflective coloured material to assist with viewing at night.

Table 4.1: Status Indicator

Colour	Vacuum Interrupter
Green	Contacts OPEN
Red	Contacts CLOSED

Usually the vacuum interrupter contacts are closed (red indicator) and only open momentarily for the dead time during a protection sequence. Alternatively when the FuseSaver is manually opened the green open indicator will be visible. After installation line current flows through the FuseSaver, the electronic module will power up and start charging the actuator capacitors. If there is a communications module fitted the charge time will be approximately 30 s [19].

Bird Guard

When the FuseSaver is hung directly from the MV line it is recommended to fit a bird guard over the load side terminals. The bird guard provides additional electrical insulation to the line side conductor which is directly above the load side terminal. The bird guard is fitted over the last shed on the FuseSaver and shrouds the FuseSaver connections and cable lug [19].

Purpose of the Communications Module

The communications module plugs into a three pin connector on the bottom of the FuseSaver and provides a short range wireless link between the FuseSaver and other devices. It also has a built-in battery [19].

The communications module has multiple purposes. It can be:

- Installed temporarily at the time of commissioning to allow the FuseSaver to be configured and tested.
- Installed temporarily during service to allow FuseSaver to be manually operated, fault data to be read and event logs downloaded.
- Installed permanently to allow three phase lockout functionality.
- Installed permanently to improve the FuseSaver performance by reducing the capacitor recharge time and increasing the accuracy of the event log.
- Installed permanently to not only enable the above but also to connect to a remote control cubicle and thereby integrating the FuseSaver into the utilities SCADA network.

Wireless Communications

Inside the communications module is an intelligent short range wireless transceiver which enables communication to the FuseSaver from ground level. The wireless link uses the public 2.4 GHz band with a proprietary protocol. The operative range of the communications module depends on the installation and site conditions. A typical range is 20 m in line of sight [19].

Battery

The communications module is normally powered by energy extracted from line current by the FuseSaver. The communications module includes a battery to provide power to run the communications module radio and to manually operate the FuseSaver when the line current is off [19].

Figure 4.19: **FuseSaver breaker protecting the Medium Voltage Fuse from Transient Faults [19]**

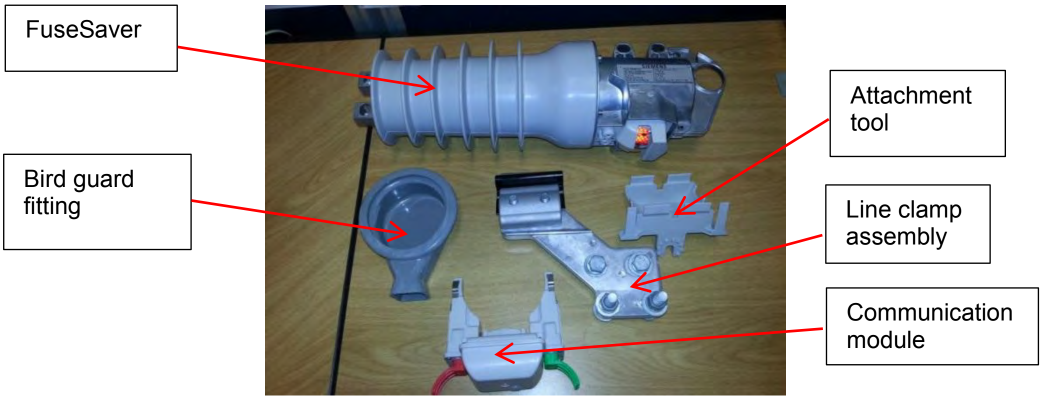


Figure 4.20: **Components of a FuseSaver**

FuseSaver Breaker Operational Process

In most network configurations, the feeder is protected by a circuit breaker or recloser. Lateral lines are usually protected by fuses. However, a fuse is unable to distinguish between temporary and permanent faults. Since most of a network's faults are temporary, 80 percent of its fuses are blown unnecessarily [19].
The FuseSaver is the perfect protection solution for overhead lateral lines. It is capable of almost completely removing the impacts of temporary fault currents on the lateral lines. The FuseSaver protects the fuse in the case of temporary faults with its unique fault-clearing speed (one-half cycle). The FuseSaver is designed to be installed in series to the fuse. It will open and stay open for a pre-determined dead time when it senses a fault current. Then the FuseSaver closes again and remains closed. There are distinct effects on the feeder depending on the type of fault," Figure 4.21 demonstrates the operational process of the FuseSaver.

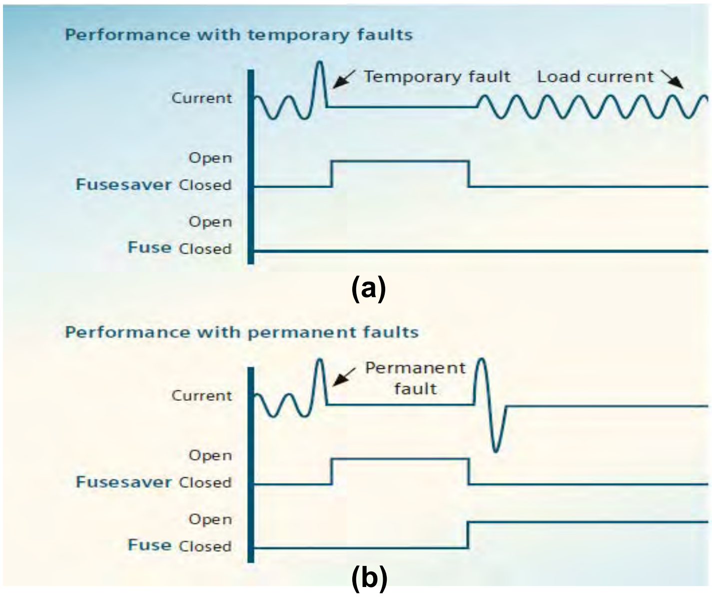


Figure 4.21: **FuseSaver Breaker Operational Process (a) Temporary Faults, (b) Permanent Faults [19]**

Performance with Temporary Faults

Figure 4.21 (a) shows the FuseSavers response to temporary faults. In this case, the fault disappears after closing and the power supply is restored. The fuse did not operate, and the FuseSaver is ready for the next fault. Only the customers on the affected T- off experienced an interruption in power during the FuseSaver dead time, while all other customers on the feeder, including nearby T- offs, did not even notice its operation in less than one cycle [19].

Performance with Permanent Faults

As shown in Figure 4.21 (b), when the FuseSaver closes, the fault is still present, resulting in an immediate fault current. The FuseSaver will not operate again and allows the fault current to blow the fuse. Loss of power is unavoidable for customers on this T - off while all other customers receive an uninterrupted power supply. The FuseSaver restricts blown fuses on T-off lines to unavoidable cases of permanent faults [19].

4.3.7 Tripsaver Cutout - Mounted Recloser

Most temporary faults on overhead distribution circuits occur on lateral lines [13]. Over time, utilities have dealt with lateral protection a couple of ways. Some utilities implement a “fuse blowing” philosophy i.e. the substation feeder breaker is properly coordinated with the lateral fuse so that the fuse will clear any downstream fault within its rating and not the breaker**.**

The problem with the “fuse blowing” philosophy is that the service to customers on the lateral lines is permanently interrupted even for a temporary fault as shown in Figure 4.22 and the utility must deal with the high cost of service calls to replace lateral fuses [13].

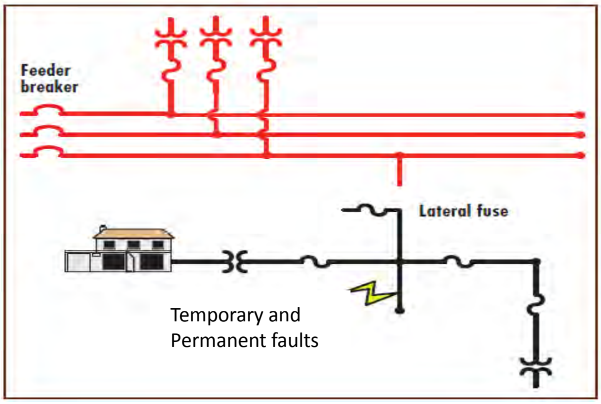


Figure 4.22: **"Fuse blowing" philosophy for momentary and permanent faults [13]**

Other utilities employ a "fuse saving" philosophy: The first trip of the substation feeder breaker is intentionally miscoordinated so that the breaker operates faster than the lateral fuse to clear a fault downstream of the lateral fuse. The second trip of the breaker is slower so that if the fault is still present, the lateral fuse will operate to clear it as shown in Figure 4.22 [13]. The problem with the "fuse saving" philosophy is that all customers on the feeder experience a momentary interruption for all faults as shown in Figure 4.23.

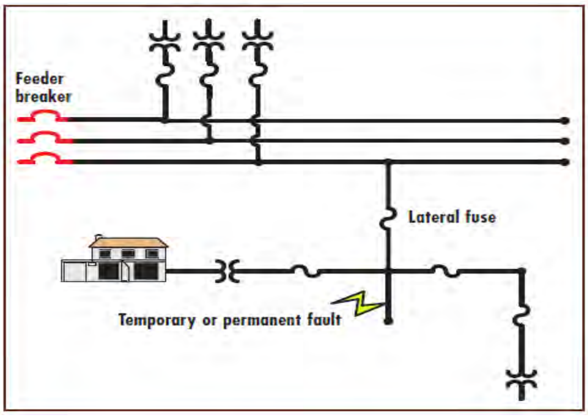


Figure 4.23: **"Fuse saving" philosophy [13]**

The Tripsaver provides better lateral line protection and eliminates these problems. It eliminates the permanent outage which results when the lateral fuse operates in response to a temporary fault. Improvement in SAIFI without sacrificing MAIFI will be seen by the utilities using the "fuse blowing" technique. Tripsaver eliminates the momentary interruption on the feeder in instances where the breaker is tripped to save the lateral fuse during a temporary fault. Utilities using "fuse saving" will see an improvement in MAIFI without sacrificing SAIFI.

Figure 4.24 below shows all the components for a typical Tripsaver Cutout Mounted Recloser.

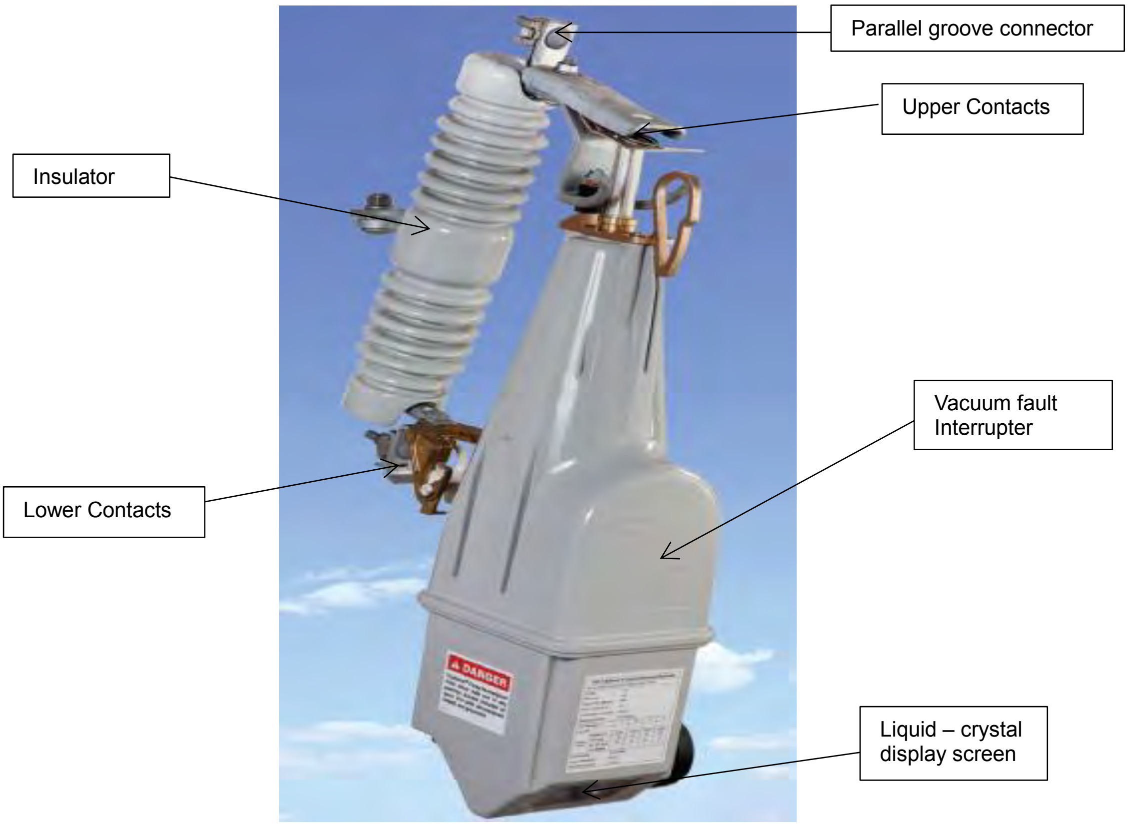


Figure 4.24: **Tripsaver Cutout Mounted Recloser [19]**

4.4. Device Location

The investment and the placement of Distribution automation equipment in a radial feeder are designed to maximise network reliability that significantly affects the system reliability index [54].So, it is important to identify the optimal position of these devices along the feeder [56]. Otherwise, huge costs will be imposed on the distribution company and customers satisfaction would not be achieved [54].

The main purpose of utilising automation equipment is to restore the upstream loads when a fault occurs on the network. This is reached by disconnecting the downstream faulted section. Sensitive loads to the reclosing operation should be placed above the automation equipment [55].This cost must be balanced against the equipment installation cost [55].

Optimal placement of the distribution automation equipment can be determined by balancing the savings obtained by the installation of these devices and their costs. These savings also depends on economic and technical factors. Technical factors are the annual number of various types of faults occurrence on the network, the network dimensions, the required maintenance time and the energy demand of the network. Economic factors consist of the period of study, interest and inflation rates, costs of equipment installation and load growth [55]. Significant time must be invested in selecting the optimal location to install DA apparatus on feeders in order to maximise profit and performance levels which accelerate the period of time before the break-even point in time on investment is reached which ultimately optimises the gain the asset renders to the utility.

Chapter 5: Reliability Evaluation of Waterkloof Distribution Network

5.1. Introduction

Historical assessment and predictive methods are normally used to evaluate the reliability of a distribution network. Most utilities focus more on historical assessment rather than predictive methods. Predictive methods are categorised into analytical and simulation methods. The difference between these methods is the way in which the system reliability indices are evaluated. This chapter is aimed at evaluating the reliability of the pilot feeder, Waterkloof Farmers 1 11 kV Feeder distribution network using Historical Data, FMEA and DIgSILENT. The results obtained from the historical, analytical and simulation methods are compared using the reliability indices such as System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) for the Waterkloof F1 11 kV Feeder.

5.2. Trial Feeder Historical Data

An extensive analysis of fault records for the Waterkloof Farmers 1 11 kV Feeder has been carried out to identify the major causes of the faults and their characteristics. The main purpose of carrying out this analysis is to identify the statistical significance of different fault incidence frequency of individual fault causes according to the season, time of day and climate. The objective is to apply this data to the network reliability studies [4] and for network performance improvement.

5.2.1 Feeder Fault Frequency Statistics

Records of faults occurring on the Waterkloof Farmers 1 11 kV distribution feeder over a 6 - year period has been collected. Over 155 faults (fault event data captured from Eskom Plant spreadsheet _ 2008 - 2013) were analysed to find statistical relationships between local climate, key design parameters of the overhead lines, and the main causes of power system faults were identified as bird related problems, overhead power line problems (unknown), weather related problems, vegetation and jumper failures.

Figure 5.1 below shows the number of faults that occurred on the Waterkloof Farmers 1 11 kV Feeder from 2008 to 2013.

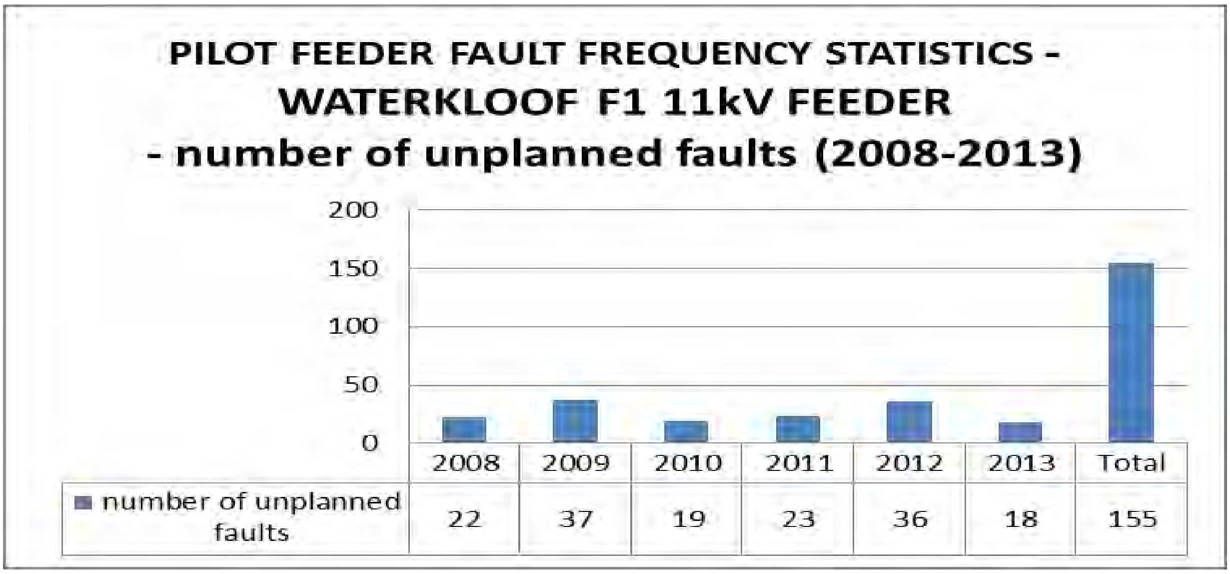


Figure 5.1: **Feeder Fault Frequency Statistics**

5.3. Analysing the Feeder Faults

5.3.1 Network Description

Waterkloof 66/11 kV 2x20 MVA transformer substation was commissioned in 2006. Waterkloof substation, shown in the aerial photograph in Figure 5.2 is situated north of the N2 highway and on the Eastern side of Somerset West Business Park in Cape Town, South Africa. The substation comprises of six outgoing 11 kV feeders i.e. Waterkloof / Farmers 1 11 kV Feeder, Waterkloof / Farmers 2 11 kV Feeder, Waterkloof / Munic Chrisnissen 1 11 kV Bulk Load Feeder, Waterkloof / Munic Wedgewood 1 11 kV Bulk Load, Waterkloof / Munic Chrisnissen 2 11 kV Bulk Load Feeder, Waterkloof / Munic Wedgewood 2 11 kV Bulk Load. The substation has greatly improved the QOS to all the customers in the Sir Lowry's Pass basin.

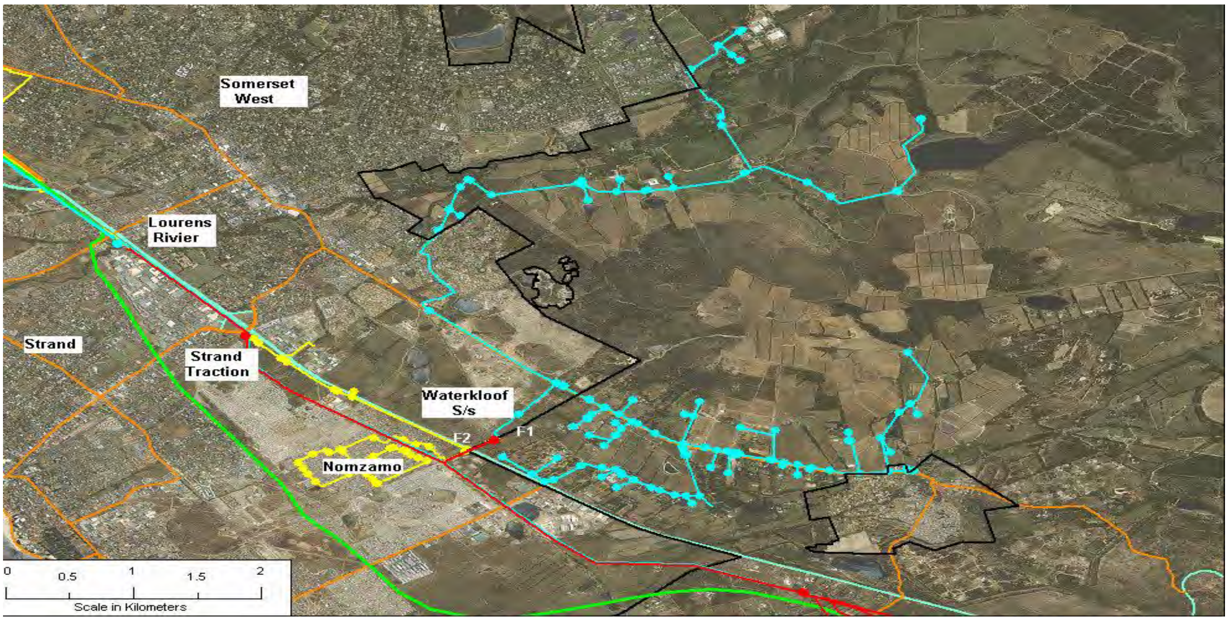


Figure 5.2: **Waterkloof Substation**

Waterkloof Farmers 1 11 kV Feeder has been identified as one of the worst performing feeders within the western region. The feeder is supplied from Waterkloof substation, has a total line length of 24.3 Km and the line mostly consist of 0.075Cu and 0.50Cu conductor and several parts consists of Chickadee and Acacia conductors. The feeder supplies a total of 86 customers i.e. it supplies 11 larger power customers (LPU), 73 small customers (SPU) and 2 prepaid users (PPU), which consist of many 3 phase pumps & compressors. The network footprint incorporates a mix of major regional towns, industrial areas, residential growth areas, and long networks. The distribution network is based on urban, rural, and rural long networks.There are 62 transformers used on the feeder with a total installed capacity of 7822 kVA. The feeder grows at about 5.8 % per year.

Below is the Aerial photograph of Waterkloof Farmers 1 and the installation positions for the new innovative equipment. (See Appendix D for the detail Single Line Diagram of Waterkloof Farmers 1)

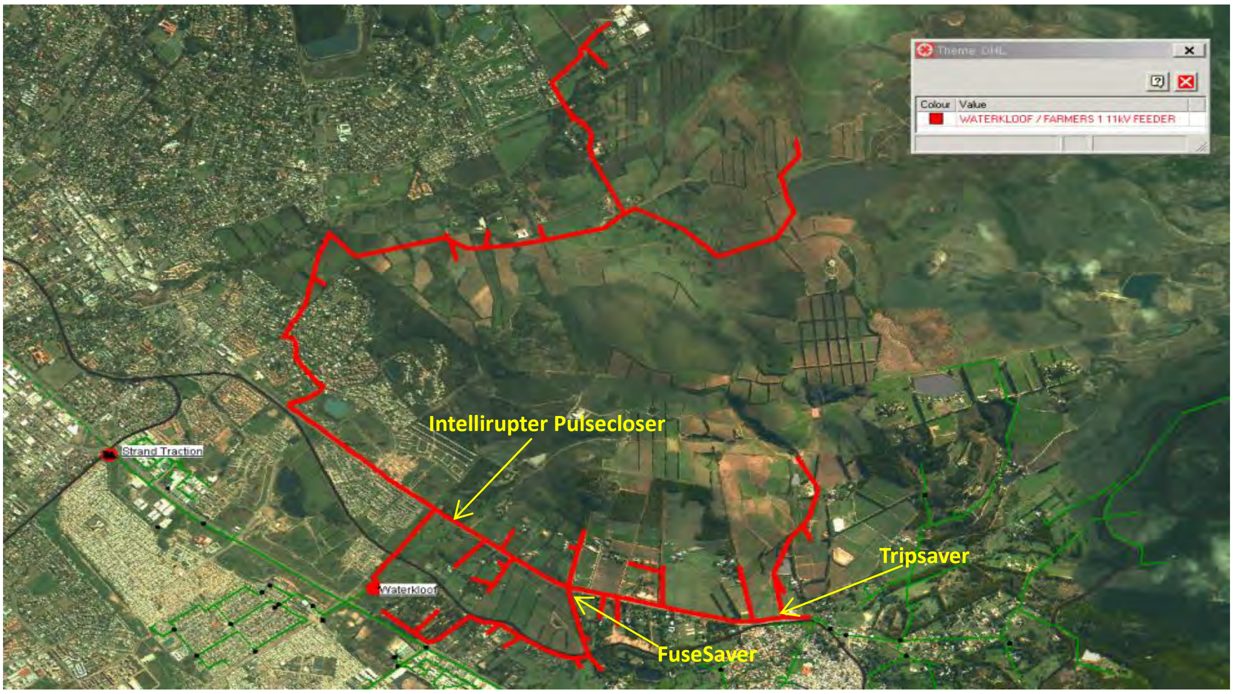


Figure 5.3: **Aerial photographs of Waterkloof Farmers 1 11 kV Feeder**

5.3.2 Fault Data Analysis - Before Installation of Equipment

Fault data records were collated in a spreadsheet format with standardised line descriptions, operating voltage, start date and time of an event, original fault description, assigned fault cause and sub-cause and Eskom distribution system region.

A total of 155 faults occurred on the Waterkloof Farmers 1 11 kV Feeder during the period 2008 to the end of 2013. The figures below illustrate the breakdown of fault causes. The six most significant individual causes of faults are the wind, weather, jumper failures, vandalism, trees/branches in contact with power lines and overhead power line problems, together causing 73 % of all faults, including those not classified. The dominant part, at least 30 % overhead line failures is random failures due to environmental factors [30]. (See comments in Appendix G)

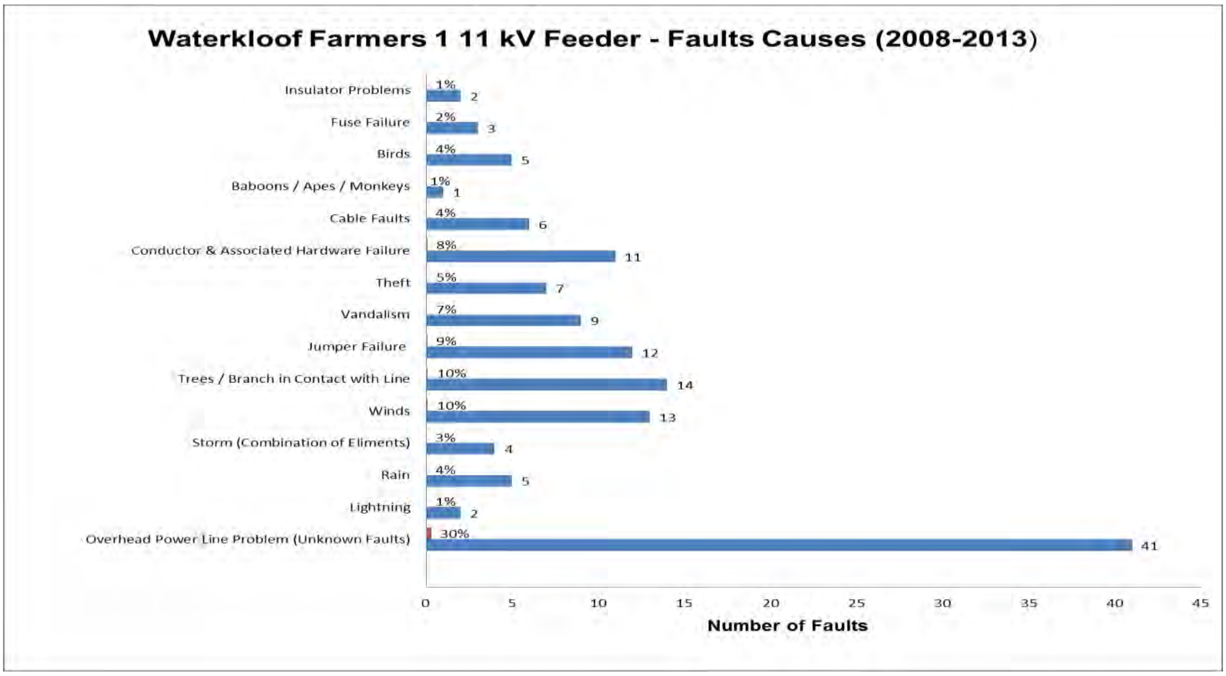


Figure 5.4: **Top causes affecting the SAIDI of Waterkloof Farmers 1 11 kV Feeder**

Customer Interruptions

The top causes affecting unplanned customer interruptions is 51 % of unknown overhead power line problems, 12 % insulator related problems, 10 % due to vandalism and 9 % due to fire/terrain conditions. Their individual contribution is plotted on a pie chart in Figure 5.5 below.

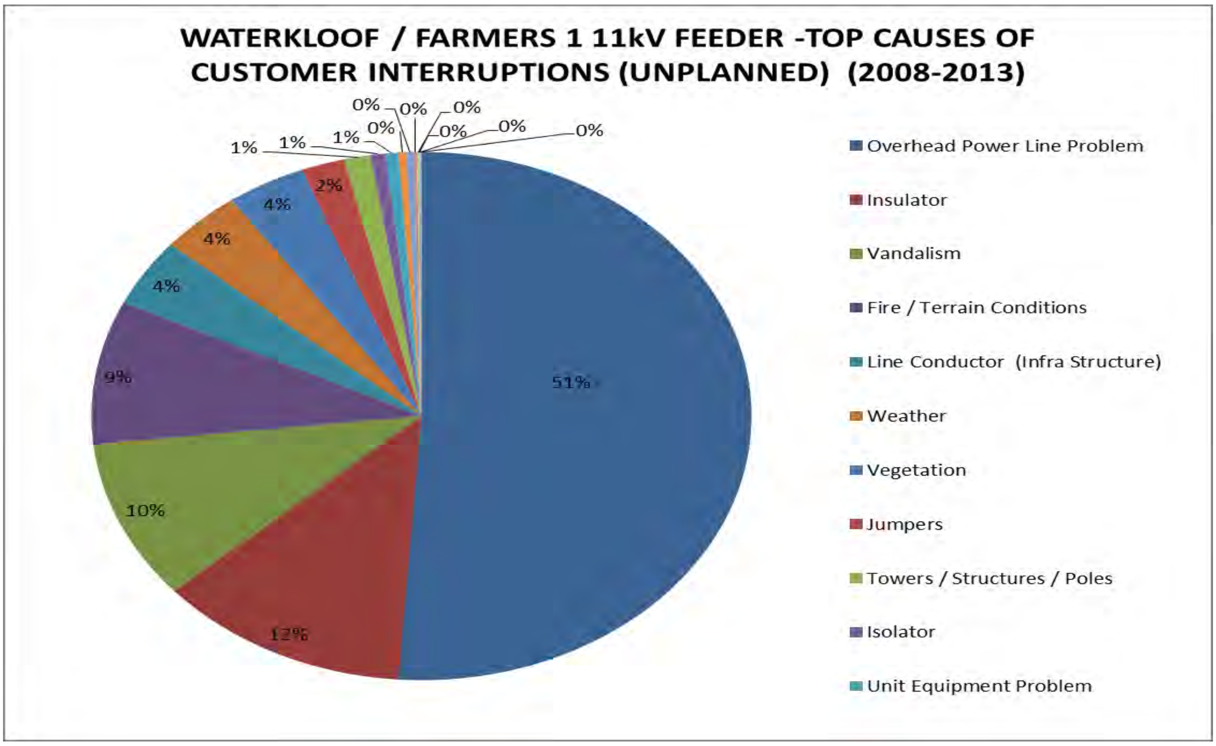


Figure 5.5: **Top causes affecting customer interruptions (unplanned)**

Sustained Interruptions

Sustained Interruptions is the interruption of supply, include outages not classified as momentary events and that last for more than two minutes. There was a sharp increase in the sustained interruptions of the feeder in the years 2009 and 2012 due to the wind and overhead line problems, then a slight decrease in the sustained interruptions in years 2010, 2011 and 2013. The figures below illustrate the yearly sustained interruptions from 2008 to 2013.

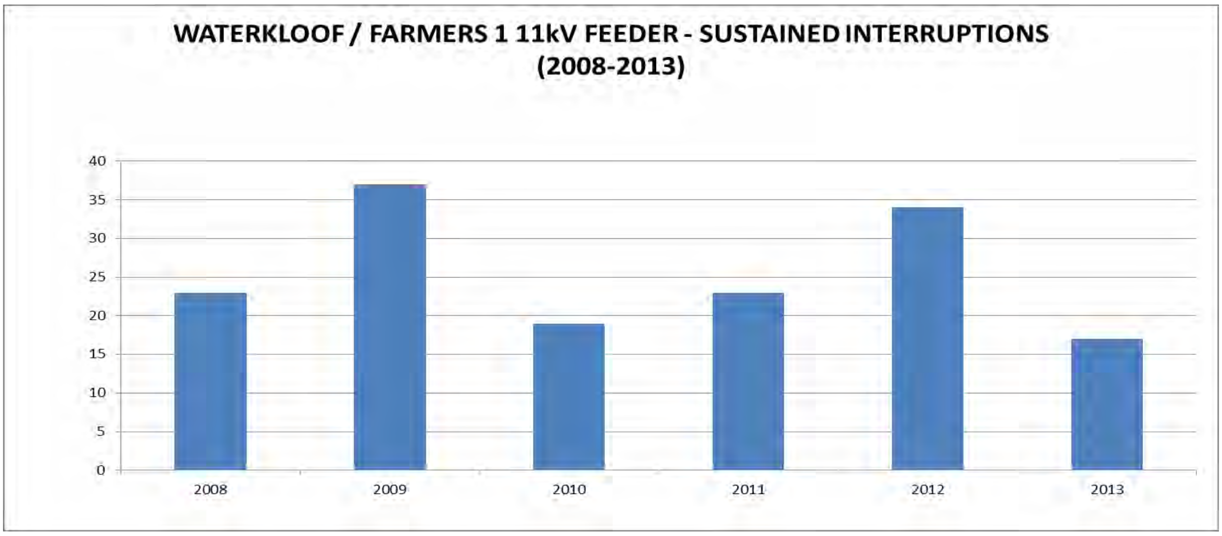


Figure 5.6: **Sustained Interruptions for Waterkloof Farmers 1 11 kV Feeder (2008-2013)**

Figure 5.7 illustrates the failure causes of sustained interruptions for the Waterkloof Farmers 1 11 kV Feeder. According to the Eskom statistics, the dominant part, at least 51 %, of the overhead line failures is random failures due to environmental factors and weather related problems [30].

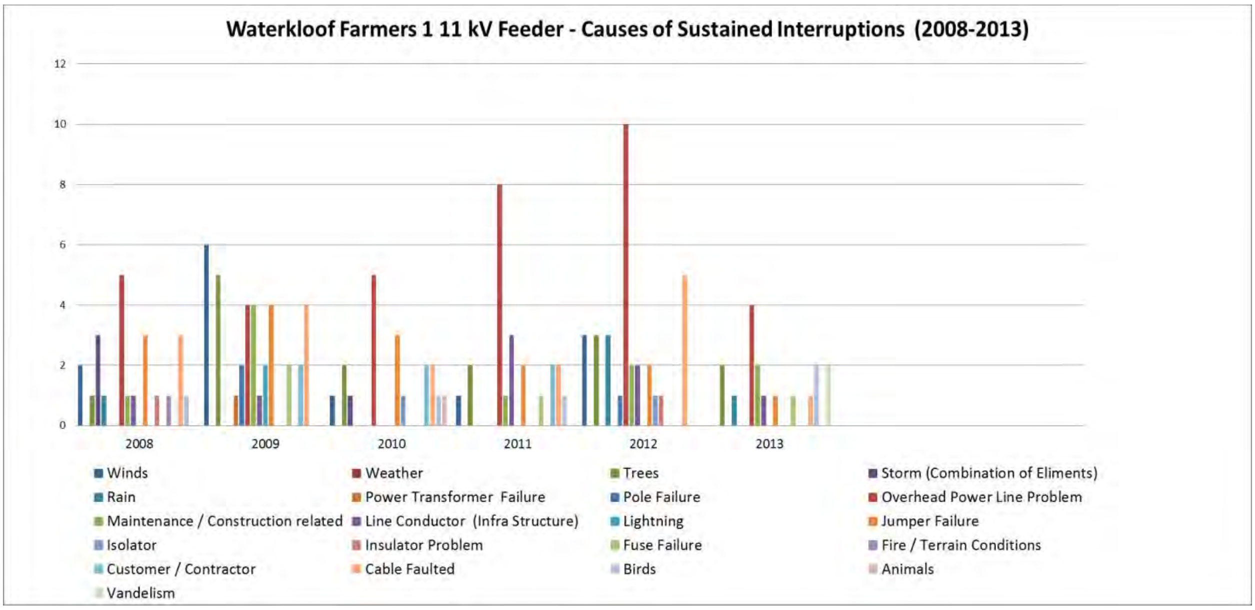


Figure 5.7: **Causes of Sustained Interruptions for Waterkloof Farmers 1 11 kV Feeder (2008-2013)**

Momentary Interruptions

Momentary interruption is the interruption of supply with duration less than two minutes. The graphs below illustrate the number and causes of momentary interruptions from 2008 to 2013. The most significant causes of momentary interruption were overhead power line problems, including those not classified. (See Appendix G for details of momentary interruptions)

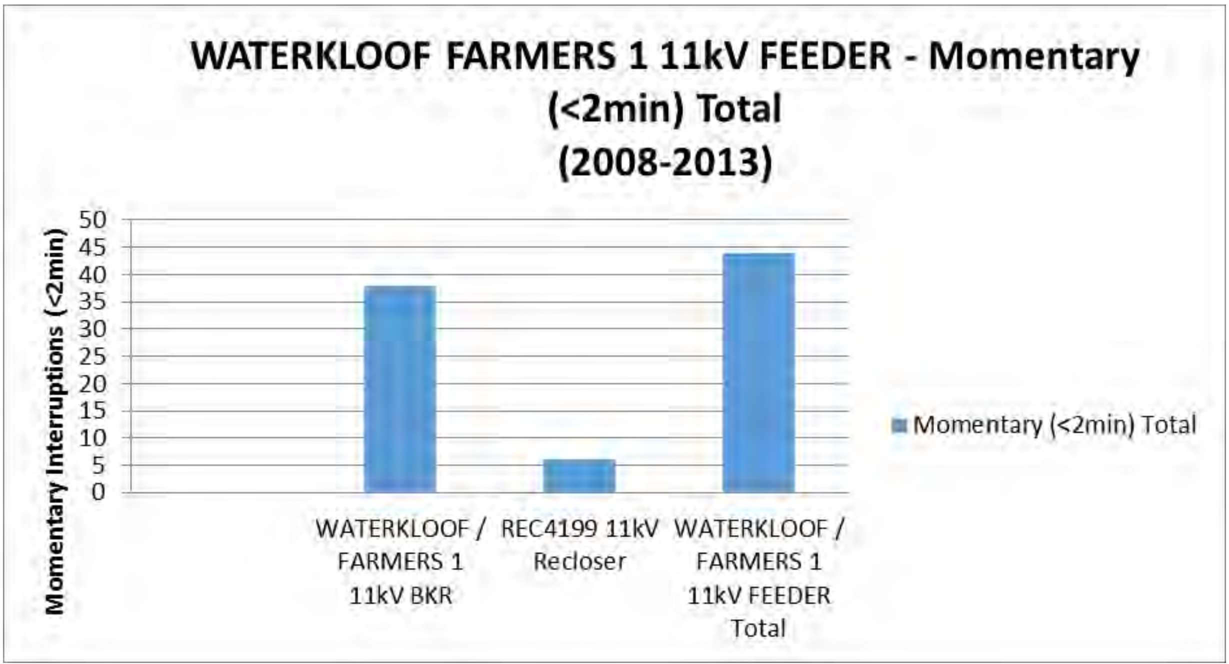


Figure 5.8: **Momentary Interruptions for Waterkloof Farmers 1 11 kV Feeder**

Figure 5.9 illustrates the failure causes of momentary interruptions for the Waterkloof Farmers 1 11 kV Feeder.

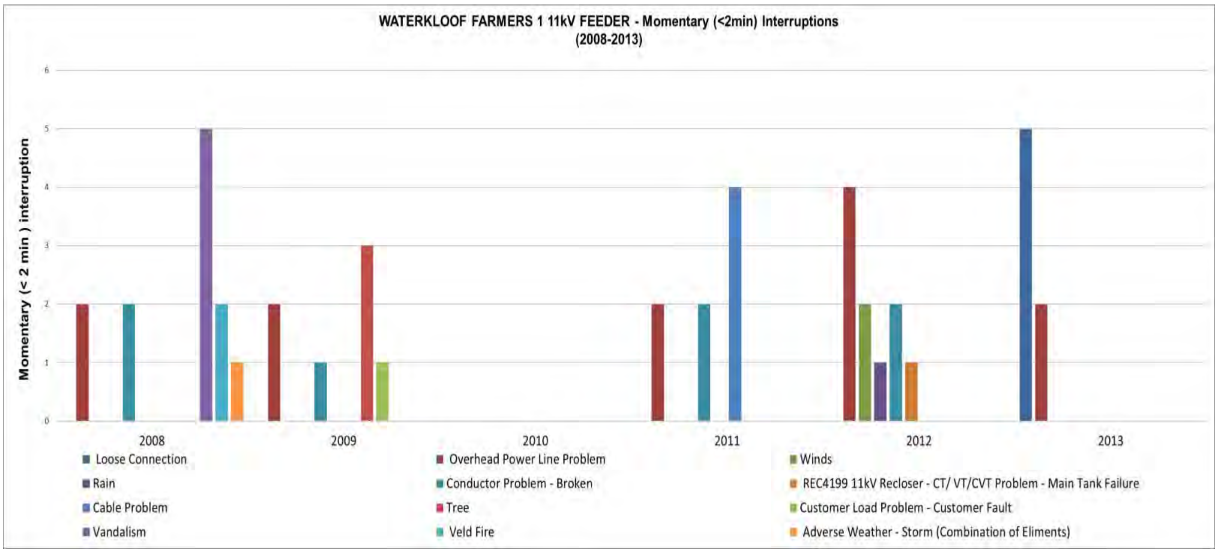


Figure 5.9: **Causes of Momentary Interruptions for Waterkloof Farmers 1 11 kV Feeder**

Unplanned MV Supply Unavailability

The top causes of unplanned RSLI are shown in Figure 5.10. 17 % of MVAhrs lost were due to unknown overhead power line problems, 28 % due to line conductor (infra-structure) problems, 16 % due to vegetation and 10 % due to severe weather related problems.

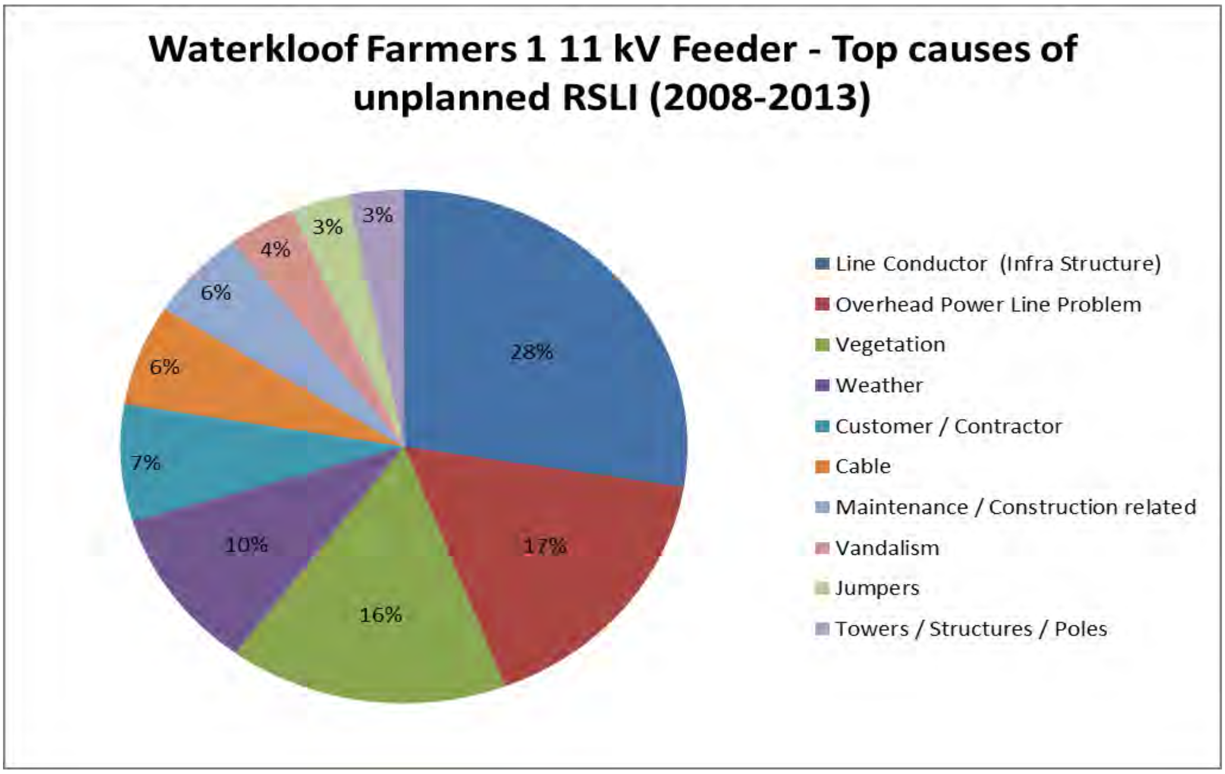


Figure 5.10: **Top causes of unplanned RSLI**

5.3.3 Time-of-Day and Time-of-Year Analysis

This analysis identifies relationships that exist between local climate and causes of power system faults. The time-of-day and time-of-year analysis for networks and specific fault causes can be graphically represented using bar charts that associate seasonal and time-of-day intervals with interruption indices proposed for system reliability studies [20]. Using a limited number of fault causes and time-season categories ensures sufficient events for statistically significant samples while achieving a useful distinction between them.

Unknown Faults

Figures 5.11 and 5.12 below show the number of unknown causes of overhead power line faults for the Waterkloof Farmers 1 11 kV Feeder. The highest incidences occur in the early hours of the afternoon from 12:00 until 17:59 during season 1 (January to March), season 2 (April to June) and season 4 (October to December) and early morning from 06:00 until 11:59 during season 3 (July to September). The underlying causes of these could be related to severe weather conditions, vegetation, jumper failures and birds colliding with conductors.

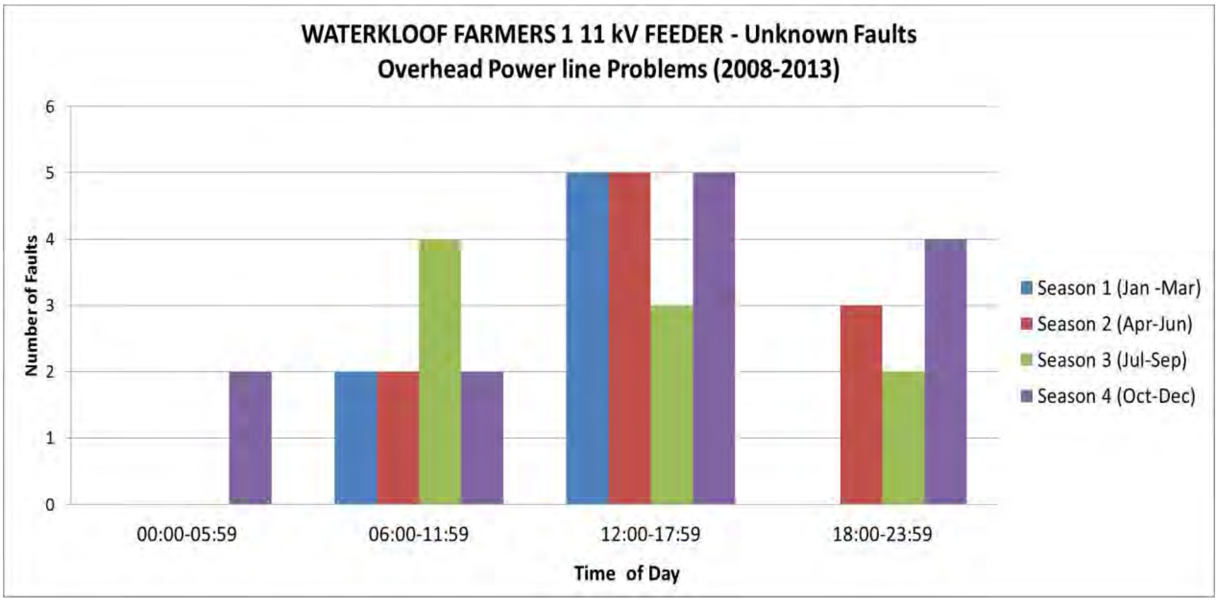


Figure 5.11: **Seasonal frequency of unknown causes of overhead power line faults on the Waterkloof Feeder**

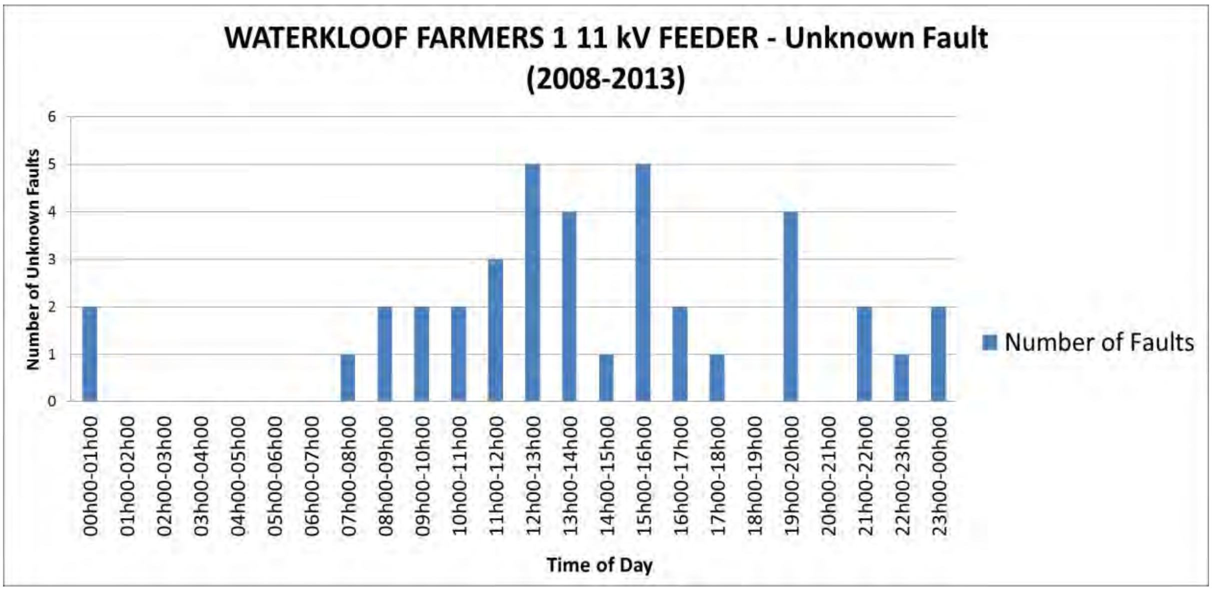


Figure 5.12: **Hour-of-day dependent frequency of unknown causes of overhead powerline faults on the Waterkloof Farmers 1 11 kV Feeder**

Bird Faults

Birds cause flashovers on the power lines in three ways [6] i.e. Bird Streamer, Bird pollution and electrocution. One of the key attributes of bird faults is a clear diurnal and seasonal pattern of occurrence. The interactions between birds and power lines differ according to the voltage level of the line [8]. Faults are due to the electrocution of birds bridging the conductors-to-tower air gap and phase to phase by the wings and body [8] Flash-overs are caused by large birds i.e. Guinea Fowls, Crows and the Blue Cranes. Birds move in and out of the area late afternoon/ early evening and early mornings when it is still dark. Figure 5.13 illustrates the diurnal and seasonal patterns commonly associated with bird faults on the Waterkloof Feeder. Fault frequency on the feeder is at its peak for Seasons 3 (July – September) and 4 (October – November) in the early hours of the morning from 06:00 until

11:59 and early afternoon from 12:00 until 17:59. The underlying causes for this could be related to the birds colliding with conductors, birds making nests with scrap wire that results in flash – overs and birds roost on the conductors causing flash-overs when taking off.

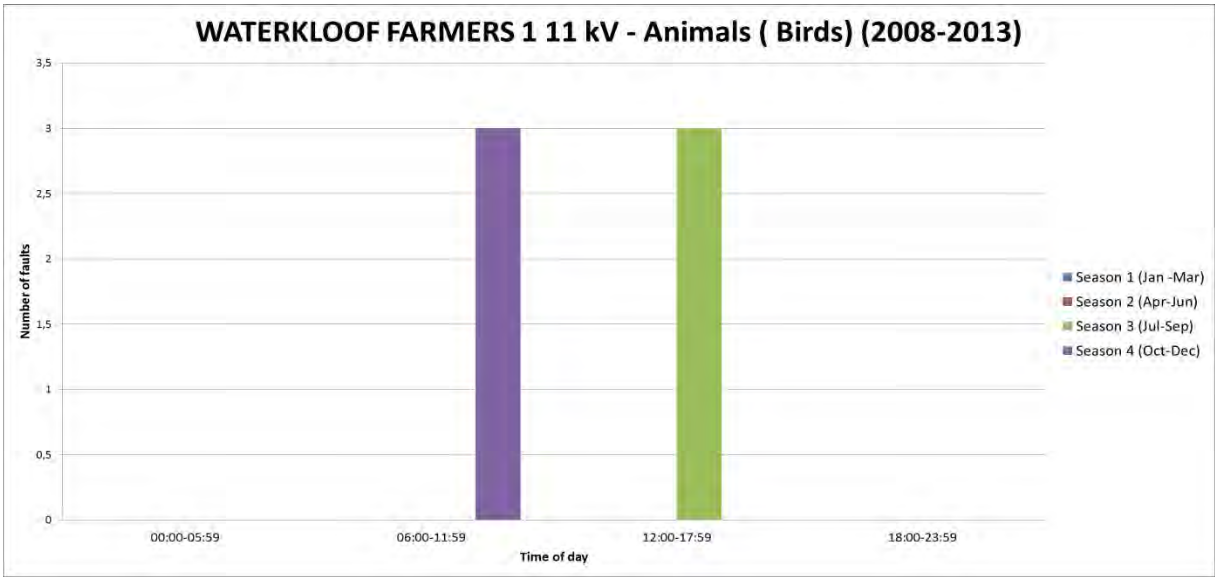


Figure 5.13: **Seasonal and time dependent frequency of bird faults on the Waterkloof Farmers 1 11 kV Feeder**

Weather Related Problems

Wind and lightning have been identified as the two major weather-related causes of outages [44]. The Eskom classification does not include the wind as a major cause of faults in South Africa. The results of the time dependant characterisation of faults due to wind and lightning for the feeder are presented in Figure 5.14 and 5.15 below. The results indicate higher levels of severe weather conditions mainly wind and lightning initiated faults in the early morning and afternoons during the periods Season 1 (January–March), Season 3 (July–September) and Season 4 (October–December). These months coincide with winter and summer in South Africa and the results indicate a significant increase in the frequency of faults on the feeder.

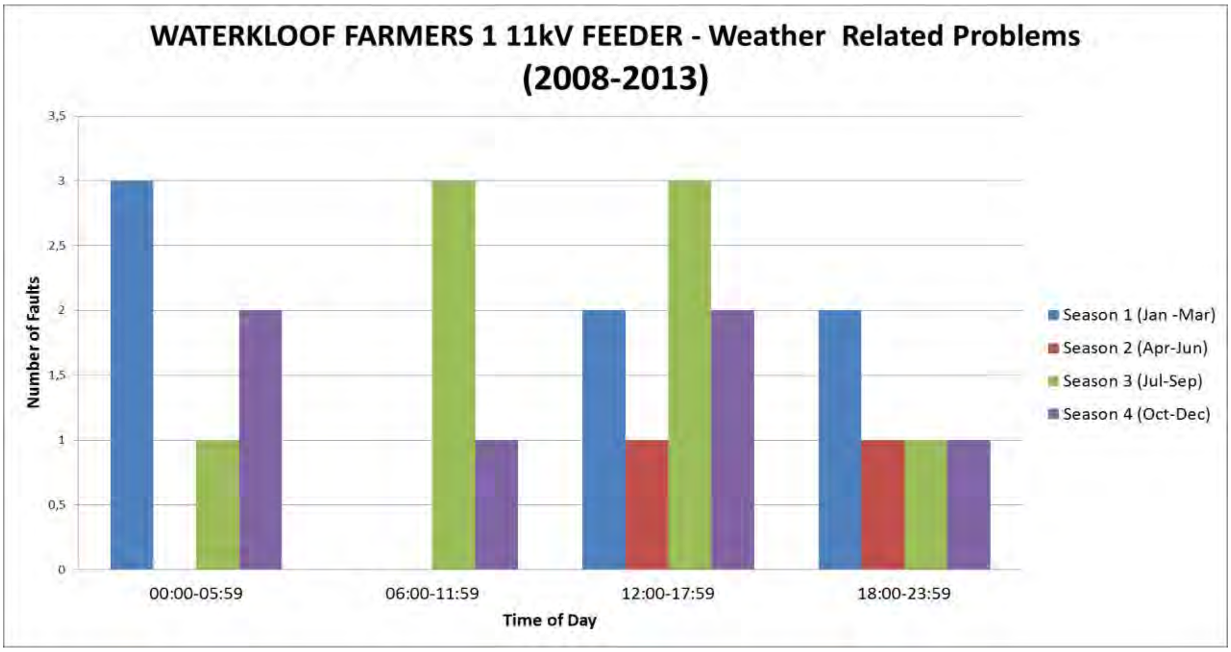


Figure 5.14: **Seasonal frequency of weather related faults on the Waterkloof Feeder**

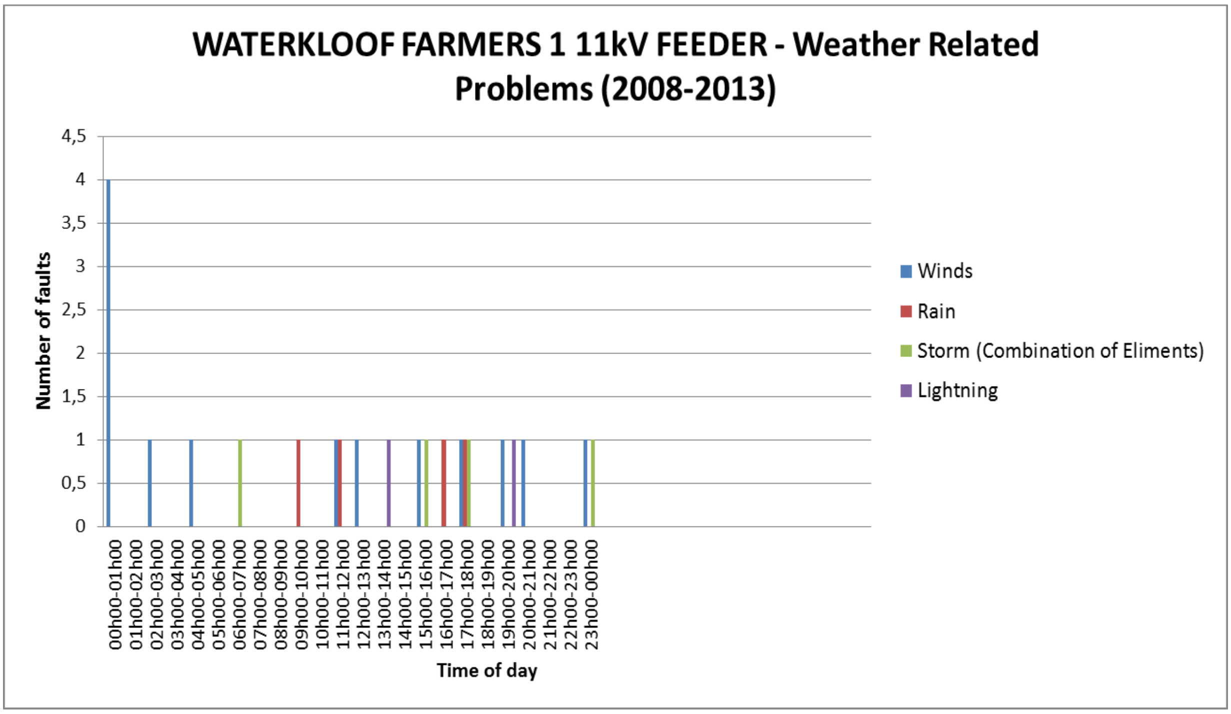


Figure 5.15: **Time dependent frequency of weather related faults on the Waterkloof Feeder**

Fuse Failures and Vegetation

Results are illustrated in Figure 5.16 and 5.17 for the feeders fuse failure number of faults and vegetation related problems that fall mostly within season 2 (April - June) and season 4 (October – December). The highest incidence occurs in the early morning hours from 06:00 until 11:59. (Appendix G provides additional information related to the Fuse Failures problems)

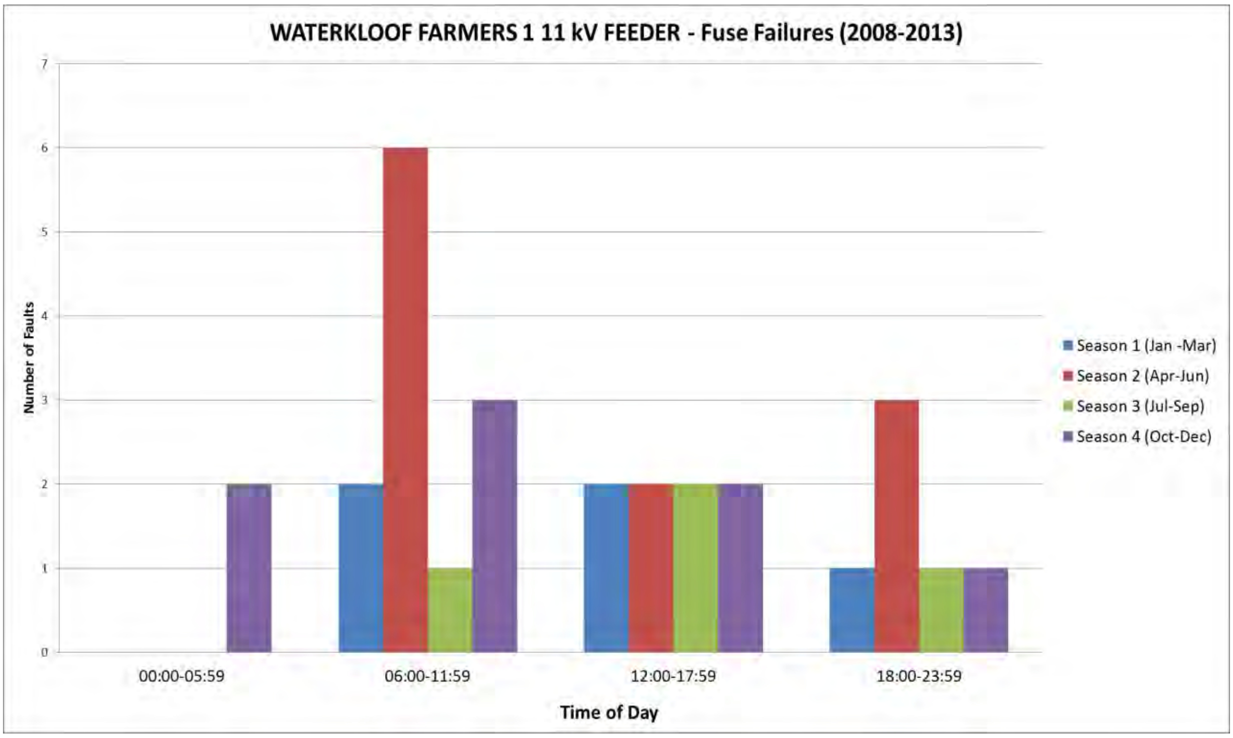


Figure 5.16: **Season and time dependent frequency of fuse failure faults on the Waterkloof Feeder**

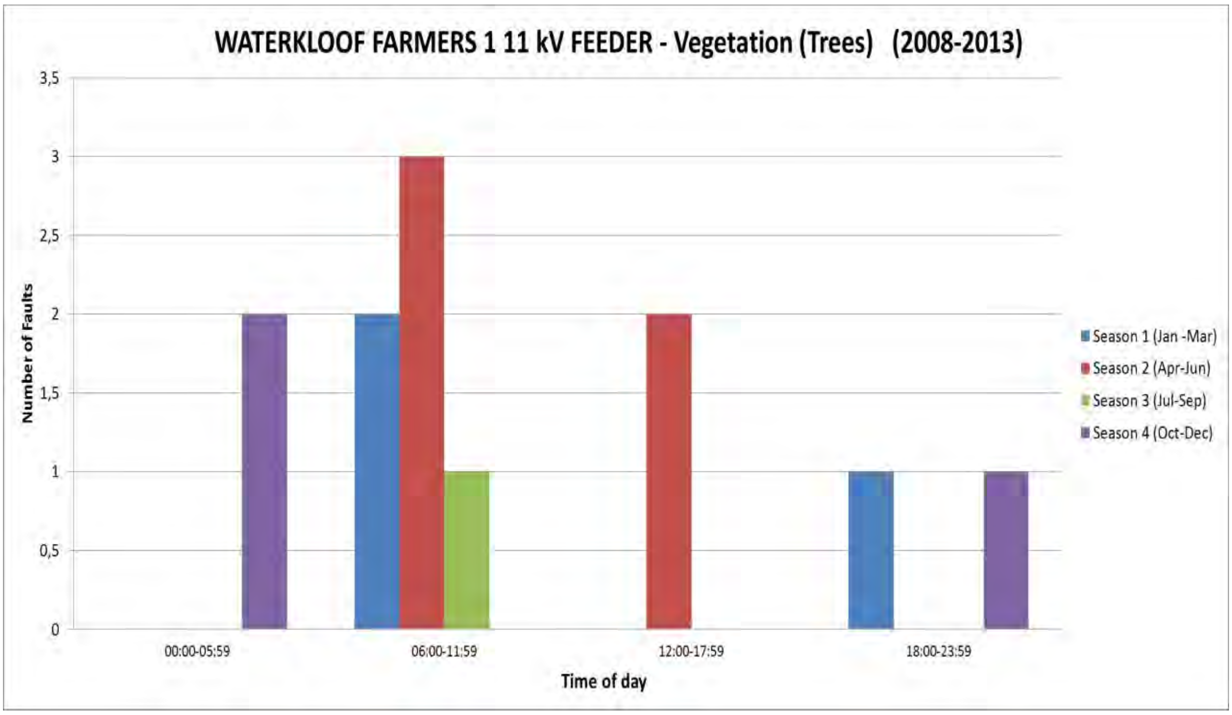


Figure 5.17: **Season and time dependent frequency of vegetation faults on the Waterkloof Feeder**

Number of Equipment Operations

Figure 5.18 below shows the number of equipment operations faults for the Waterkloof Farmers 1 from 2008 to 2013. Section fuse 617, Section fuse 451 and Waterkloof Farmers 1 11 kV main breaker operated frequently, the underlying causes were related to the unknown overhead power line problems and weather related problems.

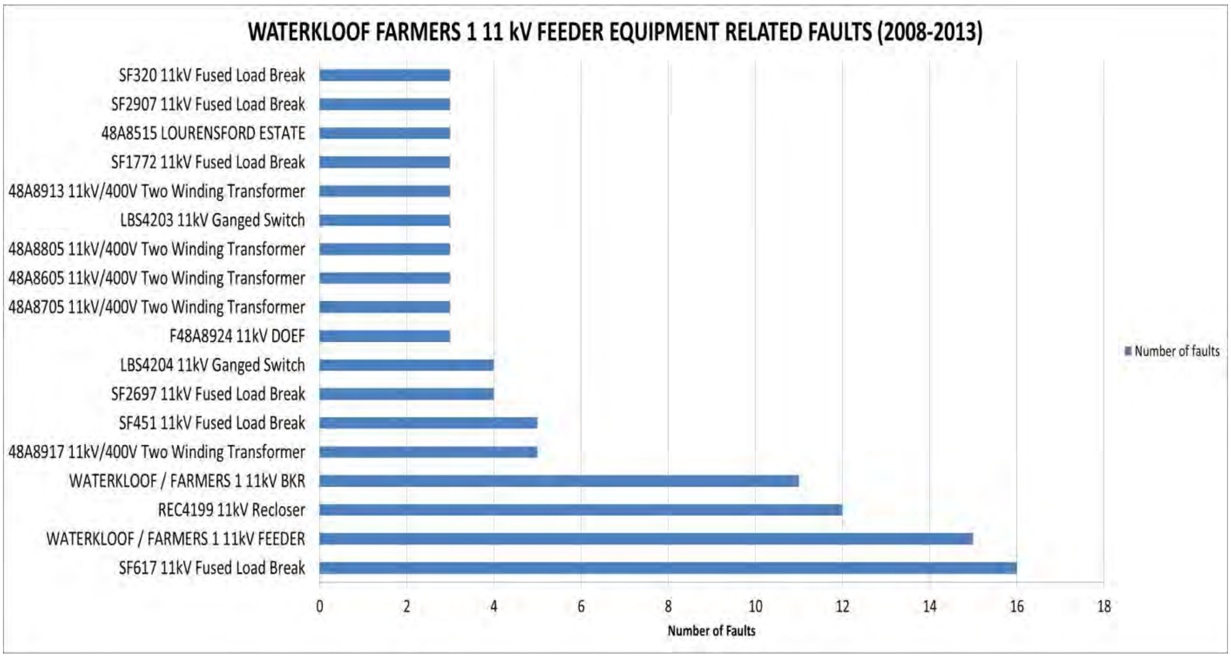


Figure 5.18: **Equipment Fault Operations (2008-2013)**

5.3.4 SAIDI and SAIFI Data Analysis

The data analysis of this feeder will show the trends of the SAIDI over the past five years as well the causes associated with the poor performance. The feeder experienced a total of 155 unplanned interruptions (faults, emergency and customers) due to overhead power line problems (unknowns), weather, birds, fuse failures, jumper failures and line conductor problems.

Performance analysis done based on factors affecting SAIDI and SAIFI for this overhead line is specified below for the period 2009 to 2013. The system did not perform very well in 2009 and 2012 in terms of the duration of interruptions (SAIDI) compared to other years. There was a sharp decrease in the SAIDI in the years 2010 and 2011. Analyses on the reference data show that overhead lines interruption play a dominant value on total indices. Over the five-year period, in the years 2009 and 2012 customers were without power the longest. The figure below shows the average time a customer was without power for the five year period: (See Appendices E and F for details).

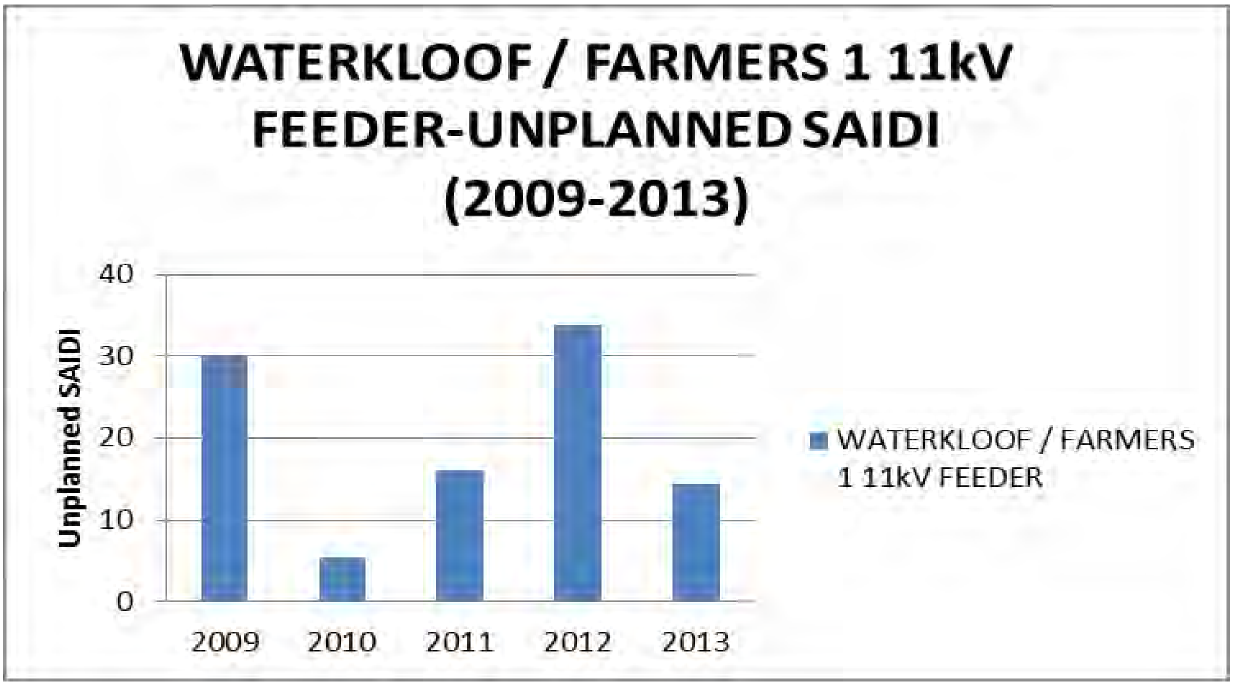


Figure 5.19: **SAIDI Performance of Waterkloof Farmers 1 11 kV Feeder (2009-2013)**

The SAIFI measure indicates that the feeder's customers being served by Eskom faced the highest frequency of interruption in 2012. i.e. approximately 21.84 outage interruptions in 2012.

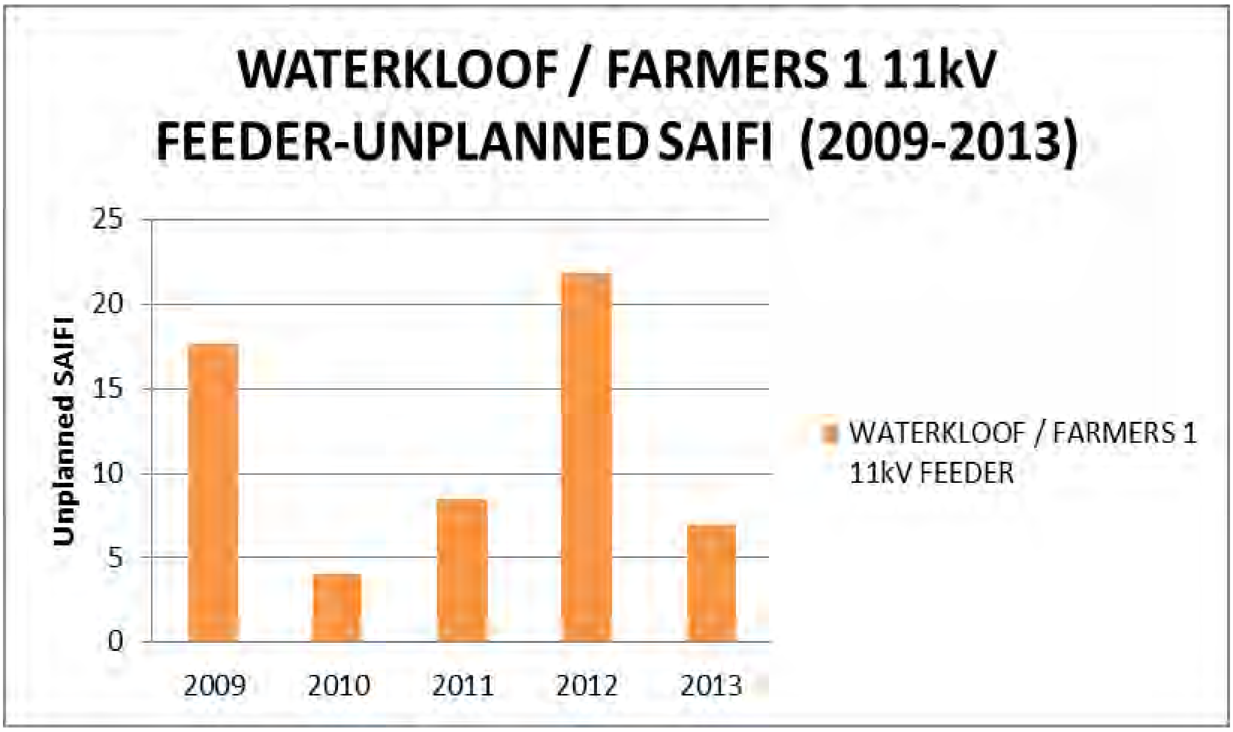


Figure 5.20: **SAIFI Performance of Waterkloof Farmers 1 11 kV Feeder (2009 - 2013)**

The following failures are the contributors on the network performance of Waterkloof Farmers 1 11 kV Feeder from 2009 to 2013.The performance of the feeder for the five year period, in terms of unplanned SAIDI, is shown in the figure below. 22 % of the unplanned SAIDI was caused by insulators problems, 21 % was due to line conductors (infra-structure), 20 % due to vegetation and 7 % due to overhead power line problems.

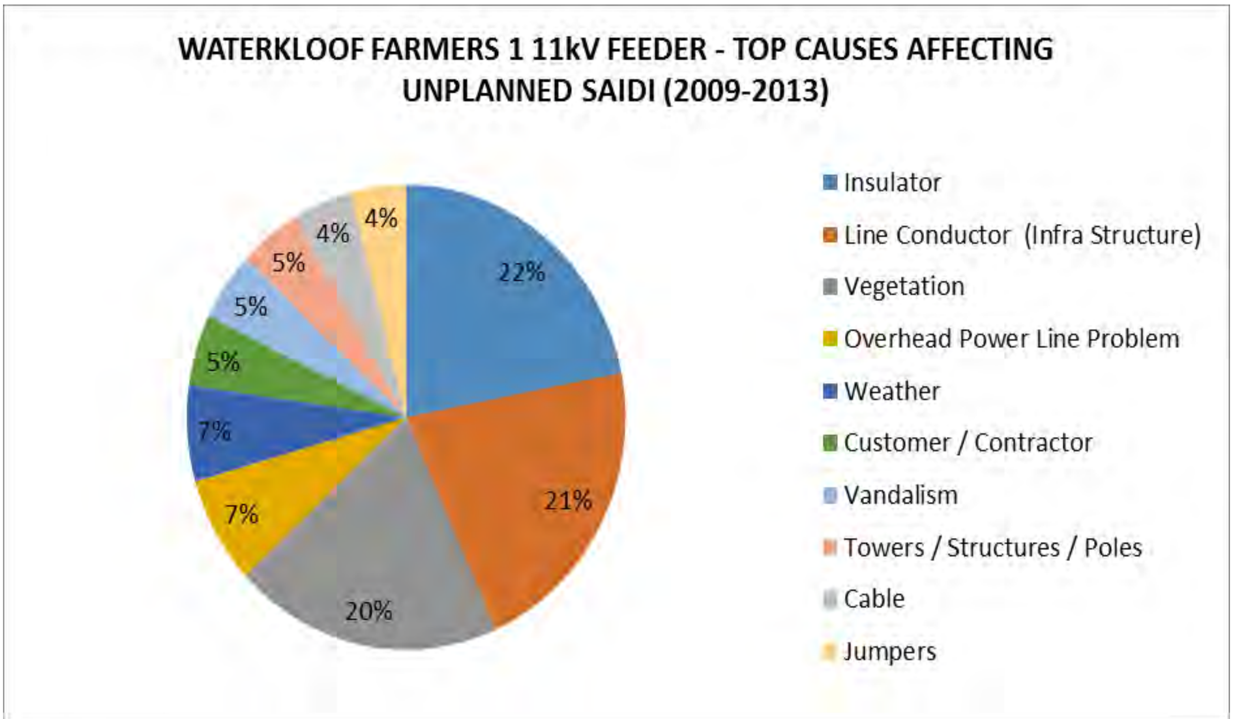


Figure 5.21: **Top causes of unplanned SAIDI**

The SAIDI value indicates that Waterkloof Farmers 1 11 kV Feeder customers being served by Eskom were without power approximately 9.55 hours on average in December 2013. In January 2009, on average the feeder's customers were without power the longest, approximately 60.24 hours.

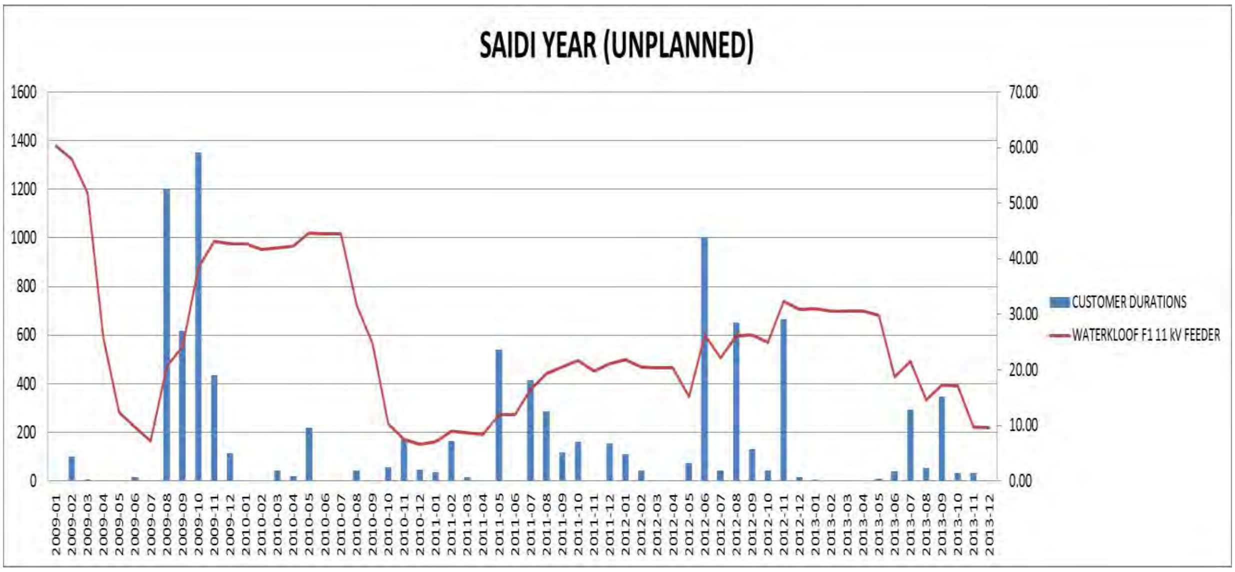


Figure 5.22: **The performance of the feeder since January 2009 – December 2013, in terms of unplanned SAIDI**

The graph in Figure 5.23 below shows the unplanned SAIFI for Waterkloof Farmers 1 11 kV Feeder in the years 2009 through 2013. The graph suggests that customers were the longest without power in November 2012, on average 24.89 times per year. At the end of December 2013, the customers were without power approximately 4.67 times per year on average.

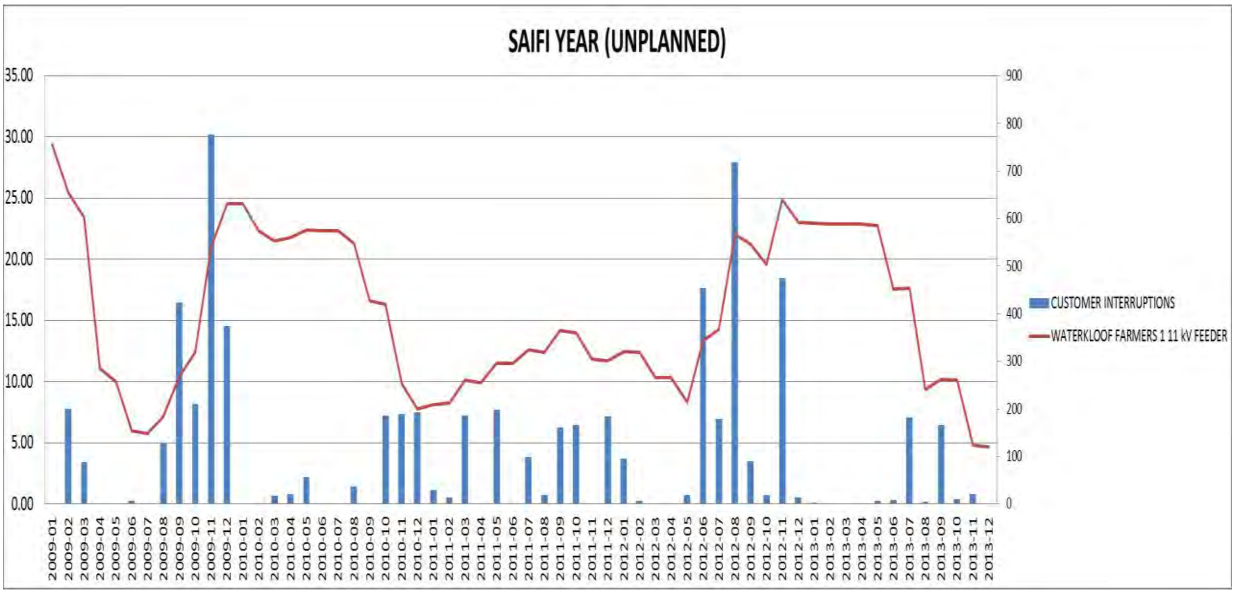


Figure 5.23: **The performance of the feeder since January 2009 – December 2013 in terms of unplanned SAIFI**

5.4. Reliability Evaluation of a Test System using FMEA

5.4.1 Example of utilising Failure Mode Effect Analysis - Reliability Analysis of Bus 6 of the RBTS

The procedure for the real network is first applied on the Distribution Test system (RBTS Bus 6) Feeder 4 [10], [60]. Feeder 4 of bus 6 is a relatively long 33 kV feeder with 3 sub feeders and the load is a combination of residential and agricultural customers. The total load is 4.815 MW and the total number of customers connected to Feeder 4 is 1183. The authors have used a failure rate of 0, 065 failures/km.yr for the main feeder and lateral distributors as per the data provided in reference [10], [60] i.e. the data given for 11 kV feeder sections.

Feeder 4 is shown in Figure 5.24 below.

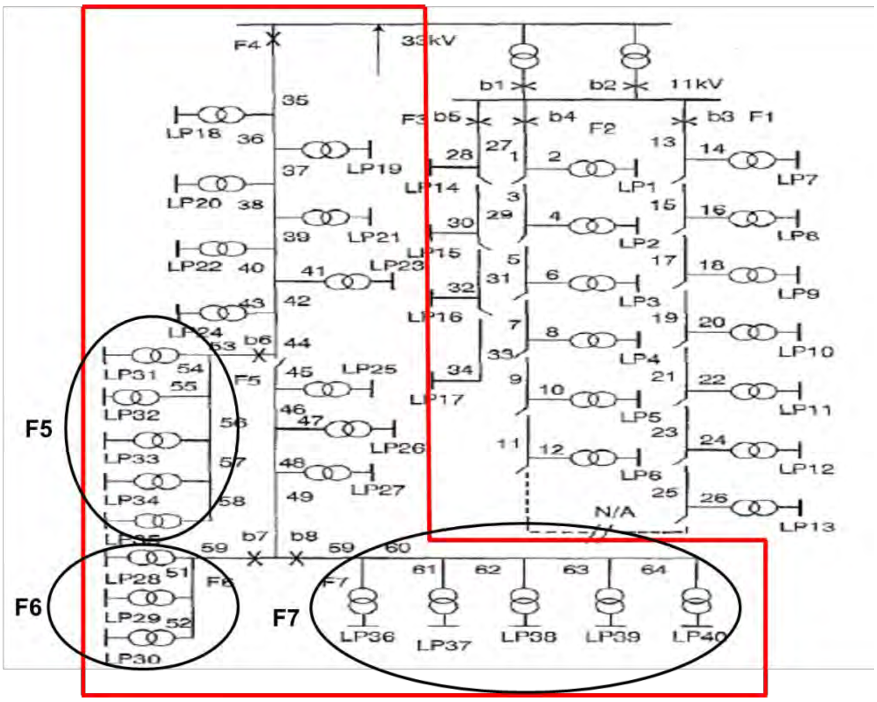


Figure 5.24: **Distribution Test system (RBTS Bus 6) Feeder 4 [10], [60]**

Conventional FMEA Approach

The conventional techniques for distribution system reliability evaluation are generally based on failure mode and effect analysis using FMEA. The FMEA technique has been used to evaluate the Distribution Test system (RBTS Bus 6) Feeder 4 with complex configurations and a wide range of components and element operating modes, the list of basic failure events can become lengthy and can include thousands of basic failure events. This requires extensive analysis when the FMEA technique is used as shown in Table 5.1 below. It is, therefore, difficult to use FMEA directly to evaluate a complex radial distribution system [62].

If any division of the main feeder fails, then the circuit breaker for Feeder 4 will be activated and all load points will be without a supply for a short period of time. When this happens, the relevant switches will be opened to isolate the faulted part of the network only. Then the circuit breaker will be closed and healthy parts of the system are restored (if possible). The faulted part of the system will only be restored once the component is repaired. It is assumed that the busbar and the circuit breakers operation are 100 % reliable. The repair time for both the main and lateral sections is 5.0 hours and switching time is 1.0 hour. Replacement time by a spare for transformers is assumed to be 10 hours. The system data of main and lateral sections including the load point information for Bus 6 Feeder 4 are shown in Appendix N.

Table 5.1: Load point indices calculations for Feeder 4 using Conventional FMEA Approach.

	Load Point 18			Load Point 19			Load Point 20			Load Point 21			Load Point 22			Load Point 23			Load Point 24		
section	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
35	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
36	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
37	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
38	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
39	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
40	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
42	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
44	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
45	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208
46	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182
48	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275
49	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.039	5	0.195	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04875	5	0.24375
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 - LP28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 - LP29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 - LP30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5 - LP31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5 - LP32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5 - LP33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5 - LP34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5 - LP35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F7 - LP36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F7 - LP37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F7 - LP38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F7 - LP39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F7 - LP40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transformer	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
Total	**1.6725**	**3.32**	**5.5515**	**1.6725**	**3.31928**	**5.5515**	**1.6725**	**3.32**	**5.5515**	**1.6725**	**3.32**	**5.5515**	**1.6725**	**3.3**	**5.5515**	**1.7115**	**3.36**	**5.7465**	**1.72125**	**3.367**	**5.79525**

									Feeder 6 (F6)								
Load Point 25			**Load Point 26**			**Load Point 27**			**Load Point 28**			**Load Point 29**			**Load Point 30**		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.039	5	0.195	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.5525	5	2.7625	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.5525	5	2.7625	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5525	5	2.7625
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
1.6725	**5.04**	**8.4375**	**1.7115**	**5.04**	**8.6325**	**1.6725**	**5.045**	**8.4375**	**2.225**	**5.03**	**11.2**	**2.225**	**5.034**	**11.2**	**2.225**	**5.034**	**11.2**

Feeder 5 (F5)														
Load Point 31			**Load Point 32**			**Load Point 33**			**Load Point 34**			**Load Point 35**		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208
0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182
0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275
0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.8645	5	4.3225	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.9165	5	4.5825	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.8645	5	4.3225	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.8645	5	4.3225	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.8645	5	4.3225
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
2.537	**3.892**	**9.874**	**2.589**	**3.91**	**10.134**	**2.537**	**3.89**	**9.874**	**2.537**	**3.89**	**9.874**	**2.537**	**3.89**	**9.874**

Feeder 7 (F7)														
Load Point 36			**Load Point 37**			**Load Point 38**			**Load Point 39**			**Load Point 40**		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.8385	5	4.1925	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.88725	5	4.43625	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.8385	5	4.1925	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.8385	5	4.1925	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.8385	5	4.1925
0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
2.511	**5.03**	**12.63**	**2.55975**	**5.029**	**12.8738**	**2.511**	**5.03**	**12.63**	**2.511**	**5.03**	**12.63**	**2.511**	**5.03**	**12.63**

The system indices - SAIFI, SAIDI, and CAIDI can then be calculated using the conventional FMEA approach from the load point indices, the number of customers and load connected at the load point [62]. The detail calculations shown below are the system indices for Feeder 4 of Bus 6 of the RBTS.

$$\boldsymbol{SAIDI} = \frac{(5.5515*147)+(5.5515*126)+(5.5515*1)+(5.5515*1)+(5.5515*132)+(5.7465*147)+(5.79525*1)+(8.4375*79)}{1183}+$$

$$\frac{(8.6325*1)+(8.4375*76)+(11.2*79)+(11.2*76)+(11.2*1)+(9.874*79)+(10.137*1)+(9.874*76)+(9.874*1)}{1183}+$$

$$\frac{(9.874*1)+(12.63*79)+(12.874*1)+(12.63*1)+(12.63*76)+(12.63*1)}{1183}$$

= 8.22 hours/ customer.year

$$\boldsymbol{SAIFI} = \frac{(1.6725*147)+(1.6725*126)+(1.6725*1)+(1.6725*1)+(1.6725*132)+(1.7115*147)+(1.7213*1)+(1.6725*79)}{1183}+$$

$$\frac{(1.7115*1)+(1.6725*76)+(2.225*79)+(2.225*76)+(2.225*1)+(2.537*79)+(2.589*1)+(2.537*76)+(2.537*1)}{1183}+$$

$$\frac{(2.537*1)+(2.511*79)+(2.5598*1)+(2.511*1)+(2.511*76)+(2.511*1)}{1183}$$

= 1.98 interruptions/ customer.year

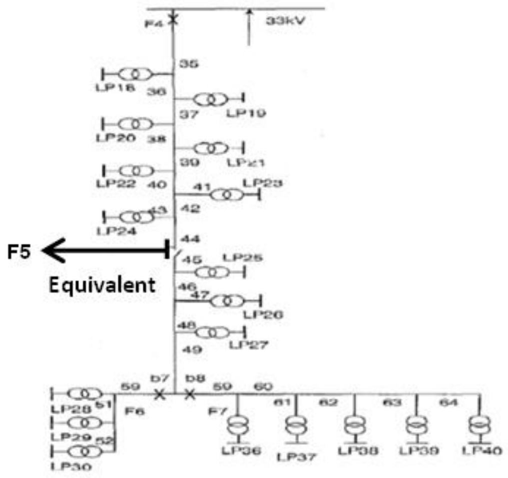
CAIDI = $\frac{SAIDI}{SAIFI}$ = $\frac{8.22}{1.98}$ = *4.16 hours/customer interruption*

Table 5.2: System Indices for Feeder 4 using Conventional FMEA Approach.

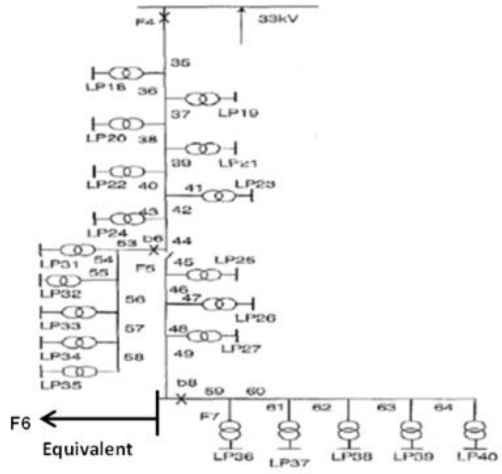
Index	
SAIDI (hours/ customer.year)	8.22
SAIFI (interruptions/ customer.year)	1.98
CAIDI (hours/customer interruption)	4.16

Reliability Network Equivalent Approach

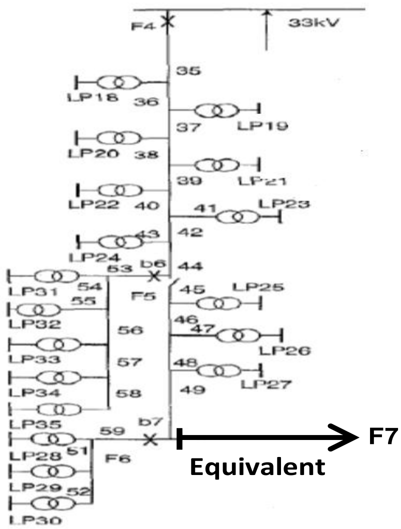
Calculating the reliability indices for Distribution Test system (RBTS Bus 6) Feeder 4 using the reliability network equivalent approach is summarised below. As shown in Figure 5.24 and Figure 5.25 all the Sub Feeders F5, F6 and F7 were replaced by corresponding equivalent lateral sections [see Appendix N for detail procedure of the equivalent lateral sections]. The system is reduced to a general distribution system. The load-point indices in Feeder 4 and the equivalent lateral sections are then calculated [62].



(a)



(b)



(c)

Figure 5.25: **Reliability Network Equivalent Approach - RBTS Bus 6 Feeder 4 (a) Sub Feeder 5 (b) Sub Feeder 6 (c) Sub Feeder 7**

The first step was to find the equivalent lateral sections of Sub Feeders 5, 6 and 7. The equivalent-lateral-section parameters for the three feeders are as follows:

Table 5.3 below shows the total length for Sub Feeders 5, 6 and 7 calculated by adding the lengths of the feeder sections (see Figure 5.24 for feeder section numbers).

Table 5.3: Feeder section numbers and lengths (Table of feeder types and lengths can be found in Appendix N)

Sub Feeders	Feeder Section Numbers	Length (km)
Feeder 5		
	53	3.2
	54	1.6
	56	2.8
	57	2.5
	58	3.2
Total length for Feeder 5 (F5)		**13.3**
Feeder 6	51	3.2
	52	2.5
	59	2.8
Total length for Feeder 6 (F6)		**8.5**
Feeder 7		
	59	2.8
	60	2.5
	62	1.6
	63	3.2
	64	2.8
Total length for Feeder 7 (F7)		**12.9**

For Feeder 5:

Note that the repair time *r* (hours) and switching time *s* (hours) for Feeder 4 is 5 hrs and 1 hr respectively. Also, note that the failure rate of the feeder and laterals is actually a function of their length (f/km year). The failure rate is calculated by simply multiplying the total length of the feeder sections of Sub Feeders 5, 6 and 7 with the component failure rate (λ = 0.065 f/km.year) [62]. i.e.

λ_{e51} = (13.3 km) x (0.065 f/km.year) = 0.8645 (occ/year)
U_{e51} = λ_{e51} x r (hours) = 0.8645 (occ/year) x 5 (hrs) = 4.3225 (hrs/year)
r_{e51} = 5 (hrs)

For Feeder 6:

λ_{e61} = (8.5 km) x (0.065 f/km.year) = 0.5525 (occ/year)
U_{e61} = λ_{e61} x r (hours) = 0.5525 (occ/year) x 5 (hrs) = 2.7625 (hrs/year)
r_{e61} = 5 (hrs)

For Feeder 7:

λ_{e71} = (12.9 km) x (0.065 f/km.year) = 0.8385 (occ/year)
U_{e71} = λ_{e71} x r (hours) = 0.8385 (occ/year) x 5 (hrs) = 4.1925 (hrs/year)
r_{e71} = 5 (hrs)

After the equivalent lateral sections of Feeders 5, 6 and 7 have been found, Feeder 4 becomes a general distribution feeder [62]. The next step is to calculate the load point indices in Feeder 4 using FMEA. As shown in Table 5.4, the load point indices i.e. the average failure rate *λ*, average outage time *r* and average annual outage time or unavailability *U* are calculated using equations (2.1) to (2.3) for LP18 to LP27 and Sub Feeders 5,6 and 7 of Feeder 4 [62]. The data used in these studies are given in Appendices N.

Table 5.4: Load point indices calculations for Feeder 4 using FMEA and Reliability Network Equivalent Approach

	Load Point 18			Load Point 19			Load Point 20			Load Point 21			Load Point 22			Load Point 23		
section	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
35	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
36	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
37	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
38	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
39	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
40	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
42	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
44	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
45	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208
46	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182
48	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275	0.2275	1	0.2275
49	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.039	5	0.195
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reliability-network equivalent- Feeder 5 (F5)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reliability-network equivalent - Feeder 6 (F6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reliability-network equivalent - Feeder 7 (F7)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transformers	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
Total	**1.6725**	**3.3193**	**5.5515**	**1.6725**	**3.31928**	**5.5515**	**1.6725**	**3.3193**	**5.5515**	**1.6725**	**3.3193**	**5.5515**	**1.6725**	**3.319**	**5.5515**	**1.7115**	**3.358**	**5.7465**

Load Point 24			Load Point 25			Load Point 26			Load Point 27			Feeder 5 (F5)			Feeder 6 (F6)			Feeder 7 (F7)		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125	0.1625	5	0.8125
0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925	0.0585	5	0.2925
0.208	1	0.208	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04	0.208	1	0.208	0.208	5	1.04	0.208	5	1.04
0.182	1	0.182	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	1	0.182	0.182	5	0.91	0.182	5	0.91
0.2275	1	0.2275	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	5	1.1375	0.2275	1	0.2275	0.2275	5	1.1375	0.2275	5	1.1375
0.104	1	0.104	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	1	0.104	0.104	5	0.52	0.104	5	0.52
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.04875	5	0.24375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.039	5	0.195	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.8645	5	4.3225	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5525	5	2.7625	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8385	5	4.1925
0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15	0.015	10	0.15
1.7213	**3.367**	**5.7953**	**1.6725**	**5.0448**	**8.4375**	**1.7115**	**5.044**	**8.6325**	**1.6725**	**5.0448**	**8.4375**	**2.537**	**3.892**	**9.874**	**2.225**	**5.03371**	**11.2**	**2.511**	**5.02987**	**12.63**

Where *λtotal* = *∑λ*, *Utotal* = *∑U* and *r* = $\frac{\sum U}{\sum \lambda}$

Note: Trfr – Transformer

The system indices - SAIFI, SAIDI, and CAIDI can then be calculated from the load point indices, the number of customers and load connected at the load point [62]. The detail calculations shown below are the system indices for Feeder 4 of Bus 6 of the RBTS.

$$SAIDI = \frac{(5.5515*147)+(5.5515*126)+(5.5515*1)+(5.5515*1)+(5.5515*132)+(5.7465*147)+(5.79525*1)+(8.4375*79)+(8.6325*1)+(8.4375*76)+(9.874*158)+(12.2*156)+(12.63*158)}{1183}$$

= 8.22 hours/ customer.year

$$SAIFI = \frac{(1.6725*147)+(1.6725*126)+(1.6725*1)+(1.6725*1)+(1.6725*132)+(1.7115*147)+(1.72125*1)+(1.6725*79)+(1.7115*1)+(1.6725*76)+(2.537*158)+(2.225*156)+(2.511*158)}{1183}$$

= 1.98 interruptions/ customer.year

CAIDI = $\frac{SAIDI}{SAIFI} = \frac{8.22}{1.98}$ = ***4.16 hours/customer interruption***

Table 5.5: System Indices for Feeder 4 using Reliability Network Equivalent Approach

Index	
SAIDI (hours/ customer.year)	8.22
SAIFI (interruptions/ customer.year)	1.98
CAIDI (hours/customer interruption)	4.16

The basic load point and system indices thus calculated are expected values. This agrees with the results published in [10], [60].

Conventional FMEA Approach versus Reliability-Network-Equivalent Approach

The conventional FMEA approach was initially used for evaluating the reliability of a complex radial distribution test system, RBTS Bus 6, Feeder 4 and then compared to the reliability-network-equivalent approach. A reliability-network-equivalent approach is introduced to simplify the analytical process and to provide a more simplified approach to the reliability evaluation of complex distribution systems. Reliability evaluations for the test distribution system have shown this technique to be superior to the conventional FMEA approach. This method avoids the required procedure of finding the failure modes and their effect on the individual load points, and results in a significant reduction in analytical calculation time [62].

As shown in Table 5.6 below, after comparing the results of the conventional FMEA approach and reliability-network-equivalent method, it can be seen that the reliability indices of the Distribution Test system (RBTS Bus 6) Feeder 4 are the same [62].

Table 5.6: Comparison between Conventional FMEA and Reliability Network Equivalent Approach

Index	Conventional FMEA Approach	Reliability-Network-Equivalent Approach	% DIFF
SAIDI	8.22	8.22	0.00
SAIFI	1.98	1.98	0.00
CAIDI	4.16	4.16	0.00

The Reliability Network Equivalent Approach is then applied to the pilot feeder.

5.5. Implementation of the FMEA on the Pilot Feeder – Waterkloof Farmers 1 11 kV Feeder

FMEA was used to evaluate the contingencies of the components failing and to see how this affects the load points. It is difficult to use FMEA only to evaluate a complex radial distribution system. A Reliability Network Equivalent Approach is introduced to simplify the analytical process. This method was demonstrated in section 5.4 using a test system.

5.5.1 Evaluation Technique - Modelled Network Reliability Calculations

The overview of Waterkloof F1 11 kV Feeder network is illustrated in Figure 5.26. The detailed Waterkloof F1 Feeder drawing is illustrated in Figures 5.27, 5.28 and 5.29.

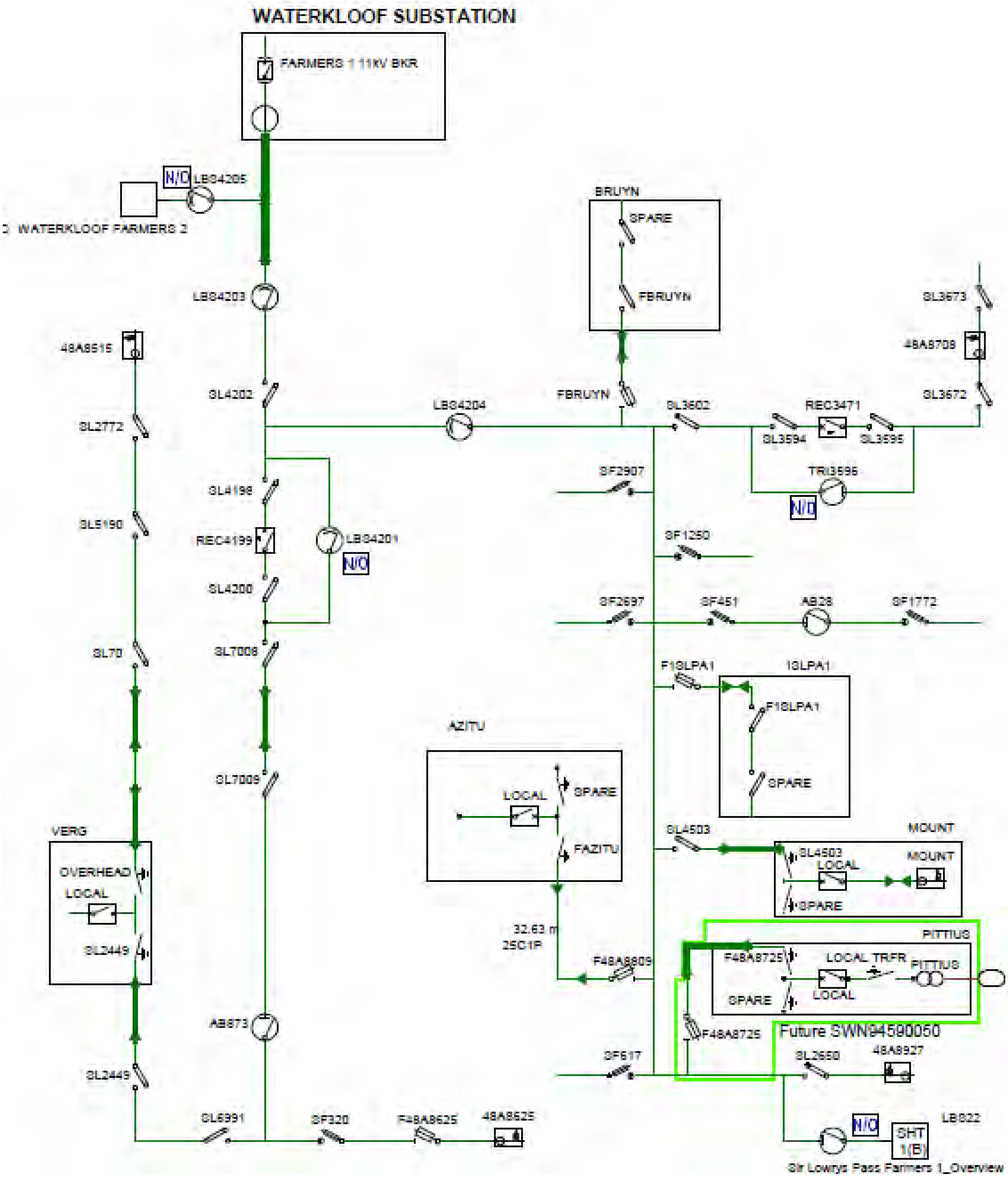


Figure 5.26: **Waterkloof Farmers 1 Overview [6]**

The Waterkloof F1 11 kV Feeder is a complex radial feeder that contains a number of sub-feeders. In order to simplify and make failure mode calculations possible a number of sub-feeders are combined into one lateral equivalent. In order to make sub-feeders A-M, as one load point, the author had to treat them as single feeders and then calculate the number of outages and their duration for individual customers as well as the overall system indices using the reliability network equivalent approach and FMEA. If any section of the main feeder fails, then the circuit breaker will be activated and all load points will be without supply. When this happens, the relevant switches will be opened to isolate the faulted part of the network. Then the circuit breaker will be closed and the healthy parts of the system are restored (if possible). The faulted part of the system will only be restored once the component is repaired. If one of the distributors fails, the section fuse will isolate the fault and hence only the local load point will be affected. To simplify the evaluation, it is assumed that the substation circuit breaker and the section fuse do not fail.

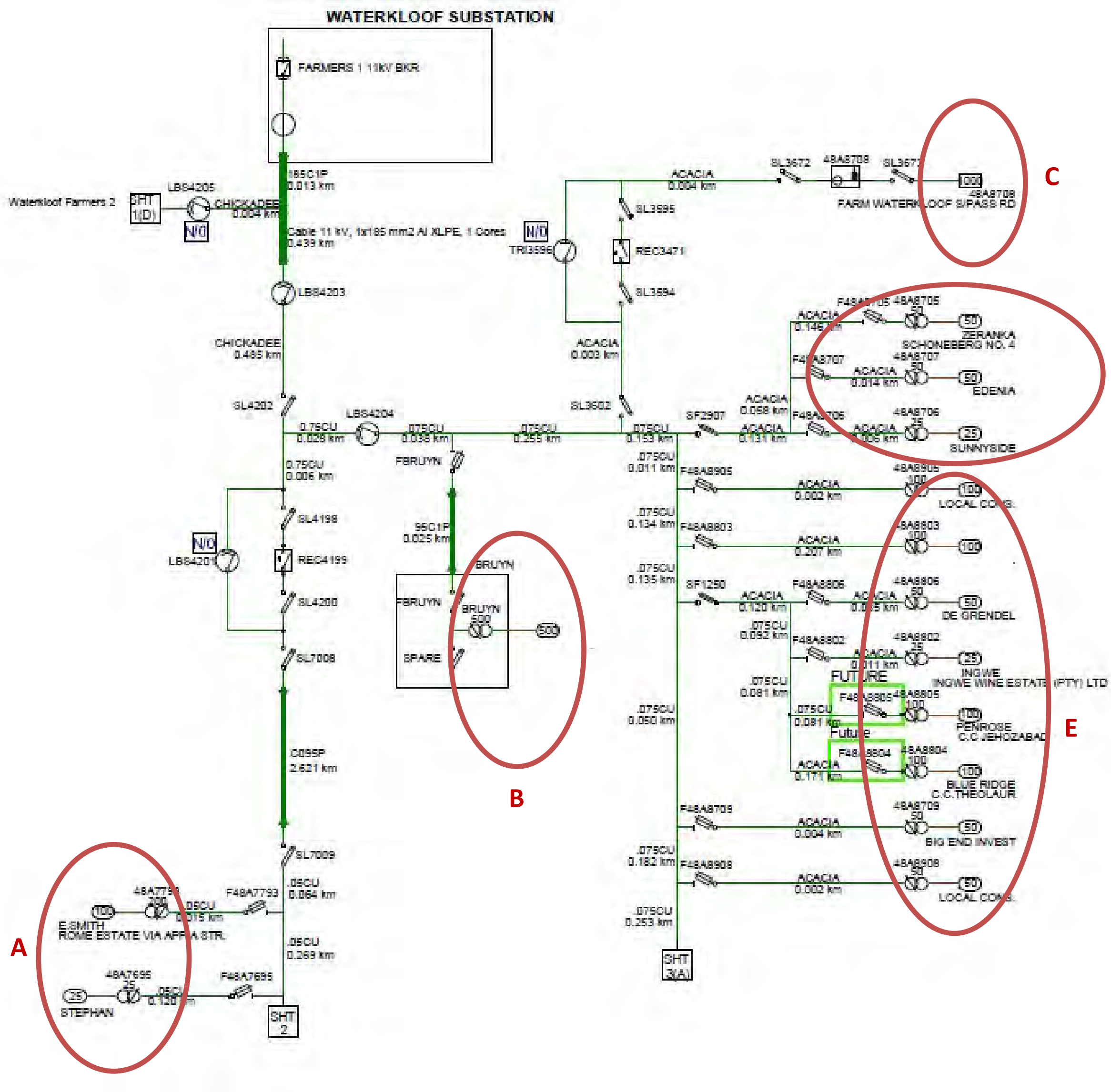


Figure 5.27: **Waterkloof Farmers 1 11 kV Feeder – Sub-feeders A-E [6]**

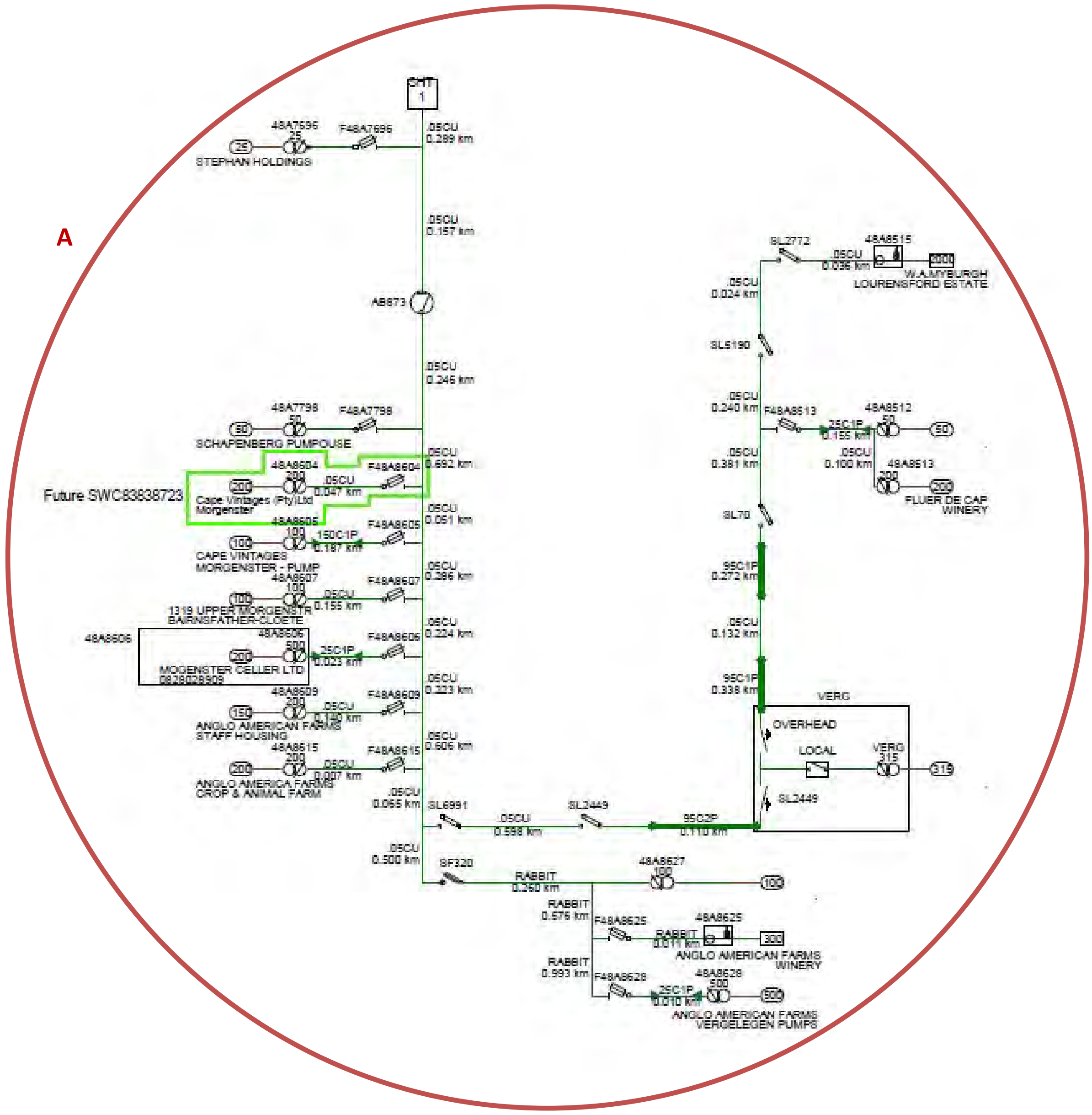


Figure 5.28**: Waterkloof Farmers 1 11 kV Feeder - Sub-feeder A [6]**

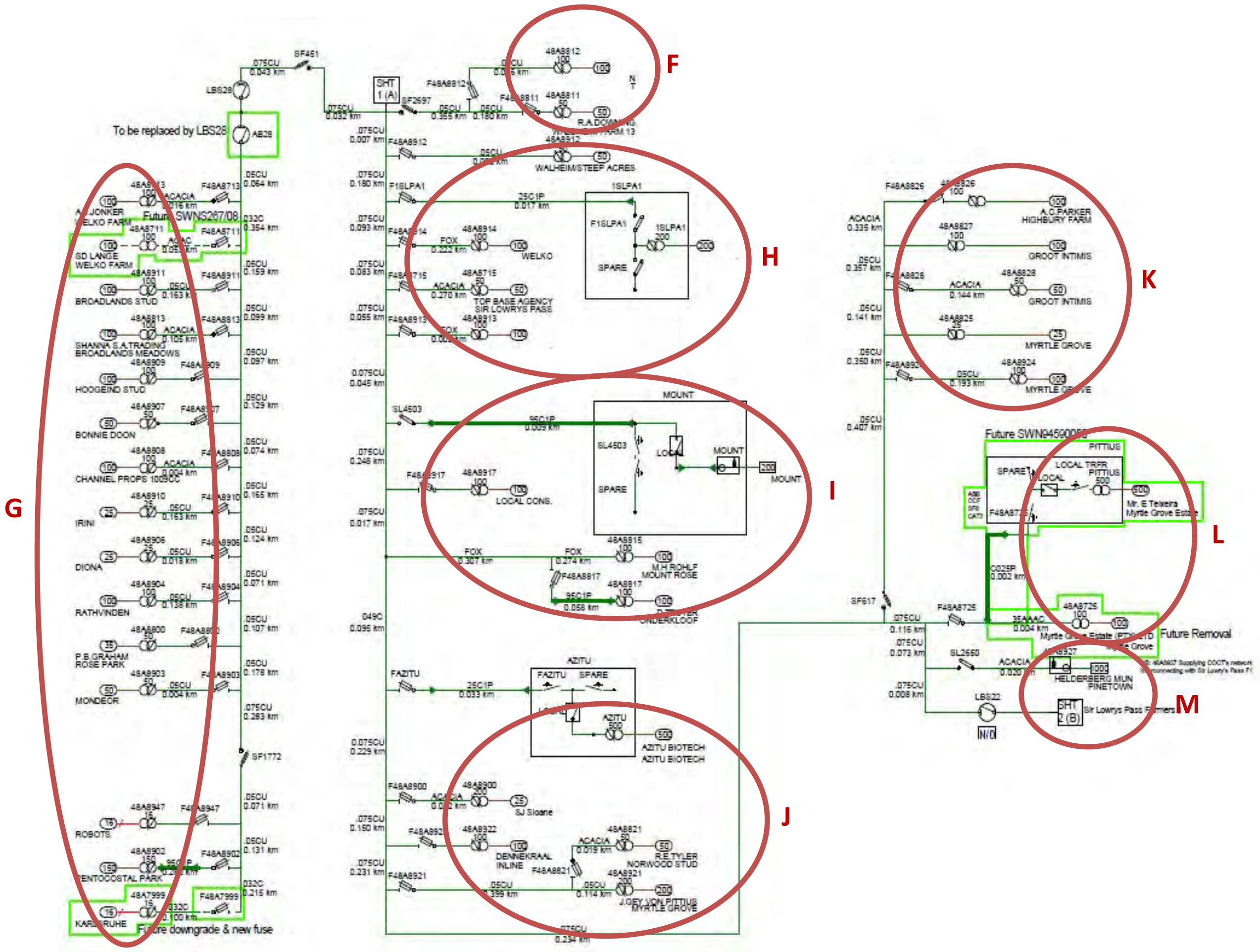


Figure 5.29**: Waterkloof Farmers 1 11 kV Feeder – Sub-feeders F-M [6]**

The Reliability Network Equivalent Approach provided a practical technique for evaluating distribution system reliability in complex configurations. Figure 5.30 presents the network reliability equivalent of the load points A - M for Waterkloof Farmers 1 11 kV. The procedure involves the development of equivalent lateral sections. The basic concepts in this approach have been illustrated using the tested distribution system shown in section 5.4 and Appendix N.

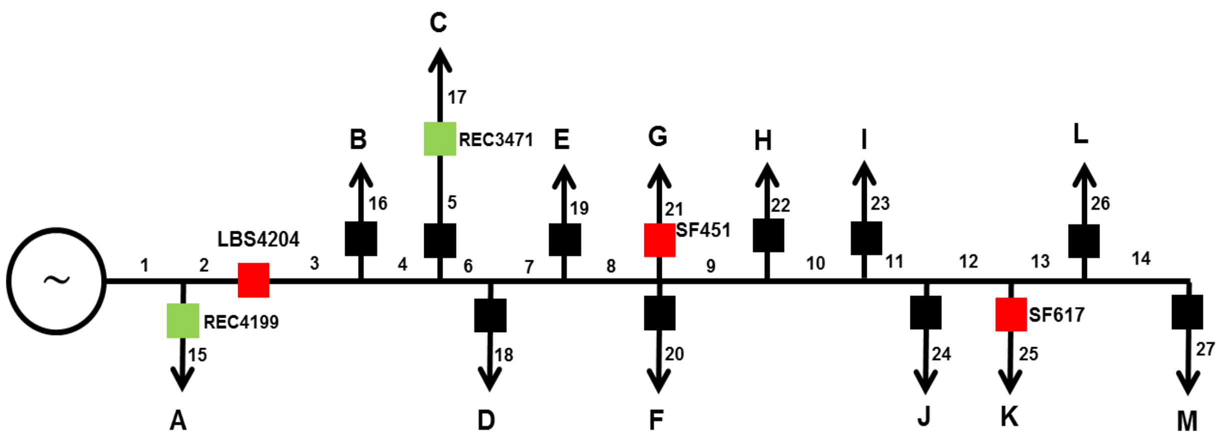


Figure 5.30: **Network reliability equivalent of lateral sections for Waterkloof Farmers 1 11 kV Feeder**

The network in Figures 5.27 – 5.29 is a series network and the equations (2.1) to (2.3) can be used to calculate the load point indices. Recall:

$$\lambda_S = \sum \lambda_i \tag{2.1}$$

$$r_S = \frac{U_S}{\lambda_S} = \frac{\sum \lambda_i r_i}{\sum \lambda_i} \tag{2.2}$$

$$U_S = \sum \lambda_i r_i \tag{2.3}$$

The above equations will be used to calculate indices for each of the load points.

Based on the failure rate from Historical data as obtained from Eskom, the lines and cables average failure rate per 100 km per annum recorded was 1.0947 for the period of 5 years (January 2009 - December 2013) (see Appendix G for details). The transformer failure rate per annum is 0.015. The protection devices have a 5% failure rate per annum. The average restoration time for the components is 5 hours before installation of equipment, irrespective of any failure due to the availability of spares at the store room. Using the above data the load point and system indices were calculated and the results of the reliability analysis of the pilot network were achieved.

The reliability parameters of this network are tabulated below.

Line: λ = 1.0947 (f/km.yr) ($\lambda = \frac{133\ faults}{5\ years * 24.3km(length\ of feeder)}$)

Table 5.7: Reliability parameters for system before installation of equipment (main section data)

Main Section	Length (km)	λ(f/yr)	r(hr/f)	s(hr/yr)		Line: λ = 1.0947 (f/km.yr)
1	0.485	0.5309	5	1		
2	0.028	0.0307	5	1		
3	0.038	0.0416	5	1		
4	0.255	0.2791	5	1		
5	0.003	0.0033	5	1		
6	0.153	0.1675	5	1		
7	0.011	0.012	5	1		
8	0.253	0.277	5	1		
9	0.007	0.0077	5	1		
10	0.045	0.0493	5	1		
11	0.095	0.104	5	1		
12	0.234	0.2562	5	1		
13	0.116	0.127	5	1		
14	0.073	0.0799	5	1		

Table 5.8: Reliability parameters for system before installation of equipment (Lateral section and transformer data)

Component	Length (km)	λ(f/yr)	r(hr/f)	s(hr/yr)		Line: λ = 1.0947 (f/km.yr)
Sections						
15	6.876	7.5272	5	1		
16	0	0	5	1		
17	0.004	0.0044	5	1		
18	0.335	0.3667	5	1		
19	1.046	1.1451	5	1		
20	0.611	0.6689	5	1		
21	2.396	2.6229	5	1		
22	0.411	0.4499	5	1		
23	0.846	0.9261	5	1		
24	1.123	1.2293	5	1		
25	1.59	1.7406	5	1		
26	0	0	5	1		
27	0	0	5	1		
Transformers		0.015	10			

Table 5.9: Reliability parameters for system before installation of equipment (Waterkloof Farmers 1 11 kV Feeder - Number of customers connected per load point)

LOAD POINT	Number of Customers
A	20
B	1
C	1
D	2
E	12
F	3
G- SF451	15
H	5
I	6
J	11
K- SF617	6
L	3
M	1
Total	**86**

5.5.2 Load Point and System Indices Calculations before Installation of Equipment

The load point and system indices are very useful in assessing the severity of the system failure for predicting future reliability. The two indices are also good and play a major role in assessing the past performance of the system. However, it is impossible to use these indices to make a prediction on the system future performance because of the changes on the topology, protection schemes and switches that are undertaken on the network.
In order to assess the past performance of the system, three important procedures should be followed [37]:

(a) Establishment of the chronological changes in system performance and, therefore, helps to identify weak areas and the need for strengthening.

(b) Establishment of the existing indices which serve as a guide for acceptable values in future reliability assessments.

(c) Compare previous predictions with actual operating experience [37].

Indices are evaluated for faults due to the overhead line, cables, transformers and the protection devices since they are the only equipment that are mostly exposed to failure. The lengths of the overhead lines are given in the network diagrams and Tables 5.7 - 5.8 above. The lengths of the overhead line serve a very useful purpose since the calculations of specific line failure rate require such data. It is assumed that the busbars operations are 100 % reliable since the busbar is just an aluminium bar that provides the connection of the incoming and outgoing voltages within substations.

Note that the switching time for all switches is between 0 to 5 hours. Also, note that the failure rate of the feeders and distributors is actually a function of their length (faults/km.year). The failure rate in Tables 5.7 and 5.8 was calculated by simply multiplying the length of the feeder/ distributors with the components failure rate (f/km.year). For example, components 1 (main feeder sections) has a failure rate of 1.0947 (f/km.year). To get the overall λ (f/km.year) of the components, the failure rate must be multiplied by the length of this feeder, 0,485 km.

So λ =1.0947 x 0,485 = 0.5309 (f/km.year)

The approach is to make an FMEA table with four different configurations used on the pilot feeder. i.e.

- **Configuration 1**: Standard Eskom MV Network with fuses, disconnects and reclosers (base case)

This is done in Table 5.10 below.

Configuration 1 - Repair time r = 5 hrs (before installation of the new devices)

Table 5.10: Load point indices for the pilot network – Configuration 1

λ = 1.0947	Load Point A			Load Point B			Load Point C			Load Point D			Load Point E			Load Point F		
section	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
1	0,5309	5	2,654648	0,5309	5	2,6546	0,531	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
2	0,0307	5	0,153258	0,0307	5	0,1533	0,031	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
3	0,0416	5	0,207993	0,0416	5	0,208	0,042	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208
4	0,2791	5	1,395743	0,2791	5	1,3957	0,279	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957
5	0,0033	1	0,003284	0,0033	1	0,0033	0,003	5	0,0164	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033
6	0,1675	5	0,837446	0,1675	5	0,8374	0,167	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374
7	0,012	5	0,060209	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602
8	0,277	5	1,384796	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848
9	0,0077	5	0,038315	0,0077	5	0,0383	0,008	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383
10	0,0493	5	0,246308	0,0493	5	0,2463	0,049	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463
11	0,104	5	0,519983	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52
12	0,2562	5	1,280799	0,2562	5	1,2808	0,256	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808
13	0,127	5	0,634926	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349
14	0,0799	5	0,399566	0,0799	5	0,3996	0,08	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996
15	7,5272	0,1	0,752716	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0,004	0,1	0,0004	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0,3667	5	1,8336	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	1,1451	5	5,7253	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,6689	5	3,3443
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transformers	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
Total	**9,508**	**1,13**	**10,72**	**1,981**	**5,03123**	**9,967**	**1,985**	**5,027**	**9,9808**	**2,348**	**5,03**	**11,8**	**3,126**	**5,02**	**15,69**	**2,6499**	**5**	**13,31**

Load Point G			Load Point H			Load Point I			Load Point J			Load Point K			Load Point L			Load Point M		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0,5309	5	2,65465	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
0,0307	5	0,15326	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
0,0416	5	0,20799	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208
0,2791	5	1,39574	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957
0,0033	1	0,00328	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033
0,1675	5	0,83745	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374
0,012	5	0,06021	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602
0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848
0,0077	5	0,03831	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383
0,0493	5	0,24631	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463
0,104	5	0,51998	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52
0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808
0,127	5	0,63493	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349
0,0799	5	0,39957	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,6229	5	13,1145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0,4499	5	2,2496	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0,9261	5	4,6306	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1,2293	5	6,1467	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1,7406	5	8,7029	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
4,604	**5,01**	**23,082**	**2,431**	**5,03**	**12,217**	**2,907**	**5,02**	**14,6**	**3,21**	**5,02**	**16,11**	**3,722**	**5,02**	**18,67**	**1,981**	**5,03**	**9,967**	**1,981**	**5,03**	**9,967**

Where $\lambda_s = \sum \lambda_i$, $r_s = \frac{U_s}{\lambda_s} = \frac{\sum \lambda_i r_i}{\sum \lambda_i}$, $U_s = \sum \lambda_i r_i$

The FMEA load point indices for Table 5.10 are summaries in the bar graph below.

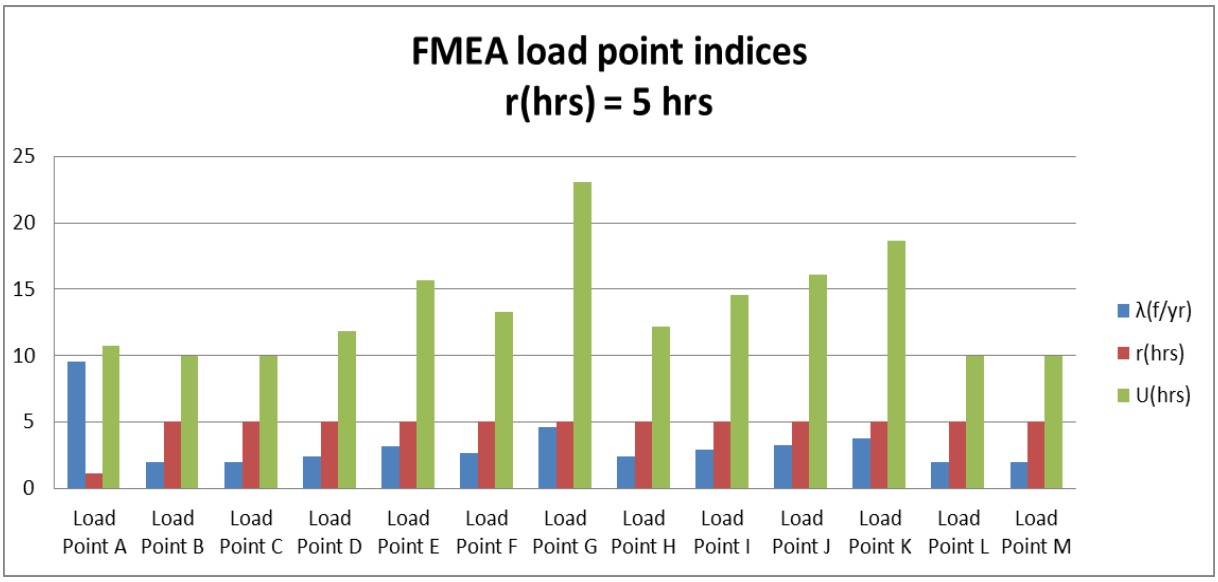


Figure 5.31: **FMEA load point indices where r (hrs) = 5 hrs**

The results shown in Table 5.10 can be used to obtain the system performance indices for the Configuration 1 used on the pilot feeder. In order to calculate the system indices, the value of the feeders load point indices, equivalent lateral sections and the number of customers connected to the feeder must be known. System indices calculations for Configuration 1 are shown below.

$$SAIDI = \frac{(10,72*20)+(9.9673*1)+(9.981*1)+(11.8009*2)+(15.6926*12)+(13.3116*3)+(23.0818*15)+(12.2169*5)+(14.5979*6)+(16.1140*11)+(18.6701*6)+(9.9673*3)+(9.9673*1)}{86}$$

= 15.24 interruption/ (customers.year)

$$SAIFI = \frac{(9.5082*20)+(1.9811*1)+(1.9855*1)+(2.3478*2)+(3.1261*12)+(2.6499*3)+(4.6040*15)+(2.4310*5)+(2.9072*6)+(3.2104*11)+(3.7217*6)+(1.9811*3)+(1.9811*1)}{86}$$

= 4.75 hours/ (customer.year)

$CAIDI = \frac{SAIDI}{SAIFI} = \frac{15.24}{4.75}$ = ***3.21 hours/customers interruption***

Configuration 2, 3 and 4 will be explained in Chapter 8 after the installation of the equipment.

5.6. Comparison between Historical Assessment, FMEA and Simulation (DIgSILENT)

5.6.1 Comparison and Discussion of Load Point Indices Results

In order to assess the reliability performance of the system, the load point reliability and system reliability indices for the chosen distribution network were determined using DIgSILENT PowerFactory software. Network reliability assessment was used to calculate the expected interruption frequencies, duration and annual interruptions costs [51].

Figure 5.32: **Network reliability assessment modelled for Waterkloof Farmers 1 11 kV Feeder using DIgSILENT PowerFactory Software**

For the simulation, DIgSILENT PowerFactory (DPF) software was used to perform system reliability evaluation to obtain the load point indices as well as the system indices such as SAIFI, SAIDI and CAIDI. The load point indices results were simulated over the period of a year. According to the results compared between DIgSILENT PowerFactory and FMEA (from section 5.5.2) as tabulated below, a small number or no deviations were recorded for the failure rate analysis and unavailability. This is because the input data and switching time used for FMEA and DIgSILENT PowerFactory were the same. A higher failure rate is experienced at some of the load points because the protection devices such as fuses failed to operate in some occasion with a high number of customers affected beyond the load point.

Table 5.11 and Figure 5.33 below show the load points indices of Waterkloof Farmers 1 11 kV Feeder using the analytical (FMEA) and DIgSILENT PowerFactory simulation approaches.

Table 5.11: Load point indices using FMEA and DPF before installation of the new equipment

Load Points	Failure rate (faults/year)			Outage Time (hrs)			Unavailability (hrs/year)		
	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF
Load Point A	9,51	9,51	0	1,13	1,13	0	10,72	10,72	0
Load Point B	1,98	1,98	0	5,03	5,03	0	9,97	9,97	0
Load Point C	1,99	1,99	0	5,03	5,03	0	9,98	9,98	0
Load Point D	2,35	2,35	0	5,03	5,03	0	11,80	11,80	0
Load Point E	3,13	3,13	0	5,02	5,02	0	15,69	15,69	0
Load Point F	2,65	2,65	0	5,02	5,02	0	13,31	13,31	0
Load Point G	4,60	4,60	0	5,01	5,01	0	23,08	23,08	0
Load Point H	2,43	2,43	0	5,03	5,03	0	12,22	12,22	0
Load Point I	2,91	2,91	0	5,02	5,02	0	14,60	14,60	0
Load Point J	3,21	3,21	0	5,02	5,02	0	16,11	16,11	0
Load Point K	3,72	3,72	0	5,02	5,02	0	18,67	18,67	0
Load Point L	1,98	1,98	0	5,03	5,03	0	9,97	9,97	0
Load Point M	1,98	1,98	0	5,03	5,03	0	9,97	9,97	0

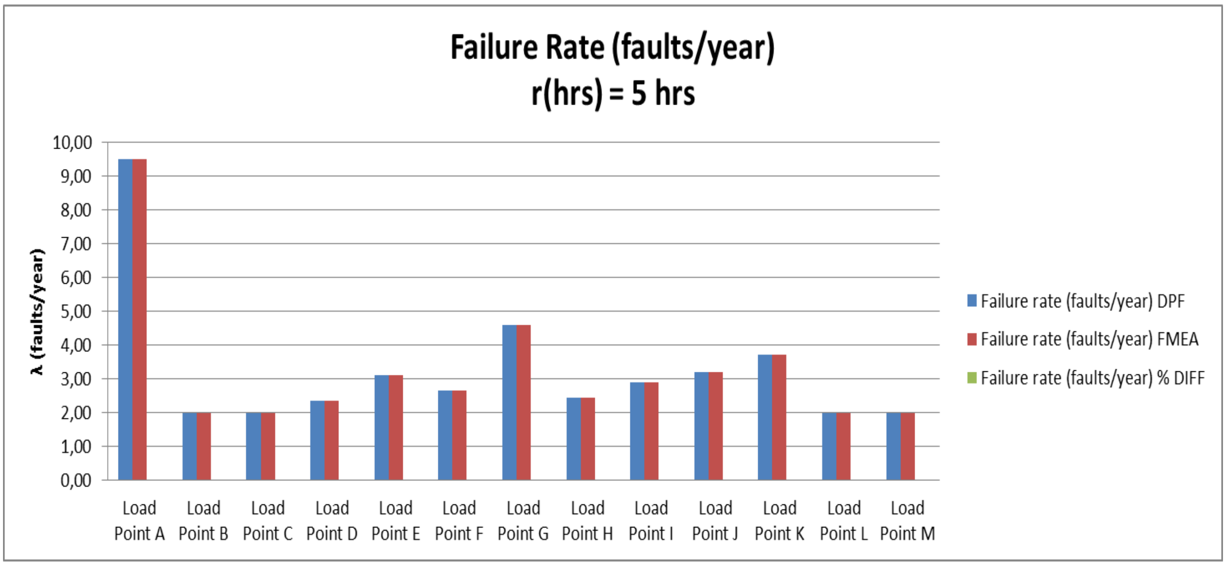


Figure 5.33: **Comparison of FMEA and DPF failure rate**

Comparing the results in Table 5.11 shows that Load point indices were found to be similar since all the assumptions made in FMEA, were stipulated in DIgSILENT Powerfactory. The results shown for both the simulation and analytical approaches are very much comparable, proving that any of these methods can be used to assess the reliability of a distribution network.

5.6.2 Comparison and Discussion of System Indices Results

The System Indices are computed using FMEA and DIgSILENT PowerFactory for the network Configuration 1. The load point indices are not presenting the full behaviour of the network which is the reason why system indices were computed to determine the performance of the modelled network.

Table 5.12: System indices using FMEA and DPF before installation of equipment

	SAIDI			SAIFI			CAIDI		
	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF
Configuration 1	15,24	15,24	0	4,75	4,75	0	3,21	3,21	0

The comparison of the total system indices using FMEA and DPF are as shown in Tables 5.12 above. The results shown in Table 5.12 for both the simulation and analytical approaches are very much comparable, proving that any of these methods can be used to assess the reliability of a distribution network. Also from the table, it can be seen that no percentage differences are observed between the results since all inputs specified in FMEA were also specified in DIgSILENT Powerfactory. Although both methods have shown a high degree of accuracy, DIgSILENT Powerfactory is still the number one choice due to many advantages 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. The disadvantage with the FMEA is the fact that it can be subjected to human error that will lead to incorrect results [37].

5.6.3 Historical vs. DIgSILENT PowerFactory Software

Table 5.13: Historical vs. DIgSILENT PowerFactory before installation of the new innovative technologies

	SAIDI			SAIFI			CAIDI		
	DPF	Historical Data	% DIFF	DPF	Historical Data	% DIFF	DPF	Historical Data	% DIFF
Whole System	15,24	18,34	-20,3412	4,75	8,94	-88,21	3,21	2,05	36,14
LBS4204	12,74	15,37	-20,6436	2,54	3,07	-20,87	5,02	5,01	0,20
SF451	2,29	0,77	66,37555	0,46	1,05	-128,26	5	0,73	85,40
SF617	0,61	0,25	59,01639	0,12	0,98	-716,67	5	0,26	94,80

As per simulation using DIgSILENT Powerfactory, the data used to calculate the SAIDI and the SAIFI are substantially noticeable with the historical data as shown in Table 5.13.The system reliability indices comparison for both simulation and historical data at the locations for the new equipment are different. Historical data is unpredictable and will vary every year to year depending on the severity of the weather and other unplanned faults. According to historical data of the Waterkloof Farmers 1 11 kV Feeder outages are relatively high, around 2 times monthly due to radial feeder configuration and high numbers of faults in the equipment and feeder sections, causing a great contribution to unavailability of electricity supply to customers. Supply restoration takes lots of time, not only due to the standard procedure reasons but also distribution protection system configuration itself; such as feeder breaker with many load break switches in the feeder. They caused poor reliability indices, especially SAIDI and SAIFI. One of the ways to improve the reliability indices of the overhead line in fault management is to reconfigure the distribution protection system by using the feeder automation. They work based on sensing and coordinating of voltage, current and time in case of any fault in the line, and use no communication facility thus improving restoration time.

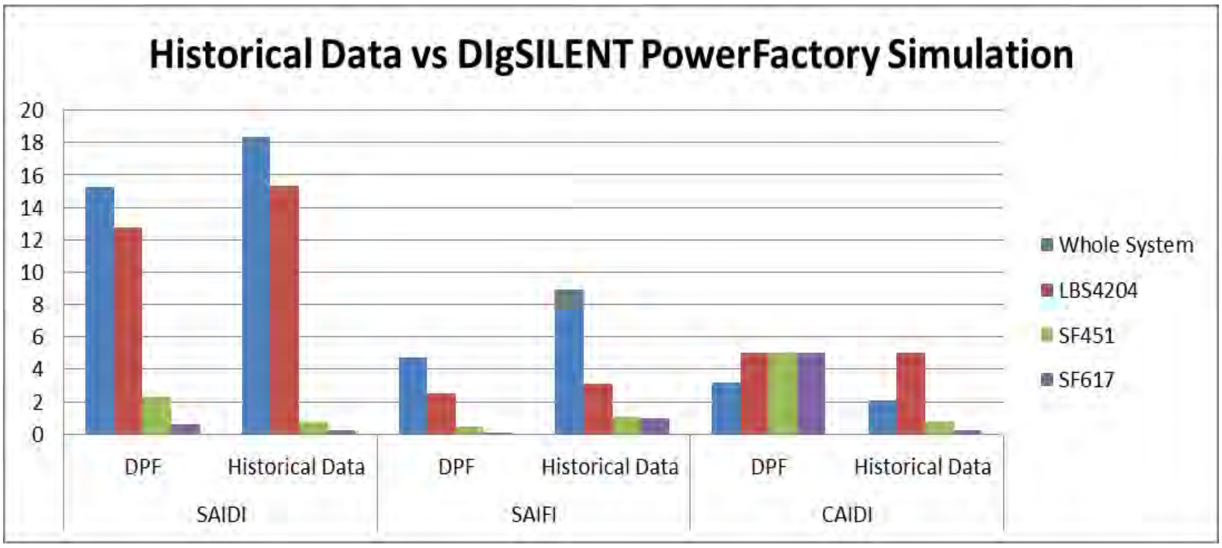


Figure 5.34: **Historical vs. DIgSILENT PowerFactory before installation of new innovative technologies**

Chapter 6: Location, Protection Coordination and Grading of Devices

6.1. Introduction

Power system protection is the process of making the generation, transmission, and distribution of electrical energy as safe as possible from the effects of failures and events that place the power system at risk. The objective of power system protection is to isolate a faulty section of the electrical power system from rest of the live system so that the rest portion can function satisfactorily without any severer damage due to fault current. Power system protection contributes to Distribution automation and can be studied together because both employ similar technology. Before installation of any Distribution automation, correct protection coordination and grading are essential.

6.1.1 Selective Coordination

Selective Protection coordination is critical for the reliability of the electrical distribution system and must be analysed. While it is very important, it is not enough to select protective devices based solely on their ability to carry the system load current and interrupt the maximum fault current at their respective points of application. It is important to note that the type of overcurrent protective devices and ratings (or settings) selected to determine if a system is selectively coordinated.

The two one-line diagrams in Figure 6.1 below illustrate the concept of selective coordination.

A system without selective coordination represented by the one-line diagram is to the left. A fault on the load side of one overcurrent protective device unnecessarily opens other upstream overcurrent protective device(s). The result is unnecessary power loss to loads that should not be affected by the fault. This is commonly known as a "cascading effect" or lack of coordination. The system to the right represented by the one-line diagram is a system with selective coordination. Only the nearest upstream overcurrent protective device opens for the full range of overload or fault currents possible for this system. All the other upstream overcurrent protective devices do not open. Therefore, only the circuit with the fault is removed and the remainder of the power system is unaffected. The power supply for other loads in the system continue to be uninterrupted and a selectively coordinated circuit would only have the immediate upstream feeder overcurrent protective device open for overcurrent that takes place on a feeder circuit [48].

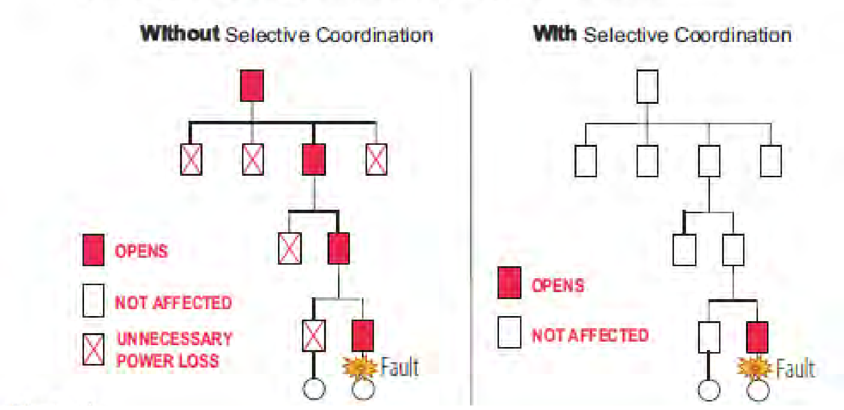


Figure 6.1: **Selective Coordination: Avoid Blackouts [48]**

Selective coordination was analysed and applied to the Waterkloof Farmers 1 11 kV Feeder before installation of the new protective devices. These devices had to be properly graded and coordinated to allow only the nearest upstream overcurrent protective device to open for both overloads and all types of short-circuits, leaving the remainder of the system undisturbed and preserving the continuity of service. Isolation of a faulted circuit from the remainder of the system is critical in today's modern electrical systems. Power blackouts cannot be tolerated.

6.1.2 Location of Distribution Automation Equipment

There were two views in the determining the positioning of the distribution automation installation.

- Equipment positioning from the view of cost reduction.
- Equipment positioning in order to reduce transient interruption, reduction of energy not supplied and satisfaction of customers [54].

Some other factors were also considered when the devices were installed at the proposed locations, such as power quality and reliability indices (SAIDI and SAIFI), load (KVA) connection, number of customers connected, protection settings, the imposed stress to the network equipment especially to the power transformer, and the characteristic of the supplied loads through the distribution automation against the reclosing close ups [55].

The devices were installed at different points along the radial distribution feeder. It was necessary to adjust their operating time (time grading) so that the device nearest on the source side clears the fault before any of the other ones operate.

Figure 6.2 below shows the different locations of the distribution automation equipment.

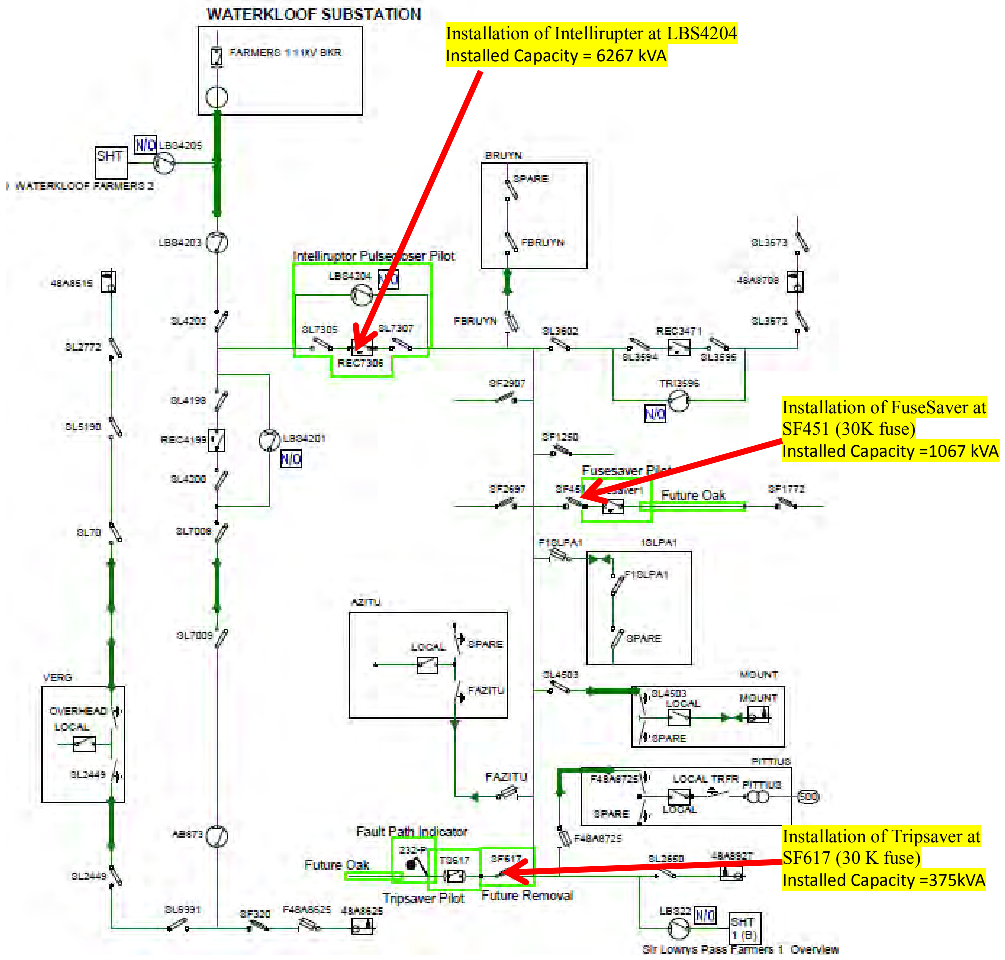


Figure 6.2: **Placement of the Distribution Automation Equipment**

An event spreadsheet (Historical data) was developed to determine the device location based on the most cost effective reliability improvement. The following information helped evaluate the distribution automation equipment location impact on customer hours lost, total load lost, and customer interruptions:

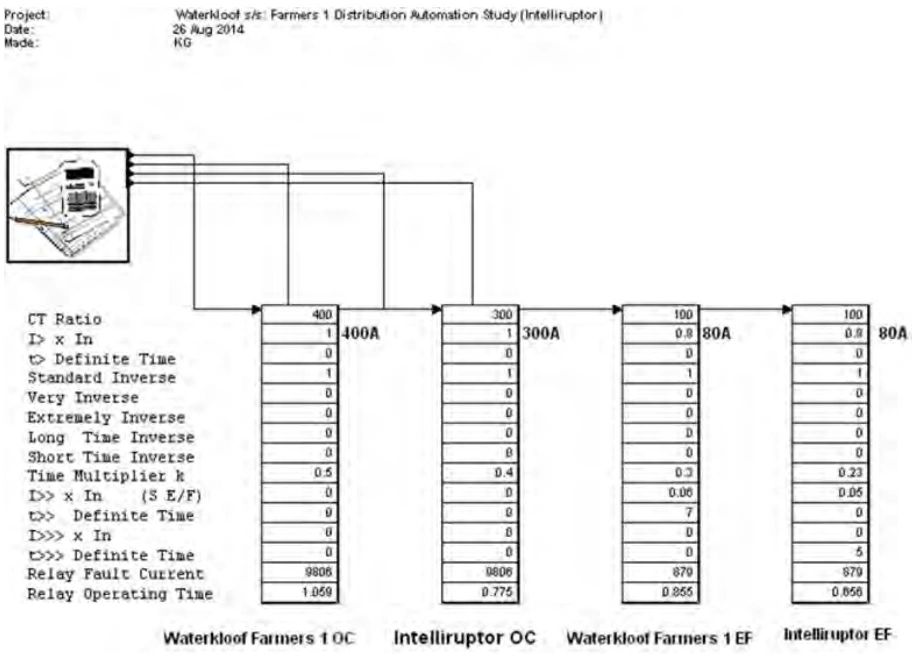
- Fault rate
- Average time to switch
- Average time to complete a repair
- Underground / overhead split

6.2. Modelling and Simulation of Protection Time/Current Characteristics of Waterkloof Farmers 1 11 kV Feeder using DIgSILENT PowerFactory Software

DIgSILENT PowerFactory was used to simulate the behaviour and co-ordination of the protective devices before the distributed automation system was connected to an 11 kV distribution system. From the simulation, the basic issue was to coordinate and grade the IntelliRupter Pulsecloser, (IR) with the upstream substation breaker's earth-protection and the downstream 30 K type fuses.

Table 6.1 below represents the mathematical concept and the software used for allocation of protection settings i.e. Settings was allocated to overcurrent and earth fault currents for Waterkloof substation breaker and the Intellirupter Pulsecloser.
The Substation Farmers 1 breaker and the Intellirupter Pulsecloser was set to the highest fault level. Moving downstream the impedance of the feeder causes the fault level to reduce, hence grading would be achieved.
The earth fault was set at 80 A for both the substation breaker and the Intellirupter Pulsecloser due to the close location of these devices to the substation. The SEF was set at 5 A for the Intellirupter Pulsecloser and 6 A for the substation breaker which was definite time. If a fault was identified to be less than 80 A and more than 5 A then the SEF would pickup and trip the Intellirupter Pulsecloser before the substation breaker would operate. An earth fault greater than 80 A on the feeder would activate and trip the Intellirupter Pulsecloser before the substation breaker would operate. Similarly, for overcurrent faults, the Intellirupter Pulsecloser would pickup and trip faster than the substation breaker due to the smaller time multiplier. The overcurrent setting for the Intellirupter Pulsecloser was set to 300A @ 0.4s NI while the substation breaker was set to operate with a backup setting of 400A @ 0.5s NI.

Table 6.1: Substation and Intellirupter Pulsecloser software settings



	Waterkloof Farmers 1 OC	Intelliruptor OC	Waterkloof Farmers 1 EF	Intelliruptor EF
CT Ratio	400	300	100	100
I> x In	1	1	0.8	0.8
t> Definite Time	0	0	0	0
Standard Inverse	1	1	1	1
Very Inverse	0	0	0	0
Extremely Inverse	0	0	0	0
Long Time Inverse	0	0	0	0
Short Time Inverse	0	0	0	0
Time Multiplier k	0.5	0.4	0.3	0.23
I>> x In (S E/F)	0	0	0.06	0.05
t>> Definite Time	0	0	7	0
I>>> x In	0	0	0	0
t>>> Definite Time	0	0	0	5
Relay Fault Current	9806	9806	879	879
Relay Operating Time	1.059	0.775	0.855	0.856

	Overcurrent	Earth Fault	Sensitive earth Fault
Substation settings	400A @ 0.5s NI	80A @ 0.3s NI	6A @ 7s DT
Intellirupter settings	300A @ 0.4s NI	80A @ 0.23s NI	5A @ 5s DT

Where:

OC = Overcurrent
EF = Earth Fault
NI = Inverse Definite minimum trip curve
DT = Definite time
SEF = Sensitive Earth Fault

Figure 6.3 is the graphical representation (grading) of the settings that was allocated to the software.

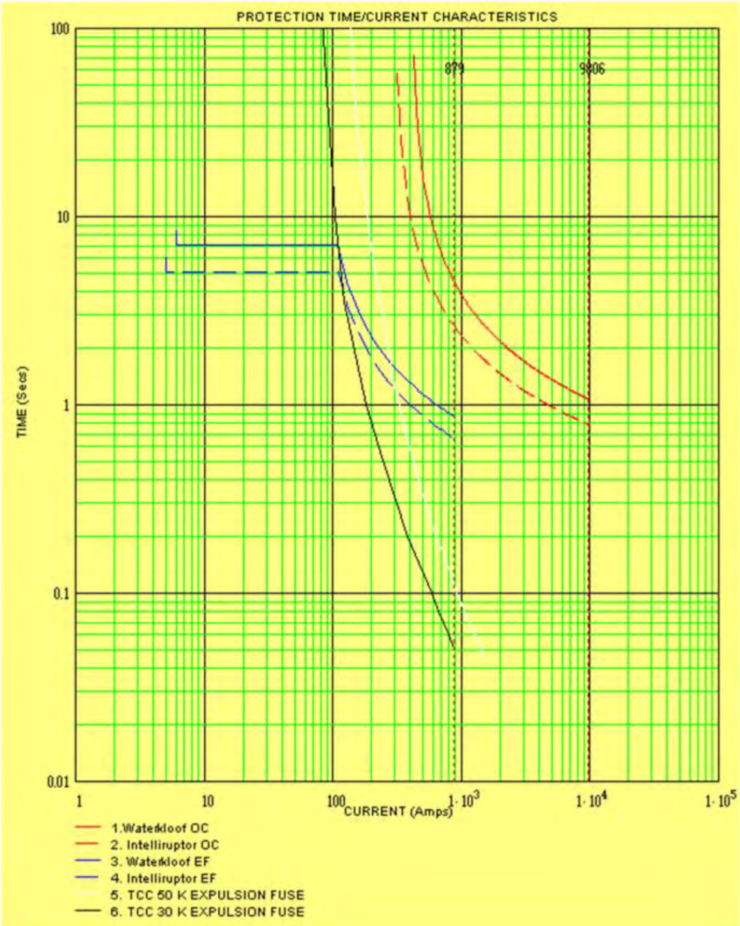


Figure 6.3: **Protection Time/Current Characteristics using DIgSILENT PowerFactory**

6.3. TCC Curves for Intellirupter Puslecloser and Tripsaver

For downstream fuses and upstream circuit breakers or reclosers, it is not a simple matter to determine if a fuse and circuit breaker will be selectively coordinated. Even if the plot of the time current curves for a downstream fuse and an upstream circuit breaker or recloser show that the curves do not cross, selective coordination may not be possible beyond a certain fault current. The only sure way to determine whether these two devices will coordinate is to test the devices together.

The basic issue faced was coordinating IntelliRupter Pulsecloser with the upstream substation breaker's earth-protection and the downstream 30 K fuses. Figure 6.4 shows the substation breaker's earth-protection (2-Relay) with a pick-up of 80 A and a Time Delay (TD = 0.3) coordinating with the 30 K fuse at low fault-currents in the neighborhood of around 60 A. Each fuse is represented by a band: the minimum melt characteristic and the total clear characteristics. Fuses have an inverse time-current characteristic, which means the greater the overcurrent, the faster they interrupt. The 2-Relays left or bottom curve illustrating its 8 % current-response tolerance just begins to touch the right-side of the 30 K fuse's maximum response curve.

There was no room to allow for another earth-protection curve (from IntelliRupter Pulsecloser) which would be in between the substation breaker and the fuse. Consequently, the options were either to reduce the size of the fuse or increase the pick-up of the substation breaker's earth-protection.

The TCC curves for the Intellirupter Pulsecloser, Substation breaker settings, downstream Tripsavers and 30 K type fuses can be seen in Figure 6.4 below. The horizontal axis of the graph represents the RMS symmetrical current in amps. The vertical axis represents the time, in seconds. (The phase faults are shown in blue and earth (ground) faults in red.)

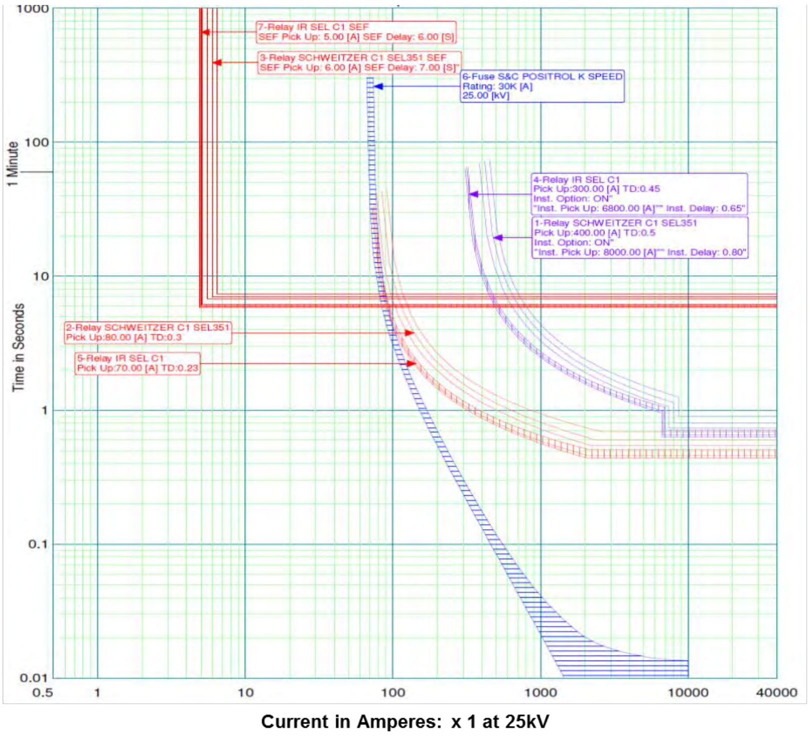


Figure 6.4: **Time-current characteristic curves for the Intellirupter Pulsecloser, Substation breaker settings, downstream Tripsavers and 30 K type fuses**

The graph in Figure 6.5 shows that by increasing the pick-up of the substation breaker's earth-protection from 80 A to 92 A (2-Relay), this provided enough room between the fuse and the breaker's earth-protection to insert IntelliRupter Pulsecloser's earth-protection and have it coordinate with the fuse and the breaker. The 30 K fuse should operate before all other devices and the Intellirupter Pulsecloser will trip before the substation breaker for a sensitive earth fault. Any current below 100 A will cause the Intellirupter Pulsecloser and Substation Breaker to operates or pick up the fault current because of the sensitive earth fault. The plots reflect minimum/ maximum "bands" of response tolerances, including the interrupting time-total faults cleared. By adding +/- % tolerances (current & time) to the nominal TCC plus fault-interrupter clearing time will give a better picture of how much margin exists between TCCs. The substation breaker had a +/- 8 % current tolerances response and +/- 4 % time-response which is a standard for SEL relays and the other relays associated to the feeder. The relay fixed-time tolerance of +/- 1.5 cycles or 30 ms for the relay (as specified by SEL) was added plus 2 cycles or 40 ms for the breaker's fault-interrupting time. The IntelliRupter Pulsecloser had +/- 2 % current and time-response tolerances and +/- 10 ms fixed-time tolerance. A 30 ms (1.5 cycles) for its fault-interrupting time was added to the IntelliRupter Pulsecloser causing the IntelliRupter Pulsecloser curves to be so much narrower than the breaker's curves.

Due to their accuracy and speed of response, often more IntelliRupters can be coordinated in series than conventional reclosers. An IntelliRupter measures current in both directions and can coordinate in either direction. Protection capabilities include simultaneous independent directional phase, ground, and negative-sequence time-overcurrent elements; simultaneous independent directional phase, ground, and negative-sequence definite-time elements; directional blocking overcurrent elements, intelligent fuse saving overcurrent elements; over voltage/under voltage elements, and sensitive earth faults [8].

IntelliRupter pulseclosing tests fault persistence by injecting a minor loop of energy after the initial interruption. Conventional reclosers must test by reclosing into the fault, which produces high-asymmetrical current and stresses all system components.

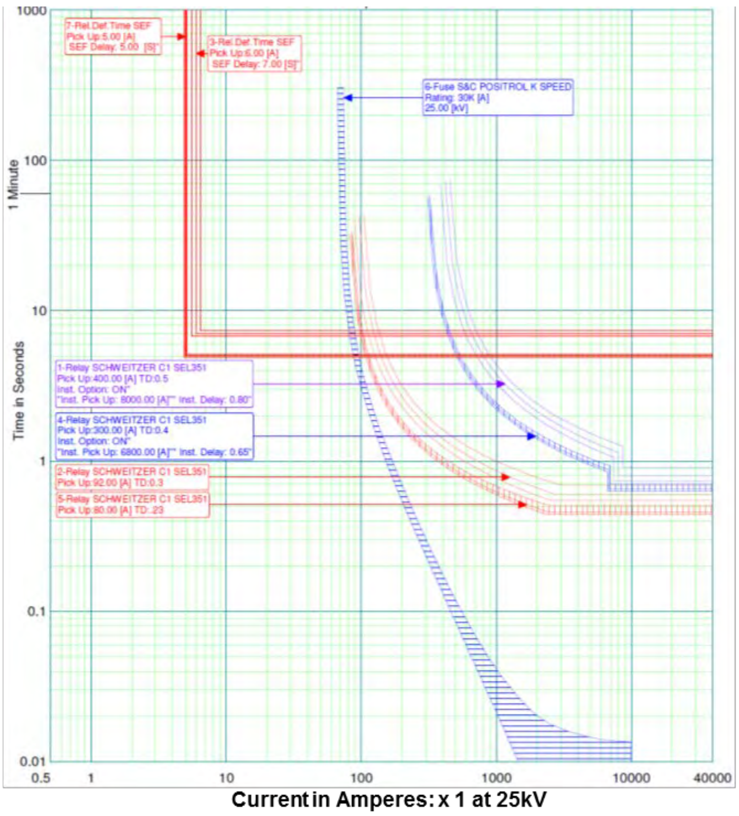


Figure 6.5: **Increasing the pick-up of the substation breaker's earth-protection (The phase faults are shown in blue and earth (ground) faults in red.)**

6.4. Protection Functionality for FuseSavers

6.4.1 Protection Algorithm Overview

The FuseSaver protection algorithm coordinates with the partner fuse melting curve. The time it takes for the fuse to melt is inversely proportional to the energy absorbed by the fuse element as the fault current flows through it. This energy is a function of the square of the current and the duration of the fault (I^2t). For large fault currents, the fuse element may melt within the first half cycle of current [19].

The FuseSaver electronics sample the line current at high speed and employs an inverse time protection algorithm which trips the FuseSaver in time to prevent the partner fuse from blowing. When more than 33 % of the energy required melting the fuse has accumulated the FuseSaver will trip. This means that for low fault levels the FuseSaver will take longer to trip and at high fault levels the FuseSaver trips very quickly.

This operation threshold is shown in Figure 6.6 below.

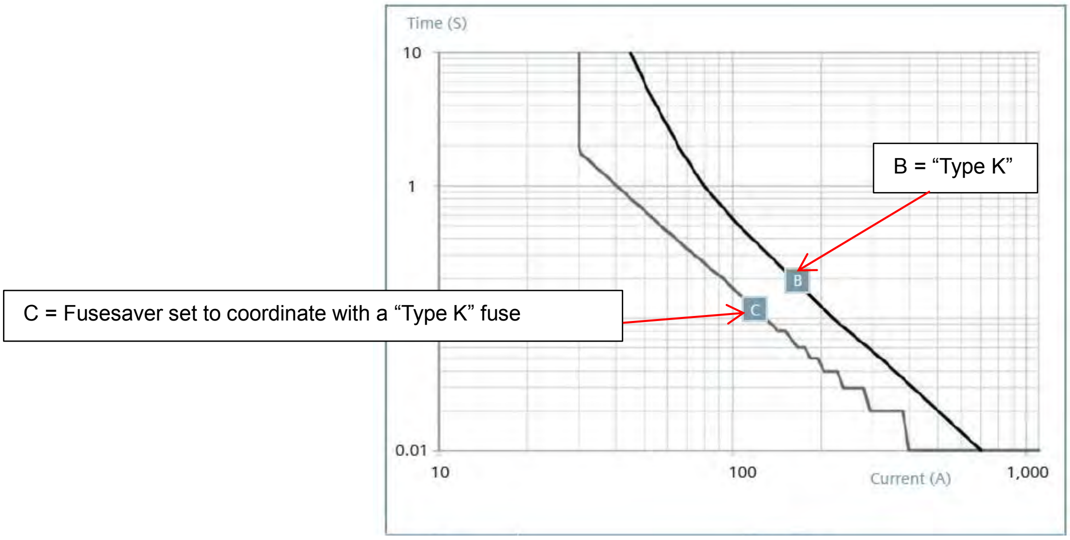


Figure 6.6: **Example: Fuse and FuseSaver time-current curve [19]**

Fault currents can have a dc offset due to the X/R ratio of the circuit and the starting phase angle of the fault. This means that the first half cycle can have a considerably higher peak current, up to 2.6 times the rms value, and therefore considerably more energy. The FuseSaver estimates the energy absorbed by the fuse during the fault, including the effects of dc offset. Both the fuse and the FuseSaver interrupt at a current zero after they have operated. At high-fault levels, the protection algorithm opens the vacuum interrupter contacts of the FuseSaver fast enough to clear the fault at the first current zero after contact part, and so limit the current let-through to one cycle. This means that if enough energy is absorbed by the fuse element in the first cycle of fault current to melt the fuse, then it is impossible for the FuseSaver to save the fuse from melting. Therefore, this current level is the limit of coordination possible between the FuseSaver and the fuse [19].

6.4.2 Advanced Protection Functionality

The FuseSaver offers additional protection features, such as instantaneous and maximum fault time settings to give more control over the FuseSaver operation. At the time of commissioning, the FuseSaver was configured to know the type and rating of its partner fuse that it is protecting. As the FuseSaver has an electronic controller, additional parameters can be set to further modify the time-current curve as follows:

Minimum Trip Current Multiplier

The minimum trip current is a multiple of the fuse rating and sets the pickup level for the protection functionality. This is the current level above which the FuseSaver senses a fault. For example, if the FuseSaver is set for a 12 A fuse and a minimum trip level of X3 is selected, then any current below 36 A will not be recognized as a fault [19].

Maximum Fault Time Setting

Once the current has risen above the minimum trip level, the FuseSaver picks up the fault and will trip on an inverse-time basis to save the fuse. However, if the inverse-time protection has not tripped the FuseSaver before the maximum fault time is reached, then the FuseSaver will trip [19].

Instantaneous Trip Setting

The FuseSaver runs an inverse time curve to match the fuse that it is protecting. However, the FuseSaver can also be set to trip instantaneously for faults above a certain level. The FuseSaver instantaneous protection works as a multiple of the fuse rating. So, for example, if the fuse rating is 10 A and the instantaneous multiplier is set to X11, then the FuseSaver will trip instantly for faults above 110 A [19].

Dead Time Setting

The dead time is the period after the FuseSaver has tripped on a fault and before it closes. In general, the longer the dead time the greater the chance that a transient fault will be cleared by the operation of the FuseSaver [19].

Three-Phase Lockout

When all the FuseSavers on a line are fitted with communications modules, it is possible to configure them so if one detects a permanent fault, then all three phases will be tripped and stay tripped.

The two options are:

Three phase LOCKOUT DISABLED, this is the default.
Three phase LOCKOUT ENABLED.

The three-phase lockout is enabled as part of the policy file settings.

The following figure below illustrates the advanced protection functionality for the FuseSaver which is configured in the policy file.

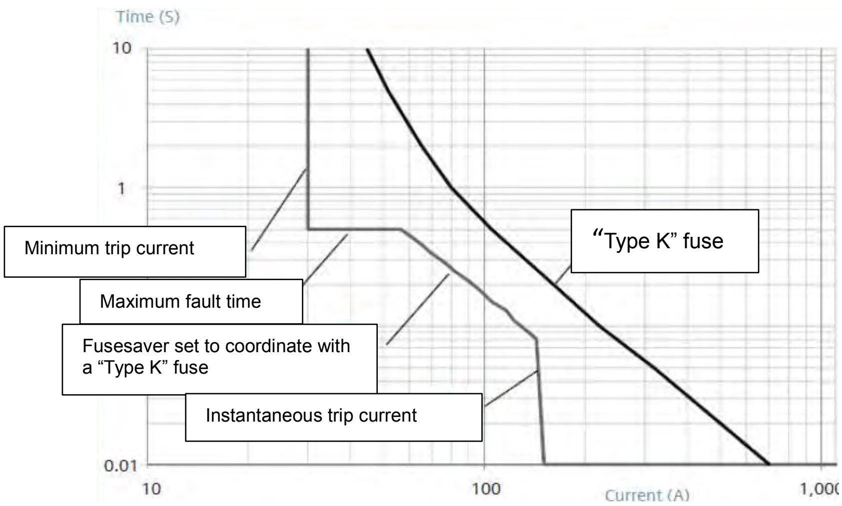


Figure 6.7: **Example: Advanced FuseSaver protection curve [19]**

6.4.3 Typical Waterkloof Feeder - Lateral Application

In the system in Figure 6.8 below there is a Waterkloof substation with a circuit breaker supplying a feeder. The feeder has a backbone and lateral lines. The backbone has a recloser at a midpoint and the lateral is protected with fuses. Coming off the lateral lines are transformers which also have fuses. The lateral line fuses are fitted with FuseSavers to prevent the fuses from blowing on transient faults. The lateral line fuse associated with a FuseSaver is known as its partner fuse. A protection coordination graph has been constructed in Figure 6.9 using settings that were applied to the Waterkloof F1 network. The recloser is set to 70 A pickup with x10 instantaneous multiplier and has a very-inverse curve with a dead time of 5 s. The fuse on the lateral line is a type K 30 A fuse with minimum pickup response of 60 A. The transformer fuse is a type K 15 A fuse. The FuseSaver was set to a type K 30 A with the following additional parameters: X3 minimum trip current multiplier, X10 instantaneous multiplier, Dead time of 5 s and Maximum fault time of 2 s.

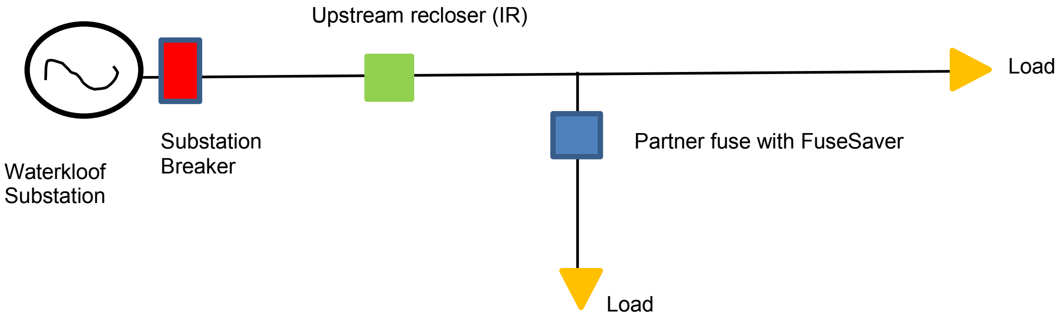


Figure 6.8: **A typical feeder - lateral application for the Waterkloof F1 Feeder**

6.4.4 Upstream Protection

The operation of the upstream recloser (Intellirupter Pulsecloser) depends upon the recloser protection settings and the location of the fault relative to the recloser and the FuseSaver.

6.4.5 Faults Upstream

For faults upstream of the FuseSaver, the upstream recloser (IR) will trip and reclose. The FuseSaver will see the line current go off and then on again. For the FuseSaver, this will re-trigger the inhibit timing (default 10 s). A fault which occurs downstream during this inhibit time will not trip the FuseSaver.

6.4.6 Faults Downstream of the FuseSaver

If the recloser (Intellirupter Pulsecloser) protection has been set as shown in Figure 6.9, then faults on the lateral line downstream of the FuseSaver will cause the FuseSaver to trip and then close after the dead time, thereby saving the fuse. The FuseSaver will trip before the upstream recloser (Intellirupter Pulsecloser), usually preventing it from tripping.

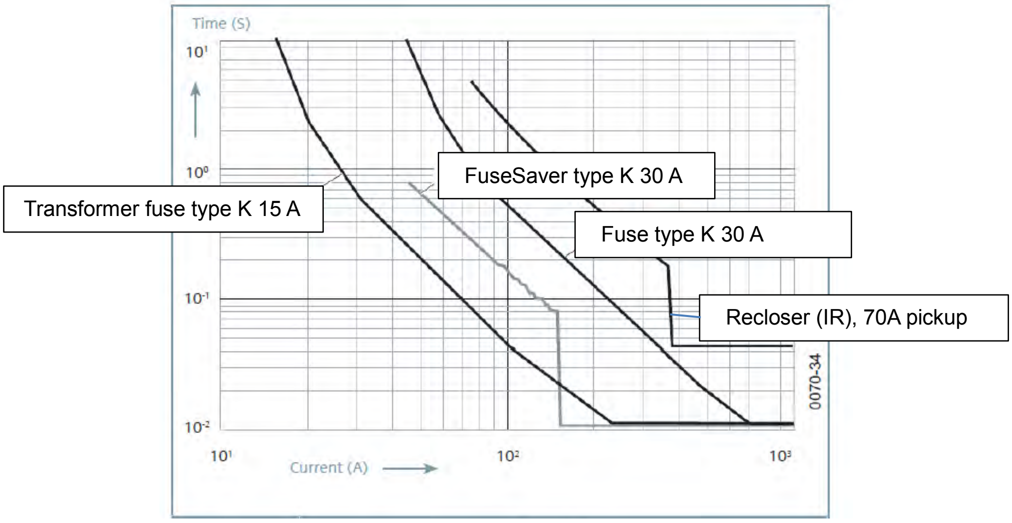


Figure 6.9: **Protection Coordination Chart [19]**

If the recloser (IR) does trip along with the FuseSaver, then the recloser will close first (provided the FuseSaver dead time has been set longer than the recloser reclose time as recommended), and then the FuseSaver will close next. If the fault is permanent, the fault will be cleared by the fuse. To avoid this situation, the following was recommended:

- If the recloser (IR) is using an instantaneous protection setting, then the FuseSaver should also have an instantaneous element.
- The reclosers instantaneous protection should be set at a higher current level than the FuseSaver instantaneous level and, if necessary, a minimum time of 50 ms should be set in the recloser [19].

6.5. Protection Setup for the Tripsaver

6.5.1 Service Centre Configurable and IntelliLink TS Setup Software

Tripsaver Service Centre Configurability feature provides flexibility to reconfigure the device, read event logs and perform functional tests. The IntelliLink TS Setup Software is a software tool used to communicate with and configure the Tripsaver Cutout-Mounted Reclosers.

Figure 6.10: **Tripsaver Configured by the Service Centre Configuration Kit**

6.5.2 TCC Curve Settings

The configuration kit and the IntelliLink TS Setup Software were used to properly configure Tripsaver units before putting it in use. The Time Current Characteristic (TCC) curves for the initial trip operation and for up to three test operations are selected using the TCC Curve Settings Screen, which is the first screen when the software is launched. The four trip operations are named: Initial Trip, Test 1, Test 2, and Test 3, respectively. Setting fields for each trip operation are grouped in separate areas identifiable by trip names shown on the left side of each area as indicated in Figure 6.11 [13].

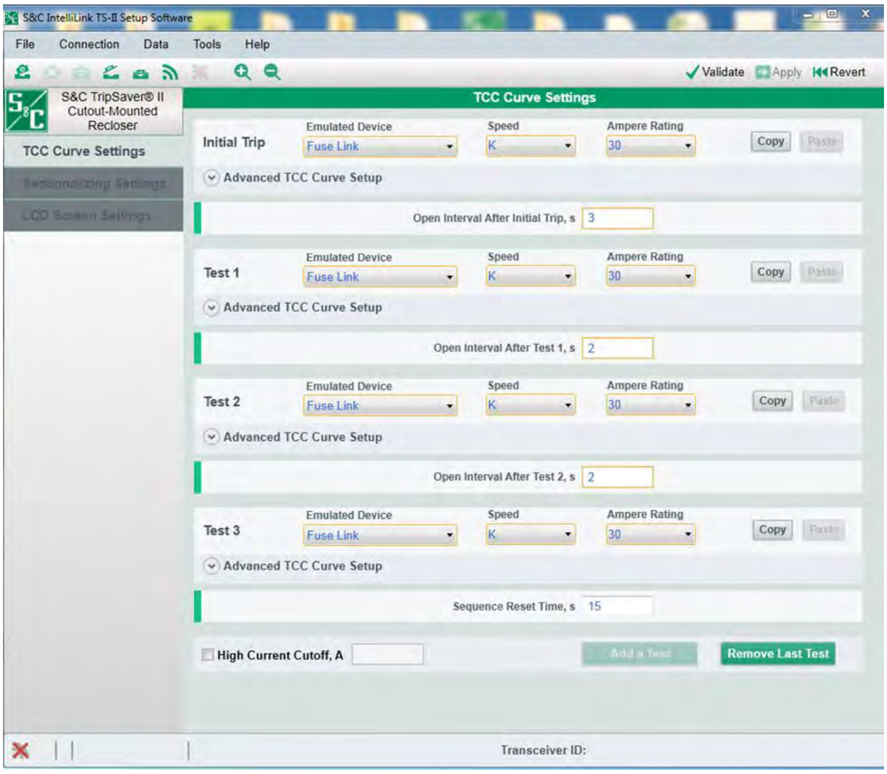


Figure 6.11: **TCC Curve Settings**

The Tripsaver for Waterkloof Farmers 1 11 kV Feeder was set using the following TCC Curve Settings:

Initial Trip (1st curve): Fuselink:
Speed: K; Ampere Rating: 30.
Open Interval After Initial Trip: 3 s.

Test 1 (2nd curve): Fuselink:
Speed: K; Ampere Rating: 30.
Open Interval After Test 1: 2 s.

Test 2 (3rd curve): Fuselink:
Speed: K; Ampere Rating: 30.
Open Interval After Test 2: 2 s.

Test 3 (4th curve): Fuselink:
Speed: K; Ampere Rating: 30.
Sequence Reset Time: 15 s.

Tripsaver Operating Sequence

Tripsaver supports up to three reclosing operations (four tripping operations in total) before it drops open. A wide variety of time-current characteristic (TCC) curves is available. The open interval between tripping operations is five seconds. The vacuum interrupter resets two seconds after Tripsaver drops open. The operator can then reclose Tripsaver into the mounting. In instances in which a temporary fault is cleared before Tripsaver reaches the end of its operating sequence, Tripsaver will return to its first TCC curve, i.e., reset after 15 seconds have elapsed since the last reclosing operation [13].

Chapter 7: Field Trial of the Innovative New Technologies

7.1. Introduction – Installation of the Tripsaver

Eskom has been focusing on a range of options for improving the outage performance of MV overhead networks and particularly lateral lines. One such option is to carry out a field trial of cut-out mounted, single-phase reclosers installed in place of the fuse elements in the cut-outs at the tee-off point from the main backbone feeder.
The high proportion of rural overhead networks comprised of three-phase tee-offs and the high proportion of interruptions due to momentary faults made the author focus on measures to lower outage rates for customers fed from the lateral lines.

In order to show the capability of the proposed methodologies, an area of the real MV South African network has been considered. The period taken into consideration for the planning study was 1 year. In order to give the best possible insight into what will be achieved with this innovative new technologies, the author has set up a fully operational scheme on the Waterkloof Farmers 1 11 kV Feeder. This feeder is one of the worst performing feeders in the WCOU (refer to appendices). The demonstration is based on the 11 kV radial system feeding the site and the locations have extreme environmental conditions allowing the equipment and system to prove itself in an unusual environment. The intention of this field trial is not only to minimise restoration time to healthy sections of the feeder but also minimise the number of affected customers.

7.2. Background

In July 2014, three of the Tripsavers (one per phase) were installed on the Waterkloof distribution feeder at tee-off SF617 protected by a fuse with suitable “30K fuse type” characteristic. This distribution feeder has kilometres of three phase lateral distribution lines passing through rural, heavily treed areas. Each of the installations locations is being monitored remotely using GridSense LineTrackers Fault Path Indicators and cellular communication technologies to document and validate the field application. See Figure 7.1 below:

Figure 7.1: **Tripsaver and FPI’s installation on the Waterkloof Farmers 1 11 kV Feeder**

7.2.1 Physical Handling of Tripsavers

With a weight of 10 Kg, it quickly became apparent that the Tripsaver could not be installed by a link- stick from a pole climber working position; a live line crew with insulated platform vehicle were required to install the reclosers in position. The installation method, using by-pass jumpers to avoid an outage, is illustrated in Figure 7.2. Installation was done under live conditions therefore bypass jumpers was installed across the fuse in order to prevent any outages being experienced by customers. It also became apparent that manual operation of the Tripsavers using link sticks from a pole working position was possible with a little care.

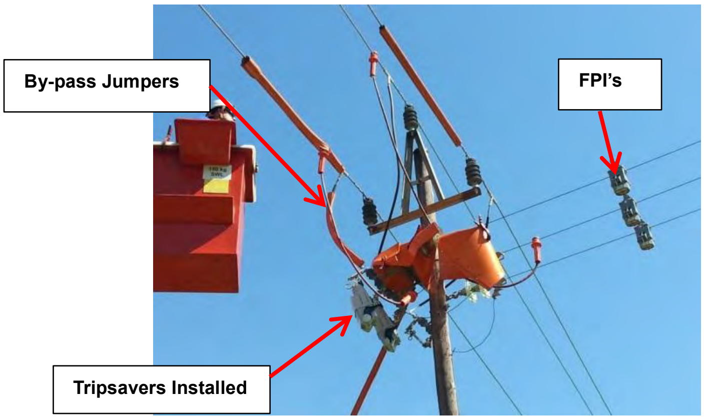


Figure 7.2: **Live installation of cutout mounted reclosers using by-pass jumpers – SF617**

7.2.2 Ratings

The particular Tripsaver in the trial operates an open-close-open dropout sequence with a 2-5 second reclosing time interval. The 11 kV rated version has a 30 Amp rating, a fusing factor of 4.8 and a maximum interrupting rating of 2 kA. It became apparent that they could only be used on tee-offs away from the feeder substation source because of the high substation short circuit (SC) current normally around 4 kA. It also became apparent that the available fault current at remote parts of 11 kV laterals would not exceed the minimum current needed to initiate the recloser sequence i.e. 4.8 x 30 = 144 Amps. These ratings also imposed limits on the laterals that could be chosen for the trials due to two factors - the SC level suitability at the tee-off point and the available current at the most remote laterals extremity.
The fusing factor of the Tripsavers, at 4.8, was also very different from the value of 2.2 for the NEMA "K" fuses. These two factors significantly reduce the impact that Tripsavers can have on minimising customer hour interrupted (CHIs) on feeders.

7.2.3 Selection of Lateral Lines

The selected lateral lines had to satisfy a number of criteria in order to optimise the trial effectiveness.

For example:

- They had to be troublesome lateral lines. Lists of worst feeders and their history were available from the Eskom's Plant Department Event Summary and from local fault response staff.

• The lateral line chosen needed to be backed up by a 3-phase recloser on the feeder with event recording facilities readily accessible.

• The location of the Tripsavers pole had to be accessible to a live line hydraulic platform vehicle.

• Only approved types of modern cutouts could be tolerated at the Tripsavers fitting position.

• The pole top construction at the laterals point had to be suitable for the space requirements of the Tripsaver and its operation using the load break tool.

Between July 2014 and March 2015, 1 lateral line meeting the above criteria was chosen and fitted with Tripsavers, three per lateral as shown by Figure 7.2.

7.2.4 Alterations to Three Phase Recloser Settings

On the day of each Tripsavers installation, reclosers at feeder source or upstream of the relevant tee-off were re-programmed from two shot reclosing to 1 fast and 1 time delayed trip to lockout, for co-ordination with the Tripsavers pre-set operating cycle. The substation relay settings were changed from 80 A to 92 A to accommodate the Tripsaver installation. The over current and earth fault settings were also changed to co-ordinate with the Tripsavers for currents greater than the pre-set trip current. It should be noted that the raising of these settings reduced the level of back up protection afforded to other lateral lines on the feeder not fitted with Tripsavers and hence still fitted with standard 15 Amp or 30 Amp fuse links.

7.2.5 Operation Monitoring and Data Collection

Although historical data was available for the outlets in which the Tripsavers were installed, it was decided not to rely on a before and after comparison of outages on the lateral lines as the main measure of its success or failure. The records of weather related events vary widely from year to year for individual lines and ongoing maintenance and refurbishment programmes in the networks in question fundamentally change their performance characteristics anyway. Because of these factors it was decided to place more emphasis on collecting detailed data and feedback on each event involving the Tripsavers protected lateral lines and to analyse them to see if:

- They operated in the way expected.
- They failed to operate when they should have.
- Customer Hours were saved or lost due to the presence of the Tripsavers.
- Anything could be learned about optimising Tripsavers with other protective devices.

7.2.6 Periodic Fault Monitoring

To gain maximum value from the trial installations, periodic and post-fault monitoring is essential to accurately assess their effectiveness and suitability. A core part of this was the downloading of the upstream event recorders (Pulsecloser) and fault path indicators as follows:

• Monthly
• After any known operation of the Tripsavers.
• After fuse blowing on any lateral of a feeder fitted with Tripsavers.
• After any operation of the source recloser.
• After a fault with any non-operation of any relevant protection.

On each of these occasions the Tripsavers location was visited and visually inspected and the number on the event counter noted. The recloser event recorder was downloaded at the same time. The local operation staff completes this work and returns the data with the specially formatted performance record sheet to enable the operations/protection specialists to analyse events and draw a considered conclusion. Occasionally, the specialists have found it necessary to visit the fault location in order to establish all facts relating to the event.

7.3. Practical PulseCloser Applications on the Waterkloof F1 11 kV Feeder

7.3.1 Introduction

The installations of the Pulsecloser at load breaker switch (LBS 4204) with SCADA indication and control was a midpoint location on the feeder circuits just before the substation breaker with heavy tree cover and many fused taps and no downstream ties to other feeders, as illustrated in Figure 7.3 below. The Pulsecloser with Intelligent Fuse Savings works well here and was installed at the head of the feeder with the intention of avoiding stress on the substation transformer from repeated fault events.

Figure 7.3: **Typical positioning of Pulsecloser location at LBS4204 – Waterkloof Farmers 1 11 kV Feeder**

7.3.2 PulseCloser Field Installation

The Intellirupter PulseCloser has an integrated design make for greatly simplified construction work in the field. There was no control box to hang, no control cables to run down the pole, no control power to run or power transformer to hang. The Waterkloof Feeder unit came with surge arresters installed, so the only field work required was to hang it on the pole and make the jumper connections. The installation on the Waterkloof Farmers 1 11 kV Feeder is shown in Figure 7.4.

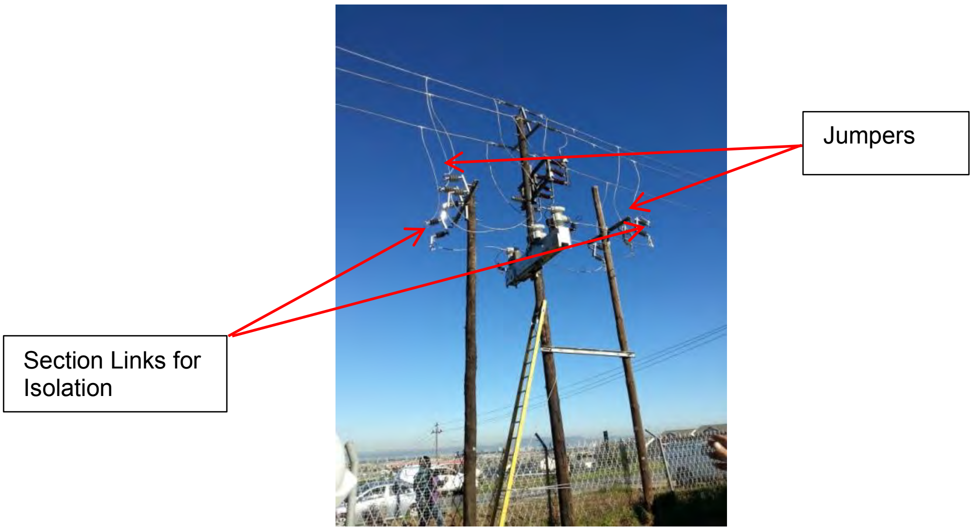
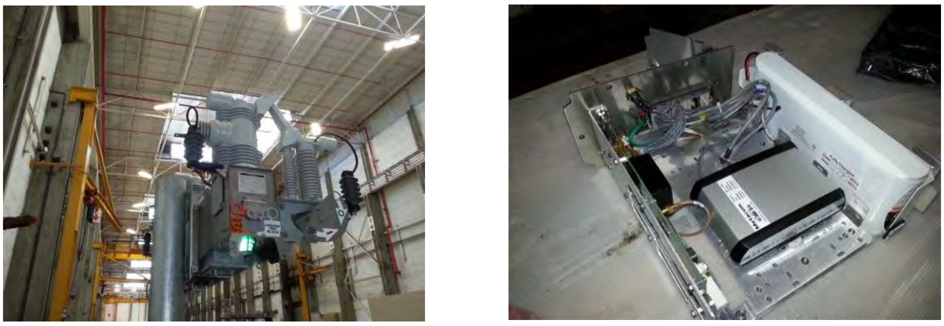


Figure 7.4: **Intellirupter Pulsecloser installation on the Waterkloof Farmers 1 11 kV Feeder**

7.3.3 Preparation for Laboratory Testing on PulseClosing

The tests that were performed included those targeted at quantifying the performance characteristics of the Pulsecloser. Subsequent analysis of the test results was used to help the author make decisions on the application of pulseclosing technology. Preparation of the Communication module, modem, SCADA and protection settings were pre-installed in the workshop before the actual installation on site.



(a) **(b)**

Figure 7.5: **(a) Laboratory testing on pulse closing (b) Modem Installation**

7.3.4 Preparation for Field Testing on PulseClosing

A plan was developed for testing the unit in different application situations in the field. These field tests were performed by Eskom (under the author's supervision), which procured and installed the pulseclosing unit and monitoring instruments, and then retrieved the data in the field. The vendor provided engineering support to Eskom to prepare for the testing. The testing involved both some staged testing and some operational runtime testing.

7.3.5 Assessment Methodology Development

Assessment methodology was developed to evaluate the life cycle costs and benefits when replacing a traditional recloser with the new technology. Key contributors may include equipment costs, deferred capital costs as a result of avoided aging effects in line and substation equipment, and increased power reliability and quality. Methodology development addressed the following:

- Requirements to represent the pulseclosing technology in existing models and distribution system simulation tools. Perform initial modelling work that can be done with existing tools in support of the testing work. Also, identify needs for new modelling and simulation tools pertaining to pulse closing that may be the basis for development in a follow up project.

- Analysis and assessment methods to examine the effectiveness of the technology for various feeder configurations, including determination of the fault distance for which pulse closing is effective.

- Methods to assess and quantify the avoided stress on line equipment and substation transformers by not reclosing into an existing fault, and to analyse the potential economics of reducing aging effects by eliminating current surges when reclosing into an existing fault.

- Methods to assess power quality impacts of the new technology on customers, including voltage sags caused by reclosing into existing faults.

- Methods to identify system integration issues for using pulseclosing in conjunction with other active components in a distribution system and proposed resolutions for any key system integration problems that may be identified. The need for follow-up project work will be determined.

7.3.6 Easy Operation of Pulsecloser

The control and communication module was easy to configure before installation and it was just as easy to configure after installation, from the security of the author's vehicle parked up 45 m away, as shown in Figure 7.6.

Figure 7.6: **IntelliRupter control and communication module is configured and operated using a secure WiFi communication link [9]**

7.4. Installation of FuseSaver Breaker

7.4.1 Location of FuseSaver

The Fusesaver is primarily targeted at providing protection and automation of low fault level lines such as laterals. By installing FuseSavers, the utility gains the benefits of improved network availability and reduced maintenance call outs because the FuseSaver prevents transient faults from blowing fuses.

The FuseSaver was recognised as the world's fastest medium voltage circuit breaker for overhead lines [19]. The first FuseSavers in South Africa was installed at SF451 on the Waterkloof F1 Feeder. The FuseSavers were trialed in quite a remote and weather exposed area; for the benefits of the FuseSaver to really stand out. An area that was windy, heavily covered with trees and particularly prone to birds striking the line. The trial involves placing FuseSavers on rural distribution laterals that were currently protected by expulsion dropout fuses. In the event of a transient fault, the FuseSaver will operate faster than the dropout fuse, 'saving' the fuse and stopping the transient fault becoming permanent. The type FuseSaver device is designed to protect the fuse in a lateral circuit from nuisance fuse operation under conditions of medium or low current faults. The 12-month FuseSaver trial was focused on assessing mounting methods, the overall effectiveness of the device, and developing standards and training.

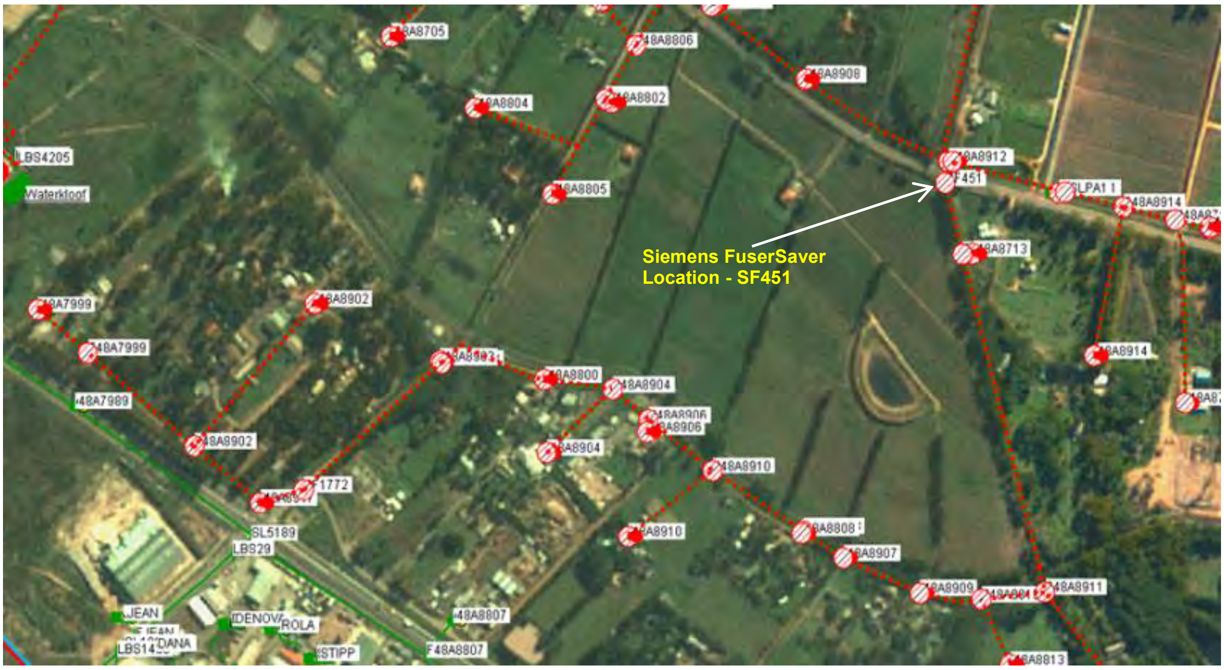


Figure 7.7: **FuseSaver device installed at SF451**

The FuseSaver was mounted on the dead-end of the lateral line or feeder line and provides the connection from the conductor to the partner fuse. Their operation can be summarised as: The partner fuse protects the lateral line from permanent faults and the FuseSaver protects the partner fuse from being blown by transient faults [19].

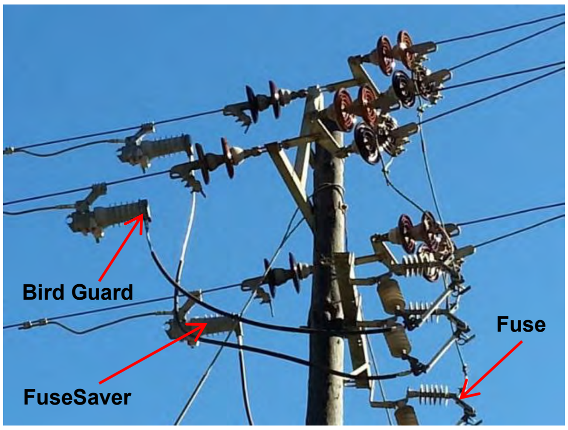


Figure 7.8: **Location of FuseSaver on the Waterkloof rural network at SF451**

In most network configurations, as shown in Figure 7.8, both the fuse and FuseSaver must be in series on the lateral line. From this arrangement, a number of points are relevant [19]:

1. It does not matter whether the fuse or the FuseSaver is adjacent to the feeder line, either configuration is acceptable.

2. While it is preferable for the fuse and FuseSaver to be located as close together as is practical, mounting the FuseSaver at a different pole to the fuse is acceptable.

3. The FuseSaver was attached on the dead end of the lateral line using a line clamp assembly.

7.4.2 Bird Guard

When the FuseSaver is hung directly from the medium-voltage line, installation of a bird guard was recommended. The bird guard provides additional electrical insulation to the conductor which was directly above the terminal. The bird guard was installed over the last shed on the FuseSaver and shrouds the FuseSaver connections and cable lug, as shown in Figure 7.10 below [19].

7.4.3 Communications Module

The communications module plugs into a three-pin connector on the bottom of the FuseSaver and provides a short range wireless link between the FuseSaver and other devices. It also has a built-in battery. The module allows the crew to interface with the FuseSaver from ground level using a laptop. It can be installed from the ground using a live-line stick equipped with a special communications module attachment tool [19].

The communications module connects directly to the electronics module in the FuseSaver and has a short range wireless communications capability so that the FuseSaver can be configured, interrogated, and controlled from ground level [19].

The communications module was needed to install and commission the FuseSavers but were optional thereafter. The communications module can only communicate with control devices such as a computer loaded with the Siemens Connect software and fitted with the USB antenna, or the remote control unit (RCU) equipped with Siemens Connect software for integration into a utility's SCADA system. When the communications module is permanently connected, FuseSavers on two or three phases can be operated in a ganged mode. See Figure 7.9 below.

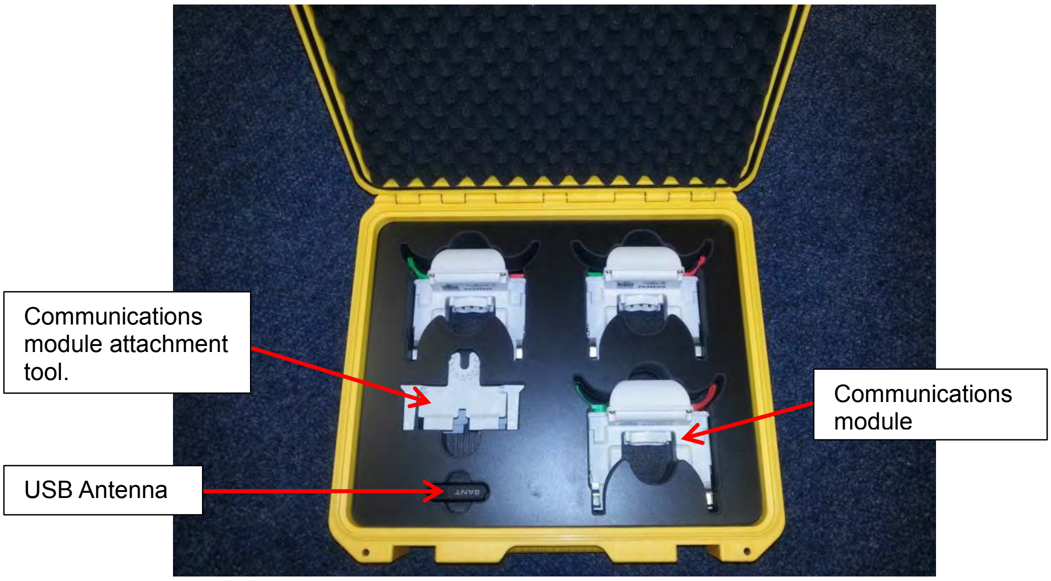


Figure 7.9: **Communications module – carry case kit**

7.4.4 Installation and Commissioning

FuseSaver installation can be accomplished using live-line or dead-line processes. The FuseSaver is an electrically floating device so requires no grounding of the device.

7.4.5 Mechanical Installation

A qualified supervisor together with the guidance of the author, who instructs workers during installation and commissioning tasks and checks for compliance with the applicable safety measures, was assigned to oversee the installation and commissioning work. The installation and commissioning work was performed by authorised qualified operators with sufficient qualifications and experience.

7.4.6 Mounting Styles

Conductor Mounting

The preferred method for mounting of the FuseSaver was to attach it directly from the line conductor using the line-clamp assembly. The line-clamp assembly connects directly to the dead-end of the conductor and ensures that the FuseSaver is hung at its centre of mass. The line clamp assembly consists of an insulating sleeve which was fitted between the clamp and the dead-end. As such, the line-clamp assembly is not an electrical connection but provides a solid mechanical mounting point. The insulating sleeve also provides a barrier to galvanic corrosion that might otherwise be possible if the line clamp and dead end are of incompatible materials [19].

It was also possible to connect the line clamp directly to the conductor if it is of suitable size. The line clamp assembly does not provide a conducting joint directly to the line. The connecting cable was still required to ensure a good electrical connection [19].
Hanging the FuseSaver from an undersized conductor may result in fatigue and premature failure of the conductor. The line clamp assembly can grip dead-ends of 8 to 19 mm in diameter

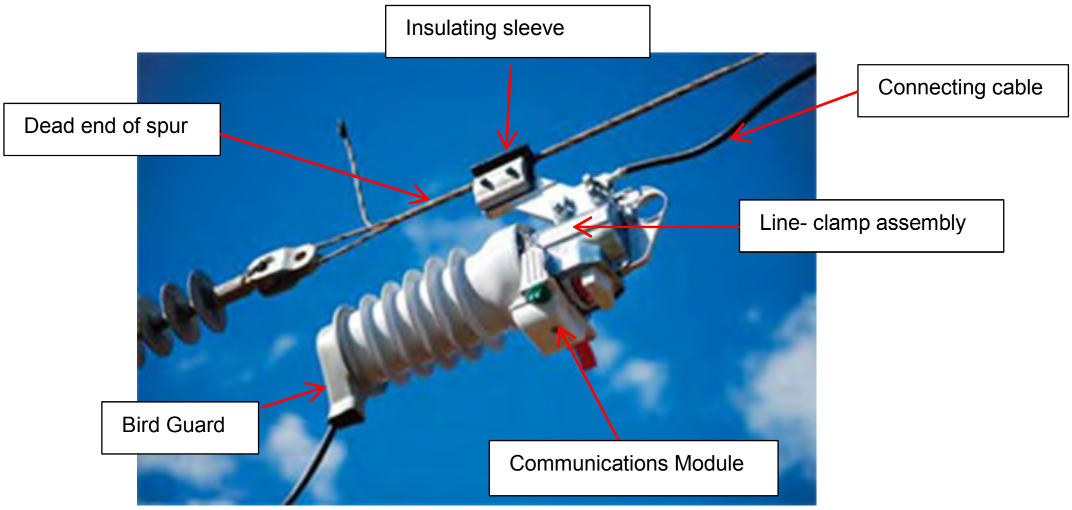


Figure 7.10: **Conductor mounting FuseSaver**

7.4.7 Configuration

Figure 7.11 shows how the FuseSavers was configured wirelessly through the Siemens Connect PC application at the site. The policy file that included the protection settings defined by the author and identified the type and rating of the FuseSaver's partner fuse were loaded. The entire process was completed within a few minutes.

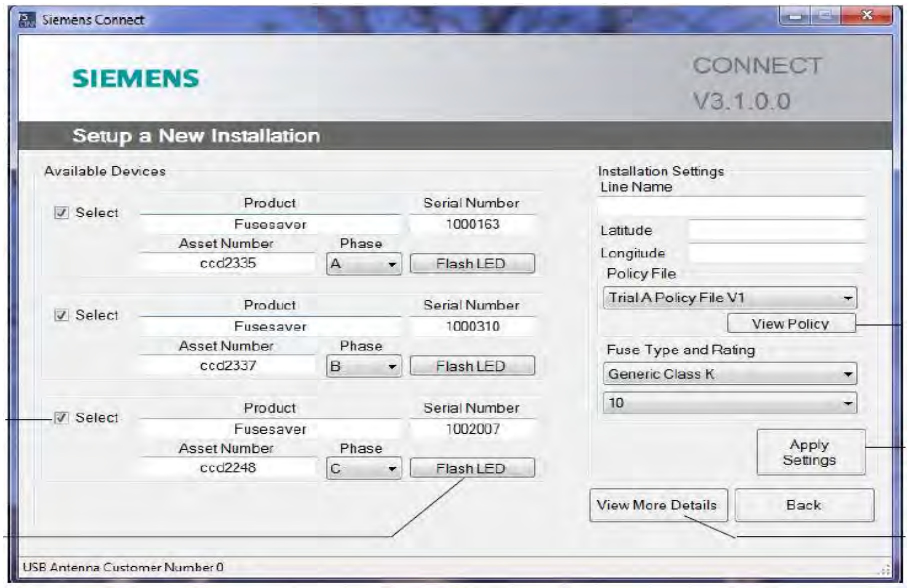


Figure 7.11: **FuseSaver connect**

7.4.8 Operation

When on-site the line crew and author could access the live data in the FuseSaver using the Siemens Connect PC application. This live data includes [19]:

- Details of the partner fuse and protection settings in the FuseSaver
- The FuseSaver open/closed status
- The load current in each FuseSaver
- The protection mode that is active
- Whether the protection is armed
- Details on the most recent fault
- Details on the FuseSaver and battery life.

The operators and author also had the ability to trip and close the FuseSaver using controls from the PC. See Figure 7.12 below.

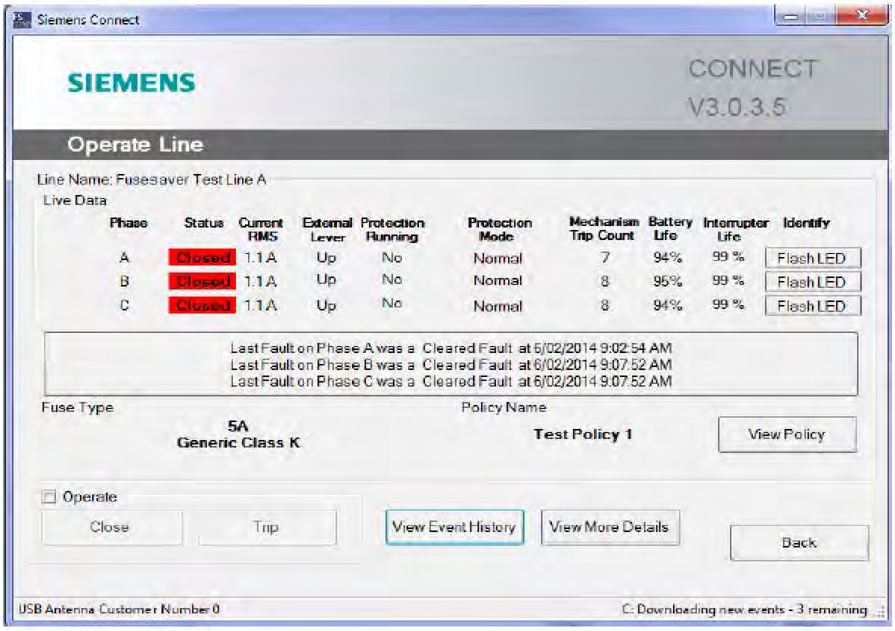


Figure 7.12: **Siemens connect - operation line [19]**

7.4.9 Event Data

FuseSaver stores a time stamped history of the major events in it's on board memory. The event record contains a history of up to 3000 (first in – first out) events including protection operations, fault data, outage durations and configuration changes [19].

The event data could be viewed using the Siemens Connect PC application as illustrated in Figure 7.13 below. Data can be filtered and exported as required. All events can be transferred to the network control centre when a RCU is connected.

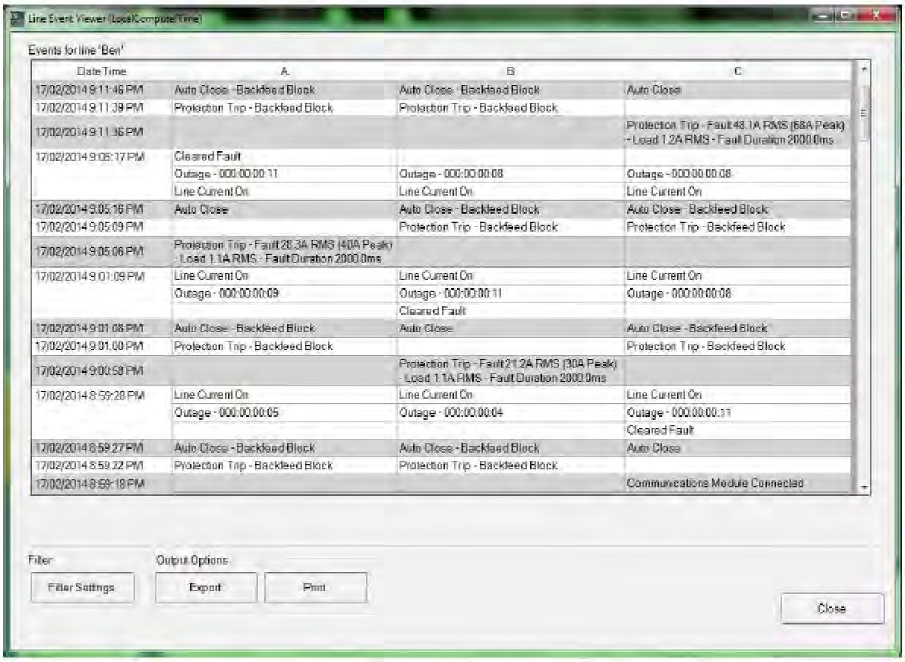


Figure 7.13: **Siemens Connect PC application - Event data [19]**

7.4.10 Network Reliability Data

The purpose of the line reliability analysis tool was to generate useful reliability performance data for the trial feeder. The analysis was conducted between a start date and end date that are selected. Figure 7.14 shows an example of the reliability statistics reported which includes the following items on a per phase basis:

- Number of momentary outages
- Total momentary outage time in the period (the time supply was off for downstream customers).
- Number of faults cleared by the FuseSaver
- Number of sustained outages
- Total sustained outage time in the period (the time supply was off for downstream customers)
- The statistics include interruptions and outages caused by upstream devices as well as the FuseSaver and its partner fuse.
- That faults cleared by FuseSaver within 5 s of each other in the event log will be counted as a single cleared fault in the installation total since this equates to a single site visit that has been saved.
- The reliability data available is dependent on whether a communications module was permanently fitted to the FuseSaver or only temporarily fitted to download the event record [19].

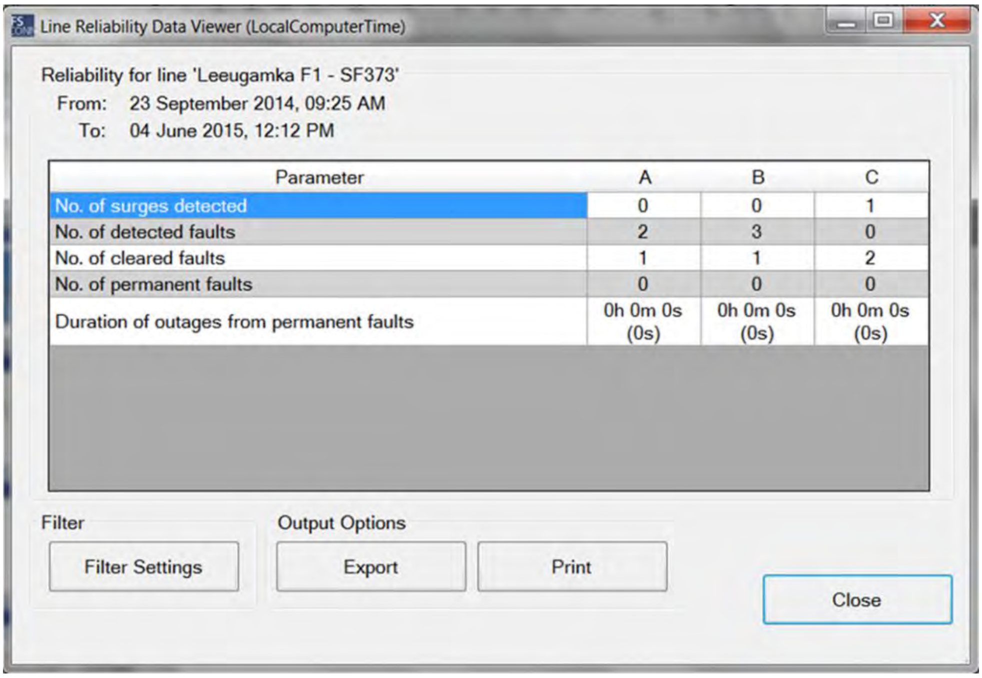


Figure 7.14: **Siemens Connect PC application - Reliability data [19]**

7.4.11 Operation

Switching

Switching covers an electrical and a mechanical switching. Switching is also carried out automatically to protect the network [19].

Mechanical switching comprises:

- Switching on the trip and close levers of the communications module

Electrical switching comprises:

- Remote switching
- Manual switching by Siemens Connect software

Mechanical switching on the communications module

The communications module (3) is fitted with two external levers (1), (2) that will trip or close the FuseSaver when operated [19].

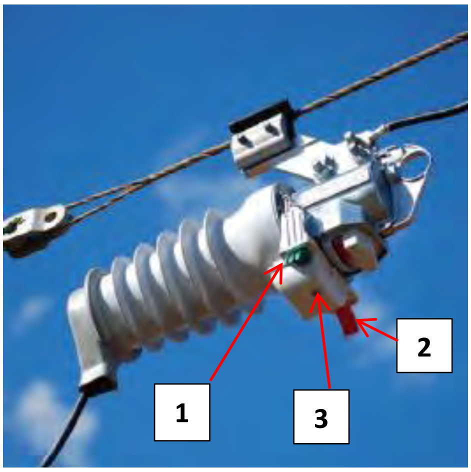


Figure 7.15: **Mechanical switching using the live - line stick**

These levers (1) and (2) are operated by pushing the live-line stick from the ground level [19]. The levers (1), (2) are colour coded: Refer to Table 7.1.

Table 7.1: Mechanical switching on the communications module of the FuseSaver [19]

Lever	**Colour**	**Operation**
Trip lever (1)	Green	Opens the FuseSaver
Closer Lever (2)	Red	Closes the FuseSaver

Chapter 8: Load Point and System Indices Calculations after installation of Equipment

8.1. Introduction

This chapter involves the reliability evaluation of the Waterkloof Farmers 1 11 kV Feeder Distribution Network after installation of the equipment using Configuration 2, 3 and 4. The approach is to make an FMEA table with Configurations 2, 3 and 4 used on the pilot feeder .i.e.

- **Configuration 2**: Configuration 1 + FuseSavers added at SF451
- **Configuration 3**: Configuration 2 + Tripsavers and FPI's added at SF617
- **Configuration 4**: Configuration 3 + Intellirupter Pulsecloser added at LBS 4204

Figure 8.1 shows the overview of Waterkloof F1 11 kV Feeder network after installation of the equipment

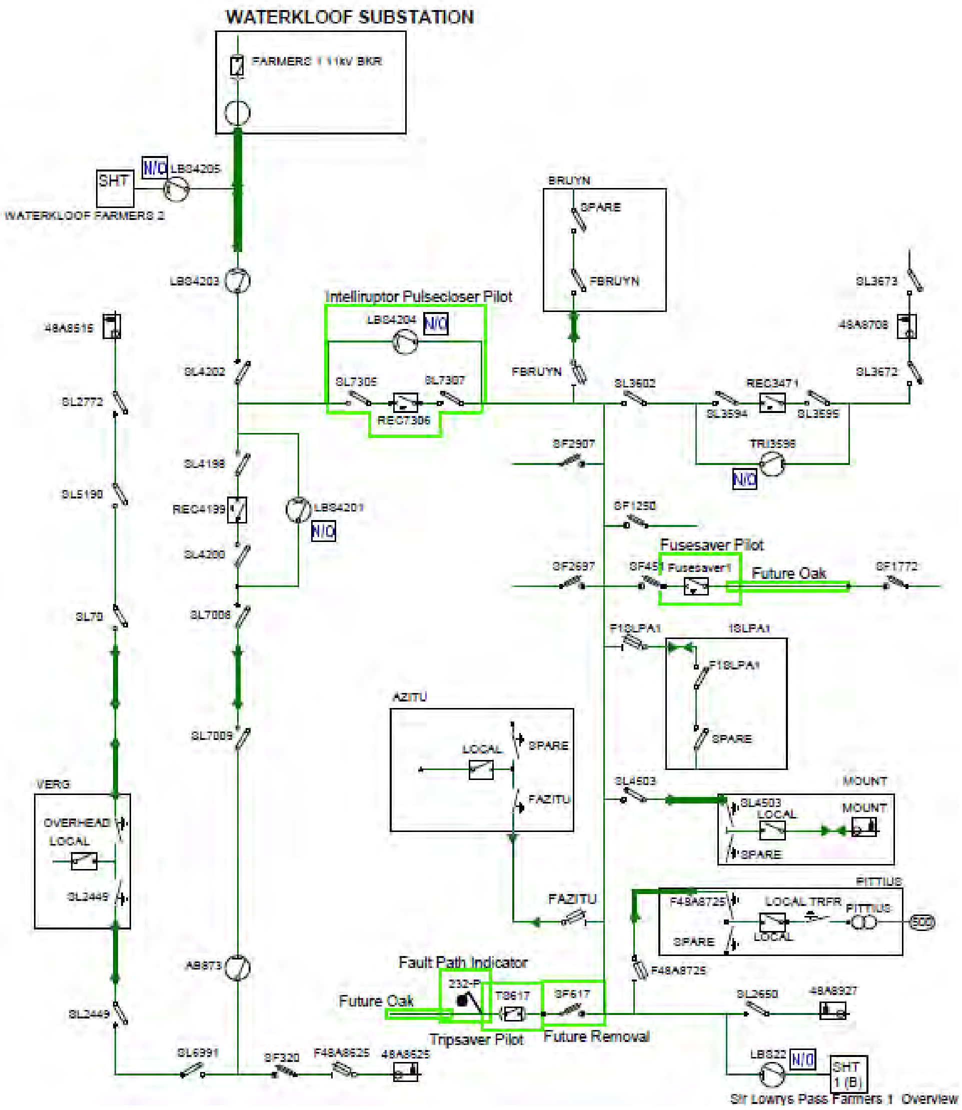


Figure 8.1: **Waterkloof Farmers 1 Overview with installation of Equipment**

The average restoration time for the components is set to 0.1 hours after installation of equipment. Transient faults were assumed to operate the new devices which eliminated most permanent faults. The results shown in Table 8.1, Table 8.2 and Table 8.3 can be used to obtain the system performance indices for the different configurations used on the pilot feeder. In order to calculate the system indices, the value of the feeders load point indices, equivalent lateral sections and the number of customers connected to the feeder must be known. System indices calculations for Configuration 2, 3 and 4 are shown below.

8.2. Configuration 2 - with FuseSaver connected to Load Point G

Table 8.1: Load point indices for the pilot network – Configuration 2

Load Point G			Load Point H			Load Point I			Load Point J			Load Point K			Load Point L			Load Point M		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0,5309	5	2,65465	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
0,0307	5	0,15326	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
0,0416	5	0,20799	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208
0,2791	5	1,39574	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957
0,0033	1	0,00328	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033
0,1675	5	0,83745	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374
0,012	5	0,06021	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602
0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848
0,0077	5	0,03831	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383
0,0493	5	0,24631	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463
0,104	5	0,51998	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52
0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808
0,127	5	0,63493	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349
0,0799	5	0,39957	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,6229	0,1	0,26229	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0,4499	5	2,2496	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0,9261	5	4,6306	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1,2293	5	6,1467	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1,7406	5	8,7029	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
4,604	**2,22**	**10,23**	**2,431**	**5,03**	**12,217**	**2,907**	**5,02**	**14,6**	**3,21**	**5,02**	**16,11**	**3,722**	**5,02**	**18,67**	**1,981**	**5,03**	**9,967**	**1,981**	**5,03**	**9,967**

Where $\lambda_S = \sum \lambda_i$, $r_s = \frac{\mathrm{Us}}{\lambda \mathrm{s}} = \frac{\sum \lambda \mathrm{i}\ \mathrm{ri}}{\sum \lambda \mathrm{i}}$, $U_s = \sum \lambda_i r_i$

$$SAIDI = \frac{(10.72*20)+(9.9673*1)+(9.981*1)+(11.8009*2)+(15.6926*12)+(13.3116*3)+(10.2296*15)+(12.2169*5)+(14.5979*6)+(16.1140*11)+(18.6701*6)+(9.9673*3)+(9.9673*1)}{86}$$

= 12.99 interruption/ (customers.year)

$$SAIFI = \frac{(9.5082*20)+(1.9811*1)+(1.9855*1)+(2.3478*2)+(3.1261*12)+(2.6499*3)+(4.6040*15)+(2.4310*5)+(2.9072*6)+(3.2104*11)+(3.7217*6)+(1.9811*3)+(1.9811*1)}{86}$$

= 4.75 hours/ (customer.year)

CAIDI = $\frac{SAIDI}{SAIFI} = \frac{12.99}{4.75}$ = ***2.74 hours/customers interruption***

8.3. Configuration 3 - with FuseSaver and Tripsaver connected to Load point G and K respectively

Table 8.2: Load point indices for the pilot network – Configuration 3

Load Point G			Load Point H			Load Point I			Load Point J			Load Point K			Load Point L			Load Point M		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0,5309	5	2,65465	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
0,0307	5	0,15326	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
0,0416	5	0,20799	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208	0,0416	5	0,208
0,2791	5	1,39574	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957	0,2791	5	1,3957
0,0033	1	0,00328	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033	0,0033	1	0,0033
0,1675	5	0,83745	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374	0,1675	5	0,8374
0,012	5	0,06021	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602	0,012	5	0,0602
0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848	0,277	5	1,3848
0,0077	5	0,03831	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383	0,0077	5	0,0383
0,0493	5	0,24631	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463	0,0493	5	0,2463
0,104	5	0,51998	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52	0,104	5	0,52
0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808	0,2562	5	1,2808
0,127	5	0,63493	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349	0,127	5	0,6349
0,0799	5	0,39957	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996	0,0799	5	0,3996
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,6229	0,1	0,26229	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0,4499	5	2,2496	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0,9261	5	4,6306	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1,2293	5	6,1467	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1,7406	0,1	0,1741	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
4,604	**2,22**	**10,23**	**2,431**	**5,03**	**12,217**	**2,907**	**5,02**	**14,6**	**3,21**	**5,02**	**16,11**	**3,722**	**2,72**	**10,14**	**1,981**	**5,03**	**9,967**	**1,981**	**5,03**	**9,967**

Where $\lambda_s = \sum \lambda_i$, $r_s = \frac{U_s}{\lambda_s} = \frac{\sum \lambda_i r_i}{\sum \lambda_i}$, $U_s = \sum \lambda_i r_i$

$$SAIDI = \frac{(10.72*20)+(9.9673*1)+(9.981*1)+(11.8009*2)+(15.6926*12)+(13.3116*3)+(10.2296*15)+(12.2169*5)+(14.5979*6)+(16.1140*11)+(10.1413*6)+(9.9673*3)+(9.9673*1)}{86}$$

= 12.40 interruption/ (customers.year)

$$SAIFI = \frac{(9.5082*20)+(1.9811*1)+(1.9855*1)+(2.3478*2)+(3.1261*12)+(2.6499*3)+(4.6040*15)+(2.4310*5)+(2.9072*6)+(3.2104*11)+(3.7217*6)+(1.9811*3)+(1.9811*1)}{86}$$

= 4.75 hours/ (customer.year)

CAIDI = $\frac{SAIDI}{SAIFI}$ = $\frac{12.40}{4.75}$ = ***2.61 hours/customers interruption***

8.4. Configuration 4 – with Fusesaver, Tripsaver and Intellirupter Pulsecloser connected to the feeder

Table 8.3: Load point indices for the pilot network – Configuration 4

λ = 1.0947	Load Point A			Load Point B			Load Point C			Load Point D			Load Point E			Load Point F		
section	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
1	0,5309	5	2,654648	0,5309	5	2,6546	0,531	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
2	0,0307	5	0,153258	0,0307	5	0,1533	0,031	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
3	0,0416	5	0,207993	0,0416	0,1	0,0042	0,042	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042
4	0,2791	5	1,395743	0,2791	0,1	0,0279	0,279	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279
5	0,0033	1	0,003284	0,0033	0,1	0,0003	0,003	5	0,0164	0,0033	0,1	0,0003	0,0033	0,1	0,0003	0,0033	0,1	0,0003
6	0,1675	5	0,837446	0,1675	0,1	0,0167	0,167	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167
7	0,012	5	0,060209	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012
8	0,277	5	1,384796	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277
9	0,0077	5	0,038315	0,0077	0,1	0,0008	0,008	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008
10	0,0493	5	0,246308	0,0493	0,1	0,0049	0,049	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049
11	0,104	5	0,519983	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104
12	0,2562	5	1,280799	0,2562	0,1	0,0256	0,256	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256
13	0,127	5	0,634926	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127
14	0,0799	5	0,399566	0,0799	0,1	0,008	0,08	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008
15	7,5272	0,1	0,752716	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0,004	0,1	0,0004	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0,3667	5	1,8336	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	1,1451	5	5,7253	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,6689	5	3,3443
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transformers	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
Total	**9,508**	**1,13**	**10,72**	**1,981**	**1,56397**	**3,098**	**1,985**	**1,569**	**3,1149**	**2,348**	**2,1**	**4,932**	**3,126**	**2,82**	**8,824**	**2,6499**	**2,4**	**6,443**

Load Point G			Load Point H			Load Point I			Load Point J			Load Point K			Load Point L			Load Point M		
λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)	λ(f/yr)	r(hrs)	U(hrs)
0,5309	5	2,65465	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546	0,5309	5	2,6546
0,0307	5	0,15326	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533	0,0307	5	0,1533
0,0416	0,1	0,00416	0,0416	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042	0,0416	0,1	0,0042
0,2791	0,1	0,02791	0,2791	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279	0,2791	0,1	0,0279
0,0033	0,1	0,00033	0,0033	0,1	0,0003	0,0033	0,1	0,0003	0,0033	0,1	0,0003	0,0033	0,1	0,0003	0,0033	0,1	0,0003	0,0033	0,1	0,0003
0,1675	0,1	0,01675	0,1675	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167	0,1675	0,1	0,0167
0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012	0,012	0,1	0,0012
0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277	0,277	0,1	0,0277
0,0077	0,1	0,00077	0,0077	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008	0,0077	0,1	0,0008
0,0493	0,1	0,00493	0,0493	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049	0,0493	0,1	0,0049
0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104	0,104	0,1	0,0104
0,2562	0,1	0,02562	0,2562	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256	0,2562	0,1	0,0256
0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127	0,127	0,1	0,0127
0,0799	0,1	0,00799	0,0799	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008	0,0799	0,1	0,008
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,6229	0,1	0,26229	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0,4499	5	2,2496	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0,9261	5	4,6306	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1,2293	5	6,1467	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1,7406	0,1	0,1741	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15	0,015	10	0,15
4,604	**0,73**	**3,3606**	**2,431**	**2,2**	**5,348**	**2,907**	**2,66**	**7,729**	**3,21**	**2,88**	**9,245**	**3,722**	**0,88**	**3,272**	**1,981**	**1,56**	**3,098**	**1,981**	**1,56**	**3,098**

Where $\lambda_S = \sum \lambda_i$, $r_S = \frac{U_s}{\lambda_s} = \frac{\sum \lambda_i\ r_i}{\sum \lambda_i}$, $U_S = \sum \lambda_i r_i$

The FMEA load point indices for Table 8.3 are summarised in the bar graph below.

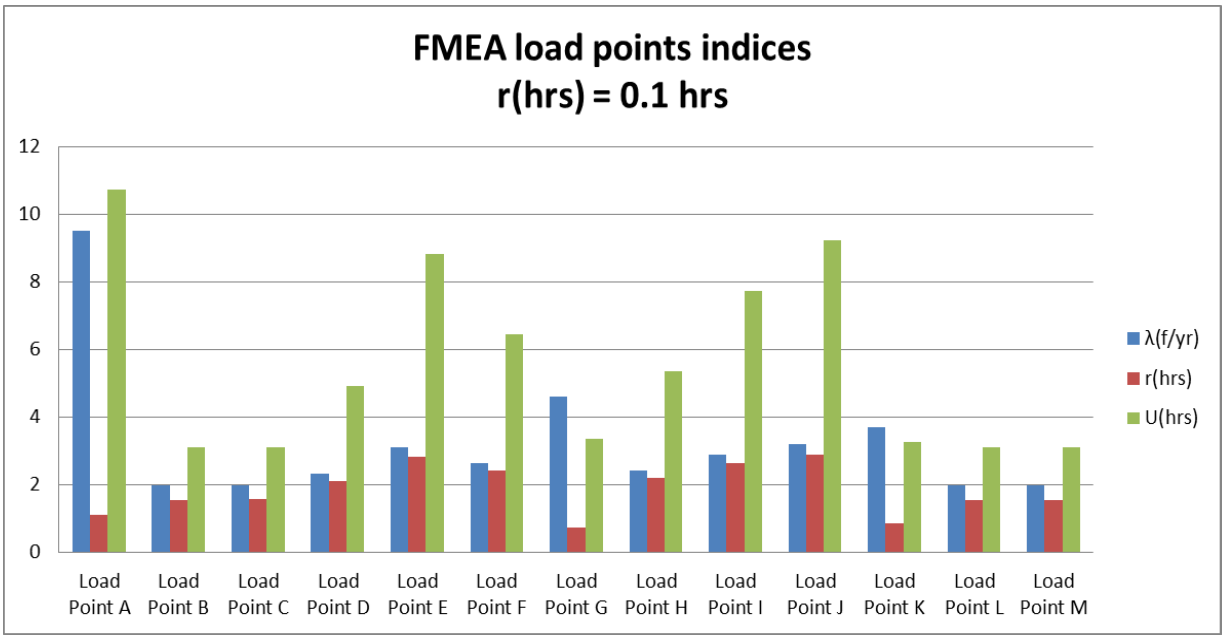


Figure 8.2: **FMEA load point indices where r (hrs) = 0.1 hrs**

$$SAIDI = \frac{(10.72*20)+(3.0984*1)+(3.115*1)+(4.9320*2)+(8.8236*12)+(6.4427*3)+(3.3607*15)+(5.3480*5)+(7.7289*6)+(9.2451*11)+(3.2724*6)+(3.0984*3)+(3.0984*1)}{86}$$

= 7.13 interruption/ (customers.year)

$$SAIFI = \frac{(9.5082*20)+(1.9811*1)+(1.9855*1)+(2.3478*2)+(3.1261*12)+(2.6499*3)+(4.6040*15)+(2.4310*5)+(2.9072*6)+(3.2104*11)+(3.7217*6)+(1.9811*3)+(1.9811*1)}{86}$$

= 4.75 hours/ (customer.year)

CAIDI = $\frac{SAIDI}{SAIFI} = \frac{7.13}{4.75}$ = ***1.50 hours/customers interruption***

Table 8.4 below summarises the system indices of the feeder for the four different configurations using FMEA and Reliability Network Equivalent Approach.

Table 8.4: System indices of the feeder for the four different configurations

	SAIDI	SAIFI	CAIDI
Configuration 1 (base case)	15.24	4,75	3.21
Configuration 2	12.99	4,75	2.74
Configuration 3	12.40	4,75	2.61
Configuration 4	7.13	4,75	1.50

The figure below illustrates the improvement of the system indices after the implementation of the new innovative technologies using FMEA method. The SAIDI improved while the SAIFI remained constant. Most permanent faults were eliminated, as a result, sustained interruptions were prevented while momentary interruptions were increased.

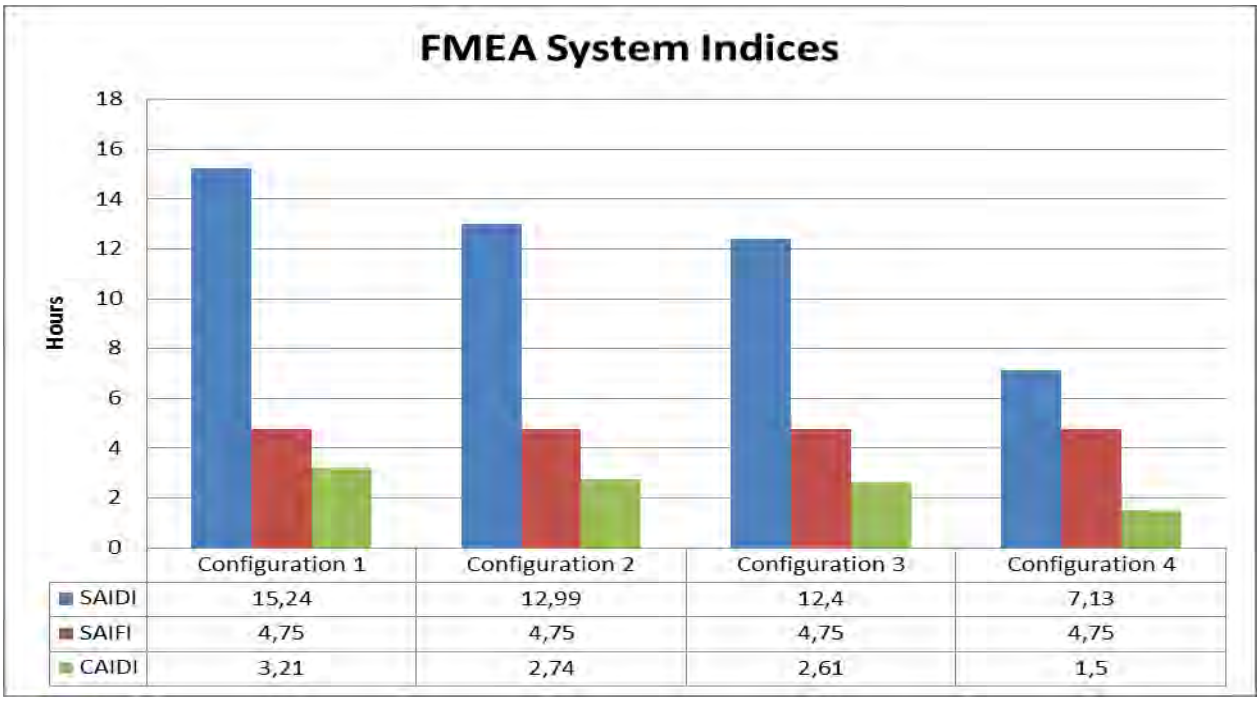


Figure 8.3: **FMEA System Indices**

Figure 8.4 compares the unavailability of load points before and after the installation of equipment. The unavailability of load points improved after implementation of the equipment.

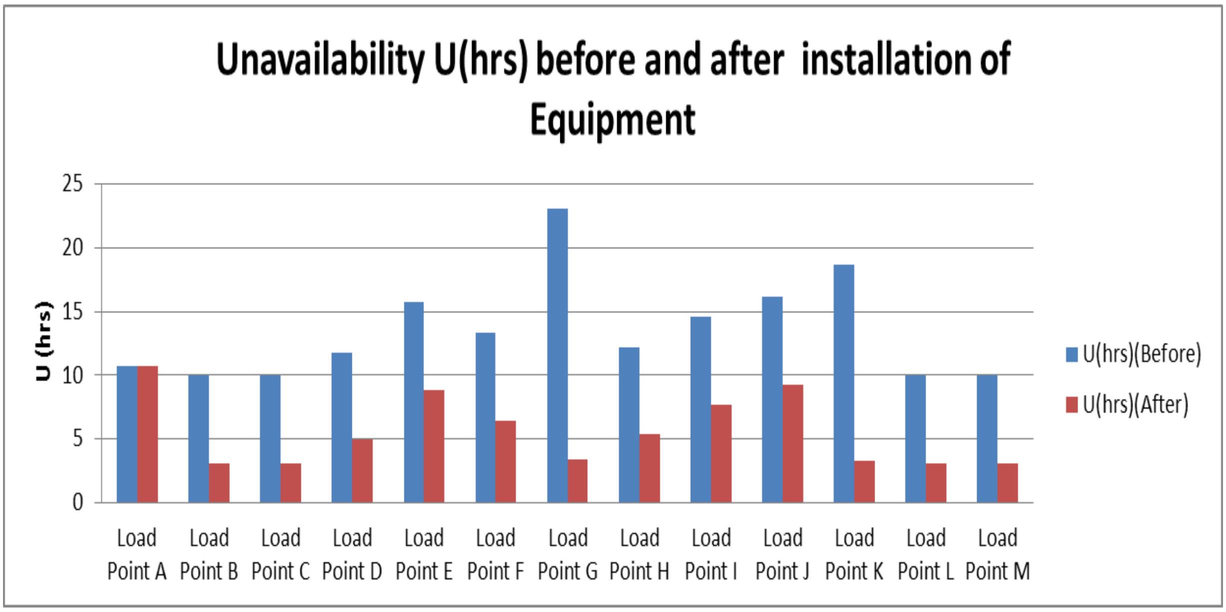


Figure 8.4: **Unavailability of load points**

Based on data taken for 6 months period, significant improvements on the system reliability indices of the tested feeder were detected. However, implementation of this new system equipment may not show the expected results due to environmental and seasonal factors, especially at faults beyond the Intellirupter PulseCloser, but at the initial stage a significant improvement on the system reliability indices of the tested feeder was noted. Additional data received over the next two years will be needed to obtain a better understanding of the impacts and they are expected to have enhanced capabilities for improving electric distribution reliability.

8.5. Comparison and Discussion of System Indices Results

The System Indices are computed using FMEA and DIgSILENT PowerFactory for the different network configurations. The load point indices are not presenting the full behaviour of the network which is the reason why system indices were computed to determine the performance of the modelled network.

The comparison of the total system indices using FMEA and DPF are as shown in Tables 8.5 and Figure 8.5 below. The results shown in Table 8.5 for both the simulation and analytical approaches are very much comparable, proving that any of these methods can be used to assess the reliability of a distribution network. Also from the table, it can be seen that the percentage differences are quite negligible and the addition of this new system devices has improved all the reliability indices of the feeder except SAIFI. As indicated in Table 8.5 below, there was an improvement in SAIDI after installation of the distribution automation. The feeder automation system used minimised restoration time (decreased the SAIDI) and reduced the impact on the affected customers suffering from interruption. The addition of this new system equipment has not reduced the failure frequency but the failure duration. Although both methods have shown a high degree of accuracy, DIgSILENT is still the number one choice due to many advantages 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. The disadvantage with the FMEA is the fact that it can be subjected to human error that will lead to incorrect results. Minor or no differences are observed between the results. The reason for this is that the failure modes analysis is based on approximate equations and differences are therefore expected. The differences will be negligible, however, provided that $\lambda r \ll 1$ for each component; this is normally the case for power system networks. It should be noted that the value of system unreliability is evaluated using a summation rule [37].

Table 8.5: System indices using FMEA and DPF

	SAIDI			SAIFI			CAIDI		
	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF	DPF	FMEA	% DIFF
Configuration 1	15,24	15,24	0	4,75	4,75	0	3,21	3,21	0
Configuration 2	12,99	12,99	0	4,75	4,75	0	2,74	2,74	0
Configuration 3	12,4	12,4	0	4,75	4,75	0	2,61	2,61	0
Configuration 4	7,13	7,13	0	4,75	4,75	0	1,5	1,5	0

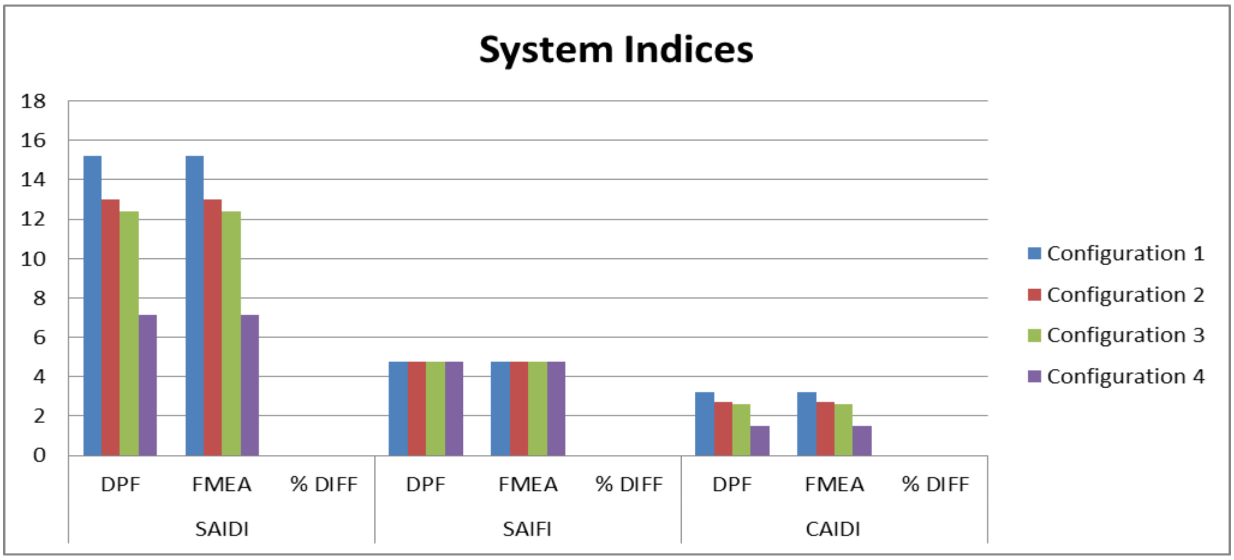


Figure 8.5: **Comparison of FMEA and DPF system indices**

Chapter 9: Cost Assessment of Reliability Improvement in Distribution Networks

9.1. Introduction

A major challenge for the power utilities today is to ensure a high level of reliability of supply to customers. Two main factors determine the feasibility of a project that improves the reliability of supply i.e.

1. The project cost (investment and operational) and
2. The benefits that result from the implementation of the project.

9.2. Reliability Cost

The most important function of the electric power system is to provide electric power to its customers at the lowest possible cost with acceptable reliability levels. The two aspects of economics and reliability often conflict and present power system managers, planners, designers and operators with a wide range of challenging problems. An acceptable method of assessing the worth of power system reliability is to evaluate the customer losses due to service interruptions, i.e. the cost of unreliability [31].
Many new challenges in the deregulated environment have been confronted by the Electric power industry. The electricity utilities have been forced to utilise network assets more effectively and reduce outage time due to faults. The final link between the bulk transmission system and the customers is provided by the distribution network. Installing reliability improving apparatus at medium voltage level is recommended since approximately 80 % of customer service interruptions are experienced at this voltage level. Service reliability is improved by implementing various strategies such as feeder length reduction, feeder splitting and installing improved switchgear and protection apparatus, for example replacing oil breakers with gas breakers at substations [42], [43]. Currently, one of the most cost-effective methods now being considered for improving service reliability is distribution feeder automation i.e. implementation of new technologies. This involves the use of remote switches to isolate the faults and restore the power supplies to the other remaining healthy section of the feeder. The costs associated with the installation of switches are quite significant; despite the fact that the feeder's switch automation can increase the system reliability. There is a growing concern in power utilities, regarding a quantitative justification of the increase in reliability due to the placement of switches rather than simply based on reduced interrupted duration. Reliability worth assessment is currently receiving considerable attention as it provides an opportunity to incorporate the costs or losses incurred by utility customers as results of power failure. In order to render a rational means of decision making on the necessity of changing service continuity levels experienced by customers, utility costs and the cost incurred by customers associated with interruptions of service must be incorporated in planning and operating practices.

New distribution automation technologies have been applied to the distribution network in order to achieve significant service reliability improvement for electricity customers [32–34]. Other approaches are the interruption cost minimisation based on appropriate switch location or relocation across a distribution feeder and investigate reliability improvement [35], [36]. The investment decisions are based on project economic feasibility studies through which the most beneficial investment alternative is determined. For an investment to be economically viable, utility's cost to improve reliability should be less that the customer's cost or cost of interruption.

Figure 9.1 shows how utility costs reflected in customer rates and customer interruption costs are combined to give the total societal cost. The utility cost curve shows how customer rates increase as more money is spent for increased distribution system reliability levels [7]. The customer interruption cost curve shows how customer cost of interruptions decreases as the distribution system reliability increases [7]. It is also important to note that for low distribution system reliability levels, the customer interruption costs are significant. [7]. However, the utility cost can also increase significantly in the additional costs of restoring the system to a normal operating state and the loss of revenue (i. e., the utility cost curve shown in Figure 9.1 is based on the belief that increased costs will achieve higher levels of distribution system reliability) [7]. When the combined utility and customer interruption costs are at the minimum, then the utility customers will receive the optimal service, as indicated by the dashed line. Therefore, a given level of service reliability can be examined in terms of the costs and the worth to the customer of providing the electric service from various proposed distribution operating configurations using the concept of value based distribution system reliability planning [45].

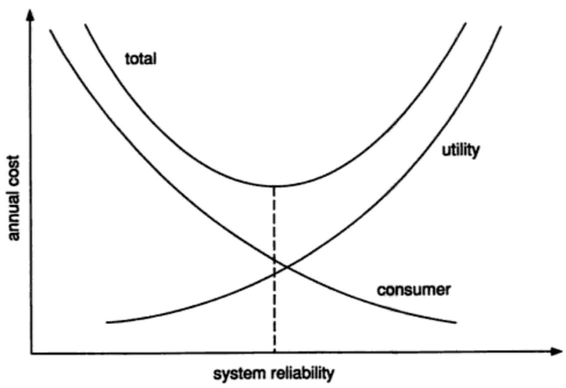


Figure 9.1: **Consumer, utility and total cost as a function of system reliability [45]**

9.3. Feeder Load Forecast

The load information was obtained from statistical metering installed at the substations for the area under study and used in the network reliability costing assessment for Waterkloof Farmers1 11 kV Feeder. The feeder registered a peak loading of 3.62 MVA at a power factor of 0.92 in the year 2013. The annual load growth is approximately 5.8 % per year. These elements were included in the costing assessment of reliability improvement in distribution networks using DIgSILENT PowerFactory software.

Figure 9.2 shows the historical load profile of Waterkloof Farmers1 11 kV Feeder

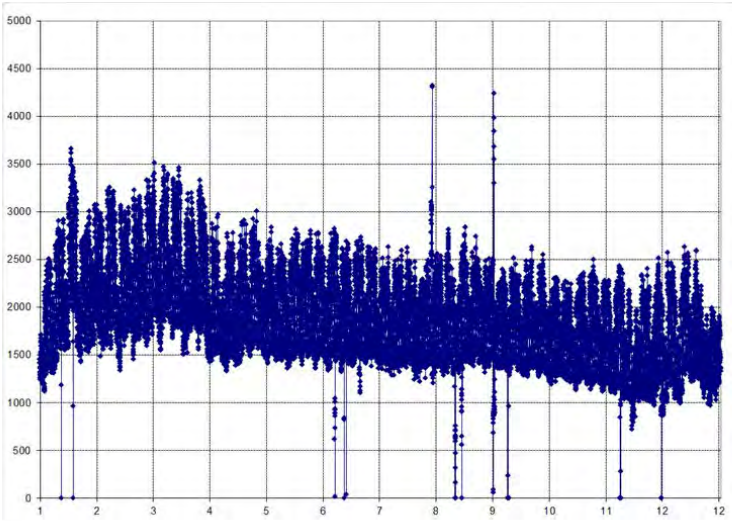


Figure 9.2: **Load profile metering of Waterkloof Farmers 1 11 kV Feeder for 2013 [6]**

9.4. Reliability Cost/Worth Planning Approach

The majority of outages seen by customers are caused by failures in the distribution systems. The reliability planning approach is based on Cost of Unserved Energy (COUE). This is the economical loss the customer experiences due to unserved energy as a result of planned or unplanned interruptions. The approach balances the cost of improving service reliability for customers and the economic benefits of such improvements. The importance of the power grid depends on the customer being supplied. In order to determine the distribution system reliability, the income that the utility gets from the customers per year must be known. This income will serve as a gate keeper which is the limit that the planners should not exceed when making a decision in terms of economic and network optimisation planning so that there will be no loss to the business. According to Eskom standard, the charges per Industrial / commercial customer is 80c /kWh and the Waterkloof Farmers1 11 kV Feeder is supplied at the notified maximum demand load (NMD) of 3.62 MVA. The load is only used for the customer interruption cost calculation based on the SAIDI impact at a business level. The power factor and load factor are also used for calculation of losses [52].

Therefore, the annual income from the Waterkloof Farmers 1 11 kV Feeder amounts to R23,326,549/yr. as shown below:

Income /year of the Feeder = 3618kVA x 0.92 x 8760hrs x R0.8/kWh = R23, 326,549/yr.

The income/year of the feeder must be multiplied with the load factor of 0.58 due to the fact that customers do not draw the maximum load. Therefore, the income/year of the feeder will amount to R 13, 529,398/yr.

Utility cost can be calculated by

Utility Cost (R) = Loss of income + Investment cost + Maintenance cost + Operation cost [27]

The utility cost includes the loss of income (due to unserved energy), the investment cost and maintenance cost; and the contractors and labours cost. The investment cost and maintenance cost of components added are listed in Table 9.1 as per Eskom data.

Table 9.1: Investment cost, Maintenance cost and Operation cost (per year)

	Fuses (each)	**Disconnects (each)**	**Breakers/Reclosers (each)**	**Conductors**	**Fusesavers (each)**	**Tripsavers (each)**	**Fault Path Indicators (FPI) (each)**	**IntelliRupter Pulsecloser (each)**
Investment cost	R 3700	R 30000	R 80000	R200000/km	R 33800	R 30000	R 32300	R 345600
Maintenance cost	0	R5000 (Labour)	R 5000 (Trip test)	R2000/km (Inspection)	0	0	0	0

The average interest rate for the contractors and labours cost is assumed to be 10 % of the material costs. The depreciation period for disconnects and breakers is assumed to be 20 years. The maintenance cost of the breakers is very low due to the fact that the (SF6) breaker is maintenance free because it does not use oil for arc quenching, and, therefore, the amount shown is only for the breaker trip test and inspections [52].

The customer interruption cost (CIC) is associated with the outage cost in a specific load point.

The CIC is calculated as follows:

$$\textbf{CIC/year} = \sum_{x=A}^{M} U_x L_x C_x \qquad (9.1)$$

Where:

x = Load points
U_x = Annual unavailability at load point x ($U_x = \lambda_x r_x$)
L_x = Average load point at load point x
r_x = Interruption duration
λ_x = Failure rate at load point x
C_x = Average cost of unserved energy per year at load point x

The average cost of unserved energy i.e. sector interruption cost for commercial customers, used by Eskom, is R21.48/kWh. The total cost of interruption was calculated by adding all the CIC of the load points.

9.4.1 Different Configurations Tested - Cost benefits analysis before and after the installation of the equipment

Table 9.2 shows four different configurations. Configuration one is the base case in which all fuses, disconnects, breakers, and alternative supply are installed. The other configurations are calculated by adding the FuseSavers, Tripsavers, FPI's and Intellirupter Pulsecloser.

Table 9.2: Four different configurations

Configuration 1	Standard Eskom MV Network with fuses, disconnects and reclosers
Configuration 2	Configuration 1 + FuseSavers added at SF451
Configuration 3	Configuration 2 + Tripsavers and FPI's added at SF617
Configuration 4	Configuration 3 + Intellirupter Pulsecloser added at LBS 4204

The following calculation is indicative of how a utility can calculate the financial benefit of installing the equipment on the basis of unplanned SAIDI improvements. The benefit relates to the particular financial penalty for sustained and momentary customer hours, interruptions and operational costs, which may not be applicable to other utilities.

Configuration 1: Standard Eskom MV Network with fuses, disconnects and reclosers – before installation of Distribution Automation Equipment

Name	In Folder	Grid	Act.Pow. MW	Number of connec....	Tariff IntTariffenergy,Int.....	AID h	LPIT h/a	LPIF 1/a	LPENS MWh/a	ACIF 1/a	ACIT h/a	LPIC $/a	TCIT Ch/a	TMVAIF
A	A	Grid	4,2458	20		1,127442	10,71999	9,5082384	4,551491	9,508238	10,71999	97766,03	214,3997	5,305777
BRUYN (B)	BRUYN (B)	Grid	0,46	1		5,031227	9,96727	1,9810812	0,458494	1,981081	9,96727	9848,46	9,96727	2,758958
C	C	Grid	0,92	1		5,026968	9,980844	1,98546	0,918238	1,98546	9,980844	19723,74	9,980844	5,505747
D	D	Grid	0,115	2		5,02635	11,80089	2,3478057	0,13571	2,347806	11,80089	2915,056	23,60178	0,582003
E	E	Grid	0,529	12		5,019789	15,69255	3,1261374	0,830136	3,126137	15,69255	17831,32	188,3106	2,010653
F	F	Grid	0,138	3		5,023345	13,31158	2,6499429	0,1837	2,649943	13,31158	3945,871	39,93473	0,618774
G	G	Grid	0,98164	15		5,013437	23,08178	4,6039824	2,265799	4,603982	23,08178	48669,37	346,2266	2,533426
H	H	Grid	0,46	5		5,025448	12,21688	2,4310029	0,561976	2,431003	12,21688	12071,25	61,08439	2,24834
I	I	Grid	0,46	6		5,021279	14,59785	2,9071974	0,671501	2,907197	14,59785	14423,84	87,5871	1,880065
J	J	Grid	0,805	11		5,01927	16,11401	3,2104293	1,297178	3,210429	16,11401	27863,38	177,2541	2,979355
K	K	Grid	0,345	6		5,016623	18,67013	3,7216542	0,64412	3,721654	18,67013	13835,69	112,0208	1,10147
L	L	Grid	0,552	3		5,031227	9,96727	1,9810812	0,550193	1,981081	9,96727	11818,15	29,90181	3,31075
M	M	Grid	0,92	1		5,031227	9,96727	1,9810812	0,916989	1,981081	9,96727	19696,92	9,96727	5,517916

Figure 9.3**: Results of the load point indices of Configuration 1 from DIgSILENT PowerFactory**

Note: ACIF (*1/a*) =λ and AID (*h*) = *r*

The CIC calculation for different load points for Configuration 1 is shown in Figure 9.4 using equation **(9.1)**

Configuration 1: Interruption cost of load points

Configuration 1								
Load	**λ(f/yr)**	**r(hrs)**	**U(hrs/yr)**	**Average Load (MW)**	**Average Load (kW)**	**Unserved Energy (kWh/yr)**	**COUE(R/kWh)**	**CIC(R/yr)**
A	9,508238	1,12744179	10,71998532	4,1535	4153,5	44525,45903	21,48	956406,8599
BRUYN (B)	1,981081	5,03122719	9,9672696	0,46	460	4584,944016	21,48	98484,59746
C	1,98546	5,026967997	9,98084388	0,9	900	8982,759492	21,48	192949,6739
D	2,347806	5,02634954	11,8008921	0,1125	112,5	1327,600361	21,48	28516,85576
E	3,126137	5,019789149	15,6925506	0,529	529	8301,359267	21,48	178313,1971
F	2,649943	5,023345258	13,3115781	0,138	138	1836,997778	21,48	39458,71227
G	4,603982	5,013436976	23,0817756	0,9603	960,3	22165,42911	21,48	476113,4173
H	2,431003	5,025447769	12,2168781	0,46	460	5619,763926	21,48	120712,5291
I	2,907197	5,021279463	14,5978506	0,46	460	6715,011276	21,48	144238,4422
J	3,210429	5,019269572	16,1140101	0,805	805	12971,77813	21,48	278633,7942
K	3,721654	5,016622608	18,6701346	0,345	345	6441,196437	21,48	138356,8995
L	1,981081	5,03122719	9,9672696	0,552	552	5501,932819	21,48	118181,517
M	1,981081	5,03122719	9,9672696	0,92	920	9169,888032	21,48	196969,1949
Total Annual Cost of Interruption								**2967335,691**

Figure 9.4: **CIC of load points - Configuration 1**

Annual cost of interruptions of feeder for **Configuration 1** = **R 2967336.00**

An example (Load point A) from Figure 9.4 using equation (9.1) is illustrated below:

CIC/year = $U_A L_A C_A$ = (10.72hrs/yr) (4153.5 kW) (R 21.48/kWh) = R 956406.86yr.

Where: $U = \lambda \, x \, r$ *and Unserved energy =* U *x Average load*

Summary of Utility cost for Configuration 1:

Loss of income = R 0.8/kWh x 3618 kVA x 0.92 x 15.24 (SAIDI) = R 40581.80
Investment cost for fuses = R 3700 x 7 = R 25900
Investment cost for disconnectors = R 30000 x 8 = R 240000
Investment cost for reclosers = R 80000 x 2 = R 160000
Maintenance cost for fuses, disconnects and reclosers = 0+(8 x R 5000)+(2 x R 5000) = R 50000
Labour cost = 10% of investment cost for fuses = R 2590
Labour cost = 10% of investment cost for disconnects = R 24000
Labour cost = 10% of investment cost for reclosers = R 16000

Utility Cost = Loss of income + Investment cost + Maintenance cost + Operation cost

Utility cost = R 40581.80 + R 425900 + R 50000 + R 42590 = R 559071.80

```
| DIgSILENT   | Project:
| PowerFactory |
| 15.1.4      | Date:  6/30/2015

| Reliability Assessment
|   Method                                  Load flow analysis
|   Network                                 Distribution (Optimal Power Restoration)
|   Calculation time period                 2015
|   Consider Maintenance                    Yes
|   Fault Clearance Breakers                Use all circuit breakers
|   Switching procedures                    Sequential
|   Consider Sectionalizing (Stages 1-3)    No
|   Time to open remote controlled switches 0.10 min.
|
| Automatic Contingency Definition
|   Selection                               Whole System
|   Busbars / terminals                     Yes          Common mode                       No
|   Lines / cables                          Yes          Independent second failures       No
|   Transformers                            Yes          Double earth faults               No
|                                                        Protection/switching failures     No

| Study Case: Study Case                                           | Annex:          / 1

| System Summary

| System Average Interruption Frequency Index    :  SAIFI  =   4.752724 1/Ca
| Customer Average Interruption Frequency Index  :  CAIFI  =   4.752724 1/Ca
| System Average Interruption Duration Index     :  SAIDI  =   15.243    h/Ca
| Customer Average Interruption Duration Index   :  CAIDI  =    3.207    h
| Average Service Availability Index             :  ASAI   =    0.9958929464
| Average Service Unavailability Index           :  ASUI   =    0.0041070536
| Energy Not Supplied                            :  ENS    =   17.868    MWh/a
| Average Energy Not Supplied                    :  AENS   =    0.464    MWh/Ca
| Average Customer Curtailment Index             :  ACCI   =    0.944    MWh/Ca
| Expected Interruption Cost                     :  EIC    =    0.774    M$/a
| Interrupted Energy Assessment Rate             :  IEAR   =   19.414    $/kWh
| System energy shed                             :  SES    =    0.000    MWh/a
| Average System Interruption Frequency Index    :  ASIFI  =   3.769955 1/a
| Average System Interruption Duration Index     :  ASIDI  =   16.471011 h/a
| Momentary Average Interruption Frequency Index :  MAIFI  =    0.000000 1/Ca
```

Figure 9.5: **Results of the system indices from DIgSILENT PowerFactory to obtain SAIDI for Configuration 1**

Calculation of system customer interruption cost for Configurations 2, 3 and 4 are summarized in Table 9.3 and Figure 9.6. The details calculations are found in Appendix L.

From Table 9.3 and Figure 9.6, it can be seen that with component addition, both customer and system reliability index such as SAIDI is improved significantly.

Table 9.3: Summary of Configurations 2, 3 and 4

	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Power Factor (Cos θ)	0.92	0.92	0.92	0.92
Load Factor	0.58	0.58	0.58	0.58
Customer type	Industrial / commercial	Industrial / commercial	Industrial / commercial	Industrial / commercial
Customer charges	80c /kWh	80c /kWh	80c /kWh	80c /kWh
Cost of unserved energy	R21.48/kWh	R21.48/kWh	R21.48/kWh	R21.48/kWh
SAIDI value using DIgSILENT	15.24	12.99	12.4	7.13
Utility cost	R 559 071.80	R 705 204.86	R 943 814.18	R 1 342 960.29
Customer Interruption cost	R 2 967 336.00	R 2 702 229.90	R 2 639 026.32	R 1 659 123.89
Total cost	R 3 526 407.80	R 3 407 434.76	R 3 582 840.50	R 3 002 084.18

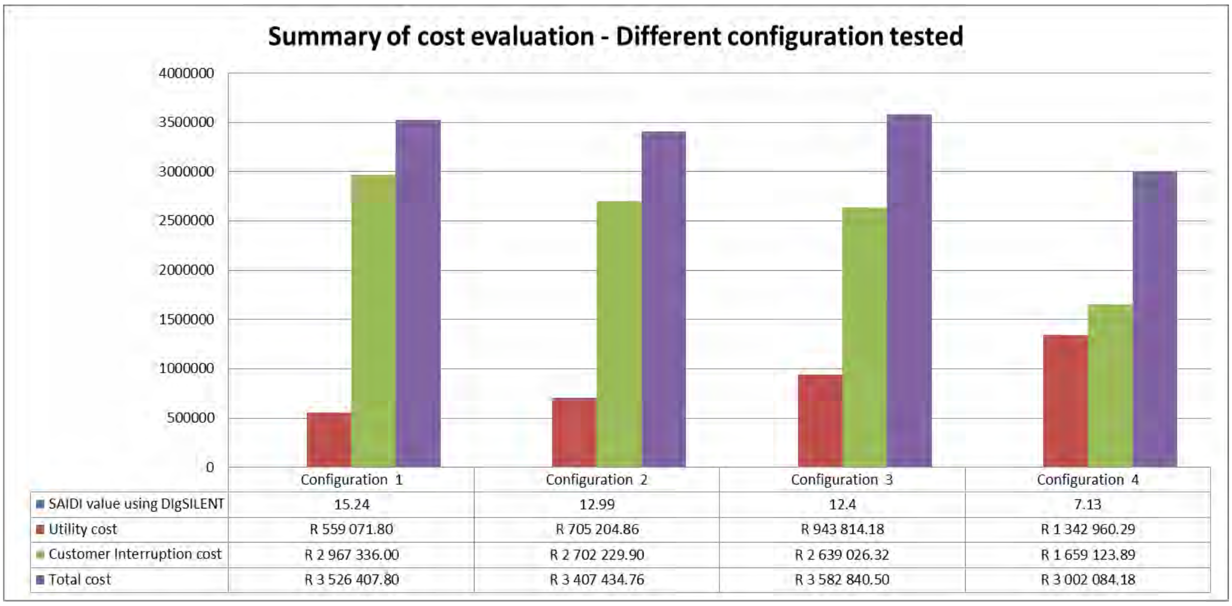


Figure 9.6: **Different configurations tested**

Results shown in Figure 9.6 provide basic information for system cost benefits analysis of the four configurations. The x-axis represents the different configurations and the y-axis represents the utility cost, customer interruption cost and total cost. Configurations 2 and 3 were designed by adding the FuseSaver and Tripsaver at SF 451 and SF 617 respectively while the configuration 4 was designed to add the Intellirupter Pulsecloser at LBS 4204 just before the substation breaker preventing unnecessary upstream substation breaker trips, dips and damage to the substation transformers. The outage cost decreased with the adding of components, so did the system reliability index i.e. SAIDI. System utility cost increased with the adding of components. The total cost is the summation of outage cost and system utility cost.

9.5. Reliability Cost Curve

The utility cost curve as illustrated in Figure 9.7 below shows how utility cost increases as more money is spent on optimising the reliability of the distribution network from which customers are supplied. The cost of an interruption is highly dependent on its duration [7].The customer interruption cost curve illustrates how customer cost of interruption decreases as the reliability of the distribution system increases. It is, therefore, important to note that the customer interruption costs are significant for the lower level of distribution systems reliability levels.

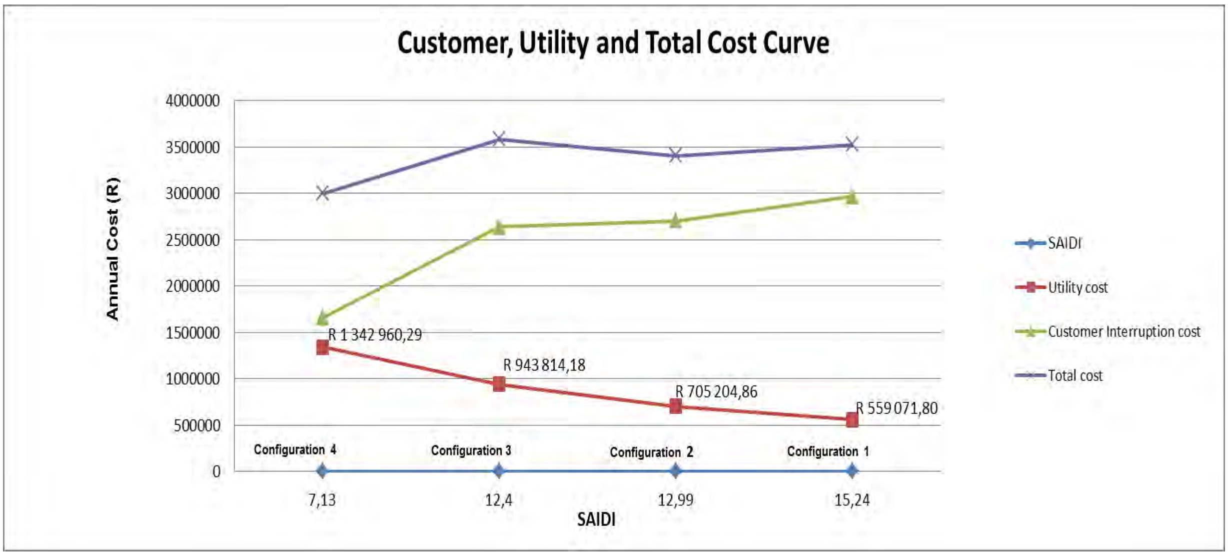


Figure 9.7*:* **Graphical representation of reliability costs.**

The total cost curve, (i.e. the sum of Utility cost and customer cost) is indicated by the purple line. The customer cost of reliability becomes important when a utility wishes to balance its costs with customer costs. The issue of whether a utility should have any regard to total cost is a matter for the regulator. In South Africa, this is badly regulated. To a great extent, the utilities disregard customer interruption costs and look only at costs incurred by the utility to meet the regulator's standard of reliability defined as SAIFI, SAIDI, etc. The cost for the utility is another issue that becomes a concern when dealing with improving power systems reliability. Cost and reliability in power systems go hand in hand in most cases, but there are some situations where lower cost is associated with higher reliability. To reduce SAIDI, the utility must spend increasing amounts of money on system reinforcements and maintenance [7]. This is evident in Figure 9.7, showing the trade-off between cost and customer interruptions. The utility cannot continuously keep on adding protection systems because reliability needs to be improved, there actually has to be a point where cost is minimal and in favour of both the customers and the utility. The result shown in Figure 9.7 has not yet reached this desirable point because the total cost curve is still decreasing, so the utility should be spending more. At this point an optimal cost is achieved when the combined utility and customer interruption costs curve is at the minimum, then the utility customers will receive the least cost service.
Seeking minimum total cost will normally lead to lower reliability in rural areas than in urban areas. In response, the Regulator usually finds it necessary to impose lower limits of acceptable reliability performance. However, to be effective, the actual performance must then be monitored properly and violations punished by the Regulator, which is not properly understood by NERSA as yet.

The graphs also depict that there is room for improvement i.e. as more money is spent for increased distribution system reliability levels, the level of customer interruption would decrease significantly until a point of intersection [the point of intersection is not necessarily the minimum total cost point. The minimum cost is where the absolutes of the gradients are equal] at which a reasonable level of reliability in power systems is achieved at minimum total costs for both the customer and the utility. However, the utility cost can also increase significantly in the additional costs of restoring the system to a normal operating state and the loss of revenue (i.e. the utility cost curve shown in Figure 9.7 is based on the belief that increased utility costs will achieve higher levels of distribution system reliability). On the basis of the above it can be seen that configuration four is the best choice among the designed configuration although there is still further room for increasing utility cost and decreasing customer interruptions to reach the minimum total cost condition [7].

9.6. Comparative Cost and Life Cycle Cost Analysis

Life-Cycle-Cost Analysis is a useful instrument to identify the main cost drivers of a power grid and to take up appropriate actions for cost reduction. For modern electrical devices efficient and reliable operation is of particular importance. They must execute their function reliably, preferably lifelong and must be as economical as possible over their complete lifetime. Concerning the assessment of single units like circuit breakers, transformers, overhead lines etc. the Life-Cycle-Cost (LCC) method has been used for quite a long time. As illustrated in Table 9.4, the concept of Life-Cycle-Cost means to take into account not only the manufacturing cost, but also to consider the operational costs.

Table 9.4: Summary of Investment Benefit/Cost Analysis for First year

Customer Interruption Cost (CIC)		
Before installation of automation devices.(Configuration 1)		R 2967336.00
After installation of automation devices.(Configuration 4)		R 1659123.89
CIC Difference (Configuration 1 - Configuration 4) (1)		**R 1308212.11**
Utility Cost (Investment Cost and Maintenance Cost)		
Investment Cost		
Fusesaver	3 x R 33800	R 101400
Tripsaver	3 x R 30000	R 90000
Fault Path Indicator (FPI)	3 x R 32300	R 96900
IntelliRupter Pulsecloser	1 x R 345600	R 345600
Maintenance Cost		
Maintenance		R 0
Total Investment and Maintenance Cost (2)		**R 633300**
Benefit in first year	**(1) – (2)**	**R 674912.11**

Since the whole investment is amortized in the first year and the automation devices are maintenance free it is not necessary to calculate the life cycle cost using the following formulas:

The total utility cost is defined as:

$$\boldsymbol{C_{Tot}^{utility} = C_I + C_M = \sum_{\tau=1}^{T} \frac{C_I(\tau)}{(1+r_{utility})^{\tau}} + \sum_{\tau=1}^{T} \frac{C_M(\tau)}{(1+r_{utility})^{\tau}}}$$

and the total reliability cost for the society is defined as:

$$\boldsymbol{C_{Tot}^{CIC} = CIC = \sum_{\tau=1}^{T} \frac{CIC(\tau)}{(1+r_{CIC})^{\tau}}}$$

where

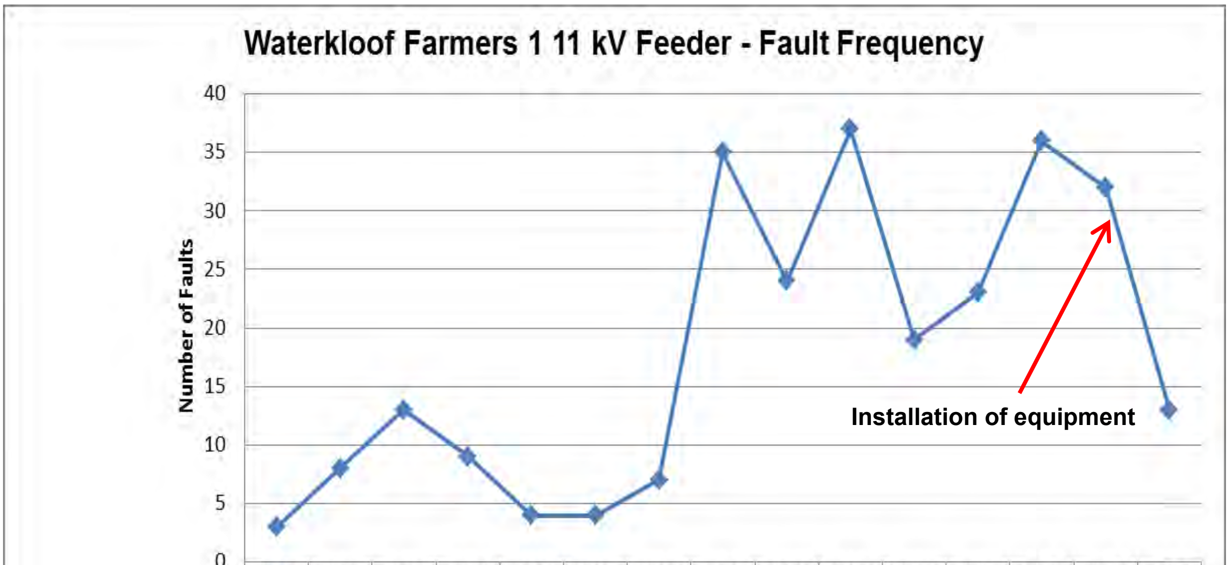
$\boldsymbol{C_I(\tau)}$ = Investment cost for year $\boldsymbol{\tau}$
$\boldsymbol{C_M(\tau)}$ = Maintenance cost for year $\boldsymbol{\tau}$
$\boldsymbol{CIC(\tau)}$ = Customer interruption cost for year $\boldsymbol{\tau}$
$\boldsymbol{T}$ = Calculation period
$\boldsymbol{r_{utility}}$ = Discount rate for the utility
$\boldsymbol{r_{CIC}}$ = Discount rate for the customer interruption cost

Chapter 10: Results and Field Data Analysis

10.1. Results of the Field Trial

At the time of writing, the equipment has been installed for six months. There have been a number of fault incidents and extensive feedback of events/data has been obtained from local operational staff.
In the area fitted with the innovative new technologies, a total of seven faults during the monitoring period to date were captured. All were temporary short circuits and all were cleared by the equipment before the first 5 second delayed reclose. No outage was experienced by the main feeder and the 5 seconds reclose period was the only outage experienced by the mainline and laterals. The circuit conditions seen by the equipment were verified by examining the downloaded recloser event recorder. In all of these cases, an outage would have arisen in the laterals if NEMA K type fuses were fitted. These were all good results. No cause of the fault was found. There have been no reported cases of the equipment operating incorrectly or dropping out of its carrier without reason.

Figure 10.1 indicates the permanent and momentary interruptions on the Waterkloof F1 11 kV Feeder in 2000 through 2014. As a point of information, a great deal of remediations work was performed on this feeder prior to implementing the DA pilot program, which helped reduce the number permanent interruptions.
Figure 10.1 below illustrates quite clearly that the number of faults for the feeder increased from 2007 to 2013 then significantly decreases after installation of the equipment. The average number of faults for the feeder declined from 32 number (2013) of faults to 13 number of faults after the new technologies were installed from June 2014 onwards, 59.4% reduction was achieved.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Number of Faults	3	8	13	9	4	4	7	35	24	37	19	23	36	32	13

Figure 10.1: **Fault frequency on Waterkloof Feeder fitted with the new technology. (unplanned faults)**

10.2. Recloser Tripping Operations

The field trial on Waterkloof Farmers 1 11 kV Feeder has been performed since June 2014. Starting from this, data collected for a period of 6 months afterwards. It is clearly shown in Table 10.1 below, that the number of breaker tripping of the feeder decreased significantly. A high number of recloser operation indicates that there were many temporary faults on the tested feeder.

Table 10.1: Performance of feeder equipment

				Number of tripping		
Feeder	**Equipment**	**Equipment Location**	**Event**	**Before**	**After**	**Results**
Waterkloof F1 11 kV	Substation Breaker	Substation	Permanent fault	17/yr.	1	Breaker tripped
	Intellirupter Pulsecloser	LBS4204	Temporary fault	-	4	IR cleared
	FuseSaver	SF451	no faults found	-	3	FuseSaver cleared
	Tripsaver	SF617	no faults found	-	0	no results

10.3. SAIDI Improvement

SAIDI constitutes the amount of time the average customer is without power over a one year period. The assumption is that a switching operation takes 60 minutes, while an automated recloser operation takes approximately 1 minute. Essentially anything that is placed on the line, whether it is a switch, sectionaliser or recloser will improve SAIDI.

Based on data taken for (thus far) 6 months period, a significant improvement on the SAIDI of the tested feeder was found. This innovative new technology was based on both strategies of switching action and reconfiguration of the distribution network. This will result in fast switching action to isolate a faulted section and restore the remaining healthy part of the feeder, hence reducing SAIDI score. However, comparison with the performance of the previous year indicates there was no demonstrable improvement. Instead, research should be directed at what occurred in May 2013 and appears to have radically improved performance as measured by SAIDI.

As expected, the addition of the protection devices increases the overall feeder reliability. The impact of these new technologies is shown in Figure 10.2, which illustrates the sharp drop in SAIDI after implementation of the devices in 2014. (See Appendix G for Root causes of the SAIDI differences related to Figure 10.2)

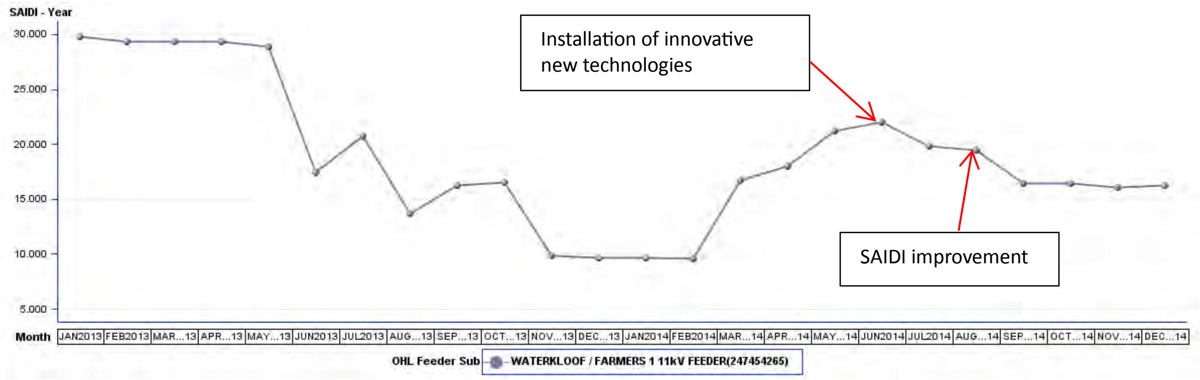


Figure 10.2: **SAIDI improvement on Waterkloof F1 Feeder fitted with the new technology**

The last six months shown in Figure 10.2 is with the automation devices fully activated. It predicts good results, but more time is required to better quantify the results. It appears that performance improved as these devices were deployed (the last six months shown in Figure 10.2).But it also looks like a great deal more improvement will be achieved through the different seasons, constant environmental changes and weather related patterns i.e. SAIDI will continue to drop over longer periods.

10.4. SAIFI Improvement

The only way to improve SAIFI is to decrease the number of sustained interruptions experienced by customers. The equipment installed on the pilot feeder eliminated the permanent outages by preventing faults from running through to the substation breaker and when the lateral fuse operates in response to a temporary fault. As a result, sustained interruptions were prevented while momentary interruptions were increased. (Refer to Figure 8.5 and Table 8.5)

10.5. MAIFI Improvement

Momentary interruptions (any interruption in service) are most effectively increased by using this equipment. The ability to interrupt faults closer to the location of the fault instead of interrupting the whole feeder provides one of the most dramatic improvements. If the feeder has sensitive loads near the substation (often the case on the typical feeder), it was advantageous to place these devices such as the Intellirupter Pulsecloser beyond that segment, vs. a switch or sectionaliser.

10.6. CAIDI Reduction

Despite the fact that the extent of sustained outages were reduced by automated feeder switching. This is due largely to the terms of the equation that is used to calculate CAIDI. For example, as the number of customers experiencing sustained outages is reduced, the denominator of the CAIDI index also goes down relative to the value of the numerator, and thus the overall index increases. Reducing CAIDI requires decreasing restoration times for those remaining without power after automated feeder switching operations have occurred. It is expected that enhanced fault detection, outage detection and notification capabilities will contribute to reductions in the duration of sustained outages for affected customers, and thus reduce CAIDI.

10.7. Operation of Equipment

10.7.1 Intellirupter Pulsecloser

Four momentary operations were detected for the IntelliRupter during the field trial. The IntelliRupter tripped upon sensing a 2700-ampere phase-to-phase fault. After a 0.3-second delay, the IntelliRupter then pulseclosed to verify that the line was clear of faults before initiating a closing operation. Fault current was indeed still detected on one phase so IntelliRupter did not close.

By contrast, a conventional recloser would have closed in this instance. The substation transformer, conductor splices, and other equipment would have been subjected to damaging fault current until the recloser decided to open again and upstream customers would have been subjected to another irritating voltage sag in the interim. The consequences would have been magnified if multiple reclosing attempts were necessary. After a 15-second delay IntelliRupter again pulseclosed, but no fault current was detected this time, so the IntelliRupter closed, restoring service to downstream customers. The source side voltage shown in the middle three waveforms was virtually unaffected by pulseclosing. Each operation of the overcurrent circuit testing sequence can be configured for either single-phase trip or three-phase trip. The last test operation specifies whether single-phase lockout is acceptable, or if a three-phase lockout is required.

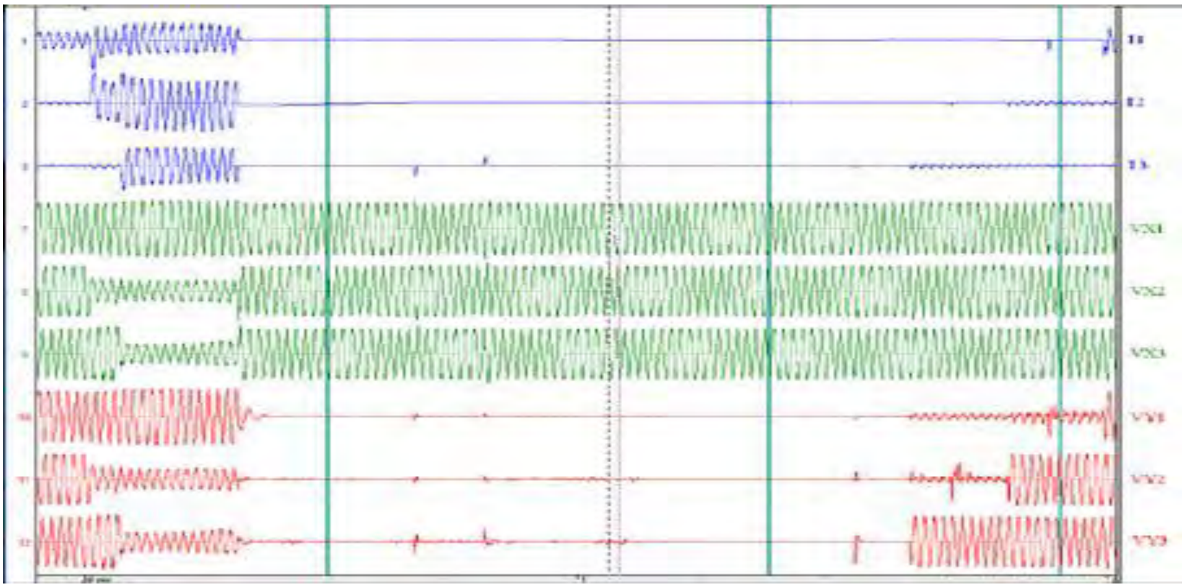


Figure 10.3: **Snapshot of the Intellirupter Pulsecloser operation sequence**

10.7.2 FuseSaver

Figure 10.4 shows that the FuseSaver operated thrice during the trial period. i.e. it operated once for the white phase and twice for the blue phase. All faults captured were momentary operations.

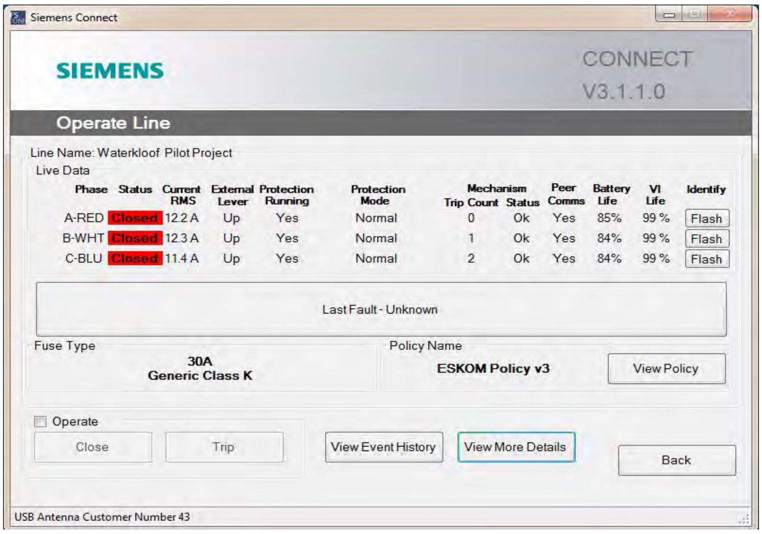


Figure 10.4: **Snapshot of the FuseSaver operation sequence**

Last Fault Data

The Last Fault Data on the Operate Line page shows the most relevant information for a line crew attempting to repair a faulted line. The last fault display was taken from the event record of the FuseSaver and shows the data for the most recent line fault which caused the FuseSaver protection to pick-up.

The event log below shows that there were no detected sustained interruptions events. This means there have been no permanent faults downstream of the FuseSaver for it to act upon unless they were SEF faults. This means the outages are either due to inadequate line current or upstream breaker operations on faults that are upstream of the FuseSaver. The “power off” / “power on” events indicates that the upstream protection device (Intellirupter Pulsecloser) was set too sensitive and operated before the FuseSaver could operate. (See Appendix M for further details on the Last Fault Data for the FuseSaver)

Table 10.2: Event record of the FuseSaver

Phase	Date and Time	Name	Duration
A-RED	2014/12/19 02:47:03 PM	Outage	0.418992
A-RED	2014/12/19 02:47:03 PM	Line Current On	
A-RED	2014/12/19 02:47:03 PM	Line Current Off	
C-BLU	2014/12/19 02:47:02 PM	Outage	0.418991
C-BLU	2014/12/19 02:47:02 PM	Line Current On	
C-BLU	2014/12/19 02:47:02 PM	Line Current Off	
B-WHT	2014/12/19 02:47:02 PM	Outage	0.418991
B-WHT	2014/12/19 02:47:02 PM	Line Current On	
B-WHT	2014/12/19 02:47:02 PM	Line Current Off	

10.7.3 Tripsaver

No operations for the Tripsaver was detected, this was due to the sensitive protection settings of the upstream Intellirupter Pulsecloser.

The most recent operational information of the Tripsaver is shown in the figures below.

Load Current: The instantaneous fundamental-frequency RMS load current in amperes is shown.

		
Red Phase	**White Phase**	**Blue Phase**

Figure 10.5: **Load Current screen**

Last Fault Magnitude: The fundamental-frequency RMS magnitude of the last fault current in primary amperes, measured just prior to the opening of the vacuum interrupter is shown. No interruptions were detected.

		
Red Phase	**White Phase**	**Blue Phase**

Figure 10.6: **Last Fault Magnitude screen**

Number of Open Operations: The number of vacuum interrupter open operations registered is shown. This was due to the testing of the Tripsavers and the sensitive protection settings of the upstream Intellirupter Pulsecloser.

		
Red Phase	**White Phase**	**Blue Phase**

Figure 10.7: **Number of Open Operations screen**

Chapter 11: Conclusion

This chapter concludes the dissertation with a summary of the work presented and highlights the significance of the research towards the field.

11.1. Conclusions of Research

The basic function of a power system is to supply customers with electrical energy as cost effectively as possible and with an acceptable degree of quality of service particularly in terms of reliability of electricity supplied to customers. Electricity service should be provided at increased levels of availability and reliability as more energy is demanded.

Poor reliability planning and faulty protection systems also contribute to the increased frequency, duration and the severity of the interruption. There are different methods that are used for reliability planning and evaluation of distribution system. The methods include Historical data analysis and Predictive reliability analysis. Reliable electricity is essential to the industrial or / and commercial businesses, as well as a necessity for the productivity, safety and comfort of residential customers. As a result, electrical utilities are striving to maintain a safe and reliable power delivery to all their customers.

There are two main types of benefits from installing new technology devices and systems to address distribution reliability challenges: reliability improvements and operational savings. New technologies can be installed to improve overhead network performance, reduce operating cost and enable smart grid capability in the near future. The challenge facing today’s network operators is how to improve network reliability and reduce operating costs on great lengths of lines that generate little income. The further challenge is how utilities will transform these same traditional assets into an intelligent, integrated, self-healing network, suitable for tomorrow.

A well-coordinated distribution automation system could be introduced for switching operation and the outage time could be reduced. The cost of implementation of these new technologies could be recovered within few months by reducing the energies not served when operating to clear faults.

The future of Distribution Automation systems lies in the outcome of the balance between benefits and cost and it is only when the outcome is positive that it can be said that the network performance has been enhanced. In the future, this enhancement may not purely be the restoration of supply but may also be the improvement of the quality of supply, which is becoming more critical to today’s user. In the case of the distribution automation trial at Waterkloof Farmers 1 11 kV Feeder the benefits are easily recognisable with quick and simple supply restoration and fault identification.

11.2. Improved Reliability

The continuity of electricity supply to customers is one of the performance measures of a utility company. Unfortunately, power interruption often experienced by customers caused by faults that mostly occur in medium voltage distribution lines [23]. The medium voltage overhead lines are usually many kilometres in length which covers wide and spread areas. They are susceptible to faults due to lightning, pollution, animal, equipment failures, trees touching, traffic accident, and people activity.

In order to achieve a better distribution system reliability indices in fault management, there are some strategies, such as [24]:

1. Reduce the number of faults
2. Reduce time of interruption
3. Reduce the number of affected customers

Reduce time of interruption may be done by switching actions to isolate the faulty section, and restore the supply for remaining healthy parts. Reduce number of affected customers may be done by reconfiguring the networks. The distribution automation equipment implemented on the pilot feeder fulfilled the two strategies above.

The operation of the DA reclosing allowed temporary faults to clear themselves. For typical overhead distribution systems, 60% to 80% of faults will be temporary in nature. If a DA recloser interrupts a temporary fault and then recloses, the problem will often be solved automatically. This is desirable since the utility does not have to dispatch crews, and no repairs are necessary. With reclosing, fewer sustained interruptions are intentionally traded-off for more momentary interruptions. In this case, the momentary interruption is a deliberate and good thing.

From the operations of the DA equipment, it can also be concluded that the most common way for utilities to prioritise distribution reliability performance and spending decisions are based on SAIDI improvement. Reducing outage duration, as measured by SAIDI, is generally related to the implementation of distribution automation and more efficiently operating and restoration practices. Isolating, reclosing, or fault location, isolation, and service restoration actions can reduce outage duration for customers on sections of feeders that are isolated from damages.
The author has found that SAIDI generally does a good job in driving investment decisions for a utility. The only potential problem is that SAIDI will sometimes encourage spending in areas that already have adequate reliability.

The pilot project has been judged to be successful based on the reliability performance improvement measured and with costs at or below expectation. The author will continue to monitor the performance of the pilot systems to better quantify the benefit versus cost ratios over a longer operating period.

11.3. Fuse Saving Technology - Protecting Lateral Lines from Transient Faults

The sustained outage caused by fuse operations is unnecessary as the fault is transient, a momentary outage should be sufficient to clear the fault. Fuse operation on permanent faults has its advantages, but the fuse needs to be protected from transient faults [19].
The FuseSaver used in the pilot project is a half-cycle interrupting circuit breaker, making fuse-saving strategies a reality. Its half-cycle functionality means it can open and clear a fault in as little time as it takes the fuse to melt, thereby avoiding a fuse operating unnecessarily. It then closes after a configurable dead time. Customers on the lateral line are unaffected and the utility avoids regulatory performance penalties and arranging a line crew. If the fault is permanent, the device simply allows the fuse to operate, thereby isolating the faulted line. The half-cycle functionality will improve network performance and reduce ongoing costs immediately, saving the fuses from unnecessary operation [19].

11.4. PulseClosing Technology

Conclusions and benefits resulting from the pulse closing technologies are listed below:

PulseClosing tests overhead distribution circuits for the presence or absence of faults:

- eliminates voltage sags from reclosing into faults
- reduces stress on power system equipment

11.4.1 Benefits of Pulse Closing

Benefits to the Public

The benefits of pulse closing technology to the general public are:

- Improved power distribution system reliability, reducing consumer inconveniences and costs associated with power outages.
- Improved power quality and reduced disturbances during outage recovery processes, due to use of pulsing to test before reclosing rather than reclosing directly into circuits which may still be faulted.
- Reduced risk of igniting fires caused by arc energy released during fault events.
- Lower consumer electricity costs due to the extension of distribution equipment life that will be possible with pulse closing.

Benefits to Electric Distribution Utilities

The benefits of the pulse closing technology assessment to electric distribution utilities are:

- Understanding of applications and limits of a new technology, pulse closing.
- Identification of impacts of a new distribution protection technology (pulse closing) on distribution automation systems.
- Understanding the technical and economic impacts of reclosing into existing faults on line and substation equipment life.
- Acceleration of the efforts of utilities to advance automation of distribution systems.

11.5. Equipment Fault Events

A detailed study of the events described, including the IntelliRupter Pulsecloser, Tripsaver and FuseSaver event recorder downloads enables a number of clear conclusions to be drawn.

- It is in the best interest of the utility to analyse feeders which have the most critical loads and have the worst reliability.
- The equipment can be expected to operate in the field in the way intended i.e. adhering to pre-set characteristics and no nuisance dropouts.
- The physical handling, installation and operational aspects of the equipment fit into normal practices in the field, with minimal adjustment of work methods and procedures necessary.

- The current ratings of the Distribution Automation devices supplied to Eskom should be lower in order to achieve greater effectiveness and co-ordination with the back-up recloser. It is expected that with a device more tailored to the specific Eskom's environment, greater benefits might have been realised.
- The field trial has been satisfactory so far and a good understanding has been reached of its application in Eskom networks. Although considerable data has been collected and analysed at the time of writing, a fuller assessment should be available by the end of 2015.

11.6. Utility Costs and Customers Interruptions

Improving of the MV network goes hand in hand with improving the reliability of the network. Distribution system reliability should be based on balancing the costs to a utility as well as the value of benefits received by the supplied customers. The value-based distribution system reliability planning approach used for the tested feeder was to locate the best solution at minimum total cost, where the total cost includes the sum of the utility cost and the customer interruption costs [35], [36].

11.7. Operational Savings

Utilities frequently operate switches to support load balancing, faults and to de-energise feeder segments for maintenance. Before automation, many of these activities required crews to travel to multiple sites and perform switching operations manually before maintenance operations began. When the maintenance work was completed, manual switching was again required to put feeders back into their original service configurations. Automated feeder switching can produce operational savings by eliminating manual switching and improving the productivity of field crews.

11.8. Final Comments

Distribution system reliability is a measure of total electricity interruptions. Electricity is essential to all customers. It is impossible to deliver uninterrupted electricity to all customers over a long period of time. This is because there are factors that are capable of interrupting the power at any time which are outside the engineers' control. These factors include adverse weather, animals and human interference to mention a few. Utilities are faced with the challenges of evaluating and planning for reliable distribution systems in order to supply the best service to all customers.

This reliability project has been initiated to improve the quality of supply customers experience in the area. Although not a very representative place for the new technologies were chosen, the new technologies implemented were added to the network to reduce the impact of faults on the customers. Apart from this they worked perfectly fine and greatly enhance fault finding techniques and thereby improving planned and unplanned restoration times.

Chapter 12: Recommendations for Future Research

The challenge of how to improve network reliability and reduce operating costs is solvable today. The challenge of how to transform traditional assets into an intelligent, integrated, reliable network suitable for tomorrow is not a problem of the magnitude it was estimated to be. Innovative new technologies can be installed on existing infrastructure to improve communication and performance, reduce cost and enable smart grid capability in the near future.

12.1. MV Overhead Feeder Loop Automation

In an effort to improve the reliability of supply, utilities are rethinking the levels of sophistication deployed in their medium voltage (MV) overhead feeders. An auto-reclose cycle should clear a transient fault without interrupting supply to the customer. In most cases, no further operator assistance would be required to clear the fault. Some faults are however more permanent.
Examples include distribution equipment, such as transformer failures and fallen power lines due to motor accidents or storms. Protection equipment is designed to minimise damage by interrupting the supply to a segment containing a fault. The supply will remain off until the fault is removed and the protection equipment is turned back on. Today's reclosers are capable of sophisticated protection, communication, automation and analytical functionality. It is possible to operate in either a 'manual' mode where the operator has to perform the reconfiguration of the network or in a 'loop automation' mode where the reclosers perform the task automatically.

Loop automation uses time, voltage, power flow, and these simple rules to isolate the fault and reconfigure the network, without any communications or operator assistance. In a loop automation network, the following actions will take place when a fault occurs:

- The recloser immediately upstream of the fault automatically trips, recloses to a lockout, and remains open.
- Reclosers downstream of the fault automatically change the protection settings in anticipation of power flowing in the opposite direction.
- The normally open tie-recloser closes automatically.

Due to the fault still being present, the recloser immediately downstream of the fault trips, and locks out without reclosing. This will automatically restore power to the healthy parts of the network. An operator can now despatch line crews to the faulted segment.

12.2. Future Development

12.2.1 The IntelliTeam Automatic Restoration System and IntelliNodes Interfact Modules

A pilot scheme for a Distribution Automation project targeting specifically self-healing (FLISR) of Eskom's Distribution Grid should be implemented in the near future. A system consisting of IntelliTeam Automatic Restoration System using IntelliNodes Interfact Modules to incorporate the existing reclosers into the IntelliTEAM.
The objectives in proposing this solution were to provide an extremely cost-effective solution that meets the network improvement performance. The IntelliTeam Automatic Restoration System automatically reconfigures the distribution system after a fault and quickly restores service to segments of the feeder which aren't affected by the fault. Although fully compatible

with SCADA, no SCADA control or central monitoring is required. Decisions are made locally, based on real-time loading data. The IntelliTeam supports complex systems of virtually any size and accommodates tie points from multiple sources. It can handle as many teams of switches as line loading will allow [13].

Radio Survey

Desktop radio survey which will include worst and best case scenarios to identify potential communication problems and the possible need for repeaters and to ensure at least two paths to each substation is achieved. The field survey consisting of the vendor (S&C) and Radius using radios and repeaters on site [13].

Installation of the IntelliNodes to the Existing Reclosers

Physical installation of the IntelliNodes in the existing reclosers' control panels, as well as electrical and communication connections, should be implemented in the near future [13].

12.3. Inspection and Maintenance Program for Utilities

Each utility should design and maintain a program to limit the frequency and duration of electric service interruptions. The program should include inspection, maintenance, repair and replacement standards that ensure service restoration as well as preventive and emergency maintenance; and should give special emphasis to the improvement of the worst performing feeders. The program should include at a minimum:

1) The age, distribution and location of equipment on each circuit.
2) The number, density and location of customers on each circuit.
3) The location and density of trees on the system.
4) An annual vegetation management plan.
5) The impacts on distribution system reliability of animals, wind, storms, ice and auto accidents.

The value of these standards in assessing an electric utility's performance can help point to specific areas where more attention by the utility is necessary to improve reliability. Causes of outages can be identified on a systemic basis and improvement plans can be developed. For example, the extent that a company routinely inspects utility poles to determine those most susceptible to deterioration and collapse, a cause for interruptions, may be established from evaluating reliability indices. A common finding, for example, is that a lack of vegetation management (commonly referred to as "tree trimming") is responsible for outages along specific circuits. There may be a number of reasons why plant life has grown too close to power lines, but the fix is often relatively simple.

Other reasons for interruptions may be more difficult to detect, such as animals on poles or along wires, resulting in shorts and the subsequent interruptions. Whatever the reason for an interruption or series of interruptions, these calculations can assist the utility to determine primary causes of outages and develop a plan to restore the reliable flow of electricity to customers.

12.4. System Improvement

System redesign is required where by the transformers should be protected and network stabiliser (NER) should be installed in all transformers where applicable. Installation of extra reclosers is required in order to achieve sufficient sectionalising points that are remotely controllable. Tie link should also be added to the network to enable interconnection with closer network and in so doing enhancing the reliability of the network. Fault path indicators can also serve as an advantage as this will add value in terms of fault finding.

12.5. Optimal Placement of Protective Devices

A popular reliability improvement strategy involves the addition of protective devices, particularly the addition of reclosers. With proper analytical tools, engineers can obtain reliability indices that would give them an idea of the locations at which an improvement is needed. However, engineers are often bounded by limited capital spending. It then becomes important to make sure the investment yields the most beneficial return. Placing the reclosers at optimal locations is considered a challenging and yet a vital decision in distribution planning. Methods and tools such as the CYME Power Engineering Software and Solutions (Optimal Recloser Placement) and Genetic Algorithm (GA) can be used for optimal placement of protective devices. CYME identifies optimal protective device locations to improve the network conditions based on selected objectives and criteria, studies the reliability indices, evaluates the expected improvement and finds the best solution.

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APPENDICES

Appendix A: Standard Fuse Ratings and Fuse Coordination

1	2	3	4
Rating	**Type**	**Color code**	**Comments**
7	D	Grey	SWER applications only
6	K	White	For fault finding purposes only
10	K	Yellow	-
15	K	Green	-
20	K	Black	-
30	K	Orange	-
50	K	Red	For application on 11 kV networks only

Table 1 – **Standard Fuse Ratings [6]**

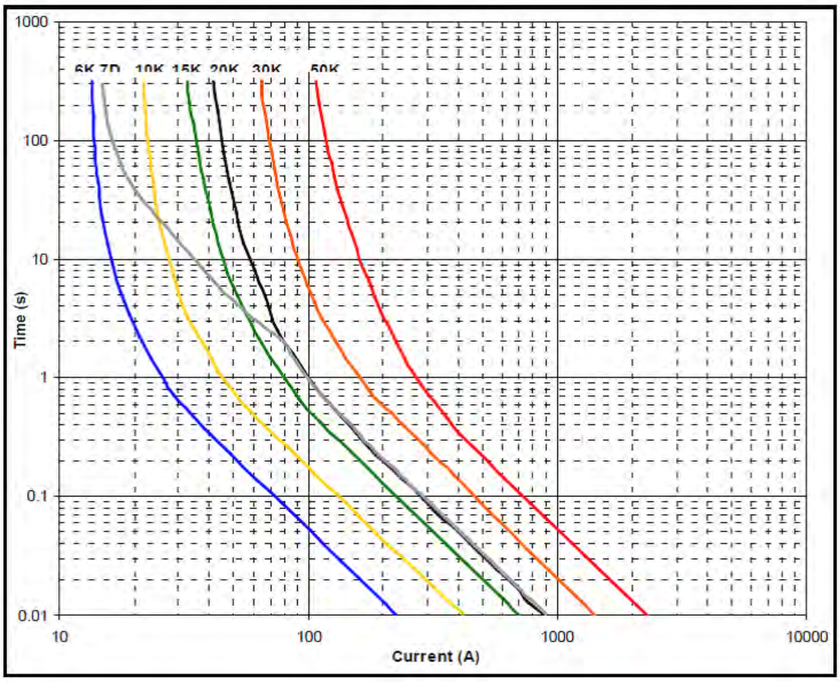
Table 2 illustrates the point at which the SE/F definite time characteristic meets the total clearing curve of a specific fuse given the standard ratings. The currents depicted in table 2 are the lowest current values at which the fuse will operate before the upstream SE/F protection, for the SE/F time setting indicated in column 1. Proper grading will only be achieved at currents above these values. [6]

1	2	3	4	5	6	7
SE/F Time	**Fuse Rating (all values are approximate)**					
	7 D	**10 K**	**15K**	**20 K**	**30 K**	**50 K**
10 s	40 A	30 A	55 A	65 A	110 A	180 A
7 s	47 A	33 A	60 A	70 A	120 A	190 A
5 s	55 A	36 A	63 A	75 A	150 A	210 A
3 s	70 A	40 A	70 A	80 A	170 A	230 A

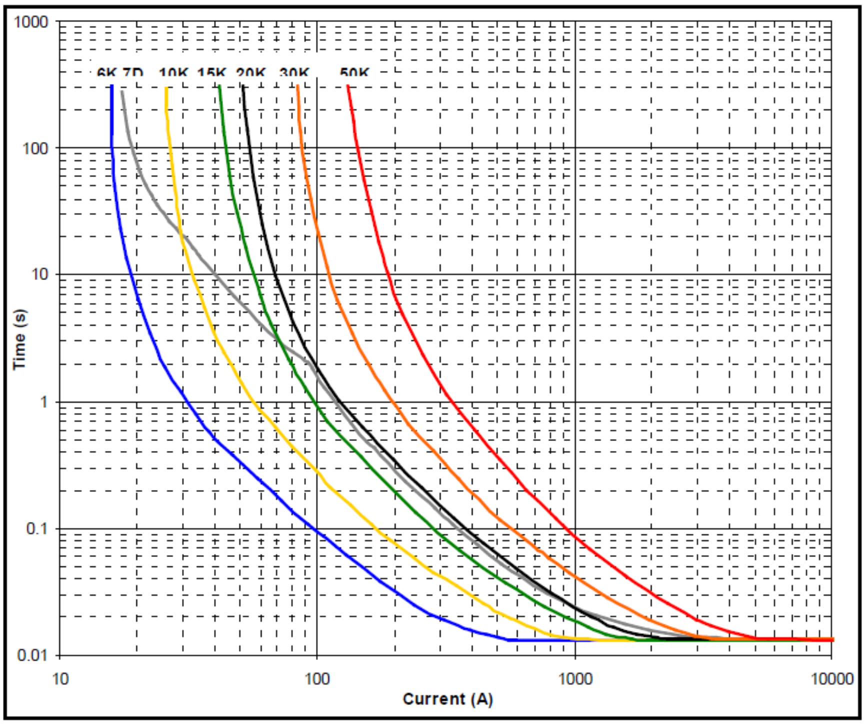
Table 2 - **Sensitive Earth Faults – Fuse Coordination [6]**

Appendix B: Time Current Characteristics (TCC): Minimum Melting Time and Total Clearing Time

Time Current Characteristics (TCC) for K and D type fuses - Minimum melting time [6]



Time Current Characteristics (TCC) for K and D type fuses - Total clearing time [6]



Appendix C: Telecommunication Site Survey – Signal Strength and GPS Coordinates

The communication path profiles (line of site) of the equipment installed on the Waterkloof F1 11 kV Feeder.

Estimated GPS co-ordinates:

1. LBS4204 (18° 52' 38.9" ; -34° 6' 23.1")
2. SF451 (18° 53' 16.3" ; -34° 6' 47.6")
3. TS617 / SF617 (18° 54' 16.6"; -34° 6' 57.7")

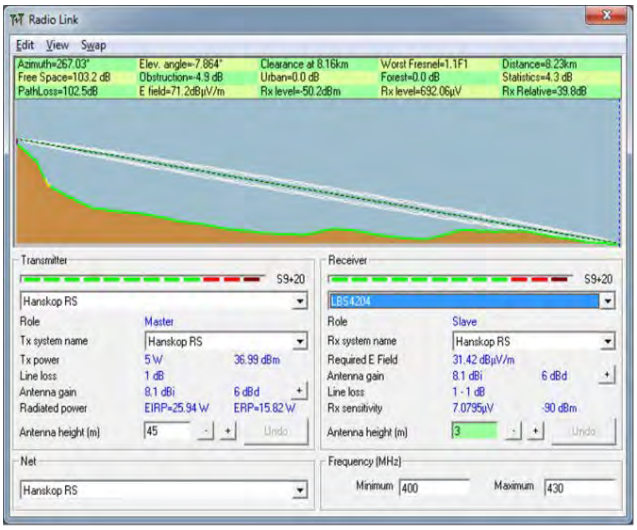


Figure 1: **Load Break Switch - LBS4204**

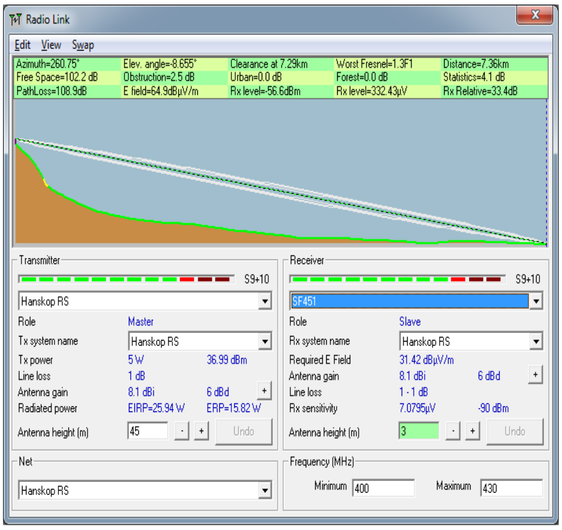


Figure 2: **Section Fuse - SF451**

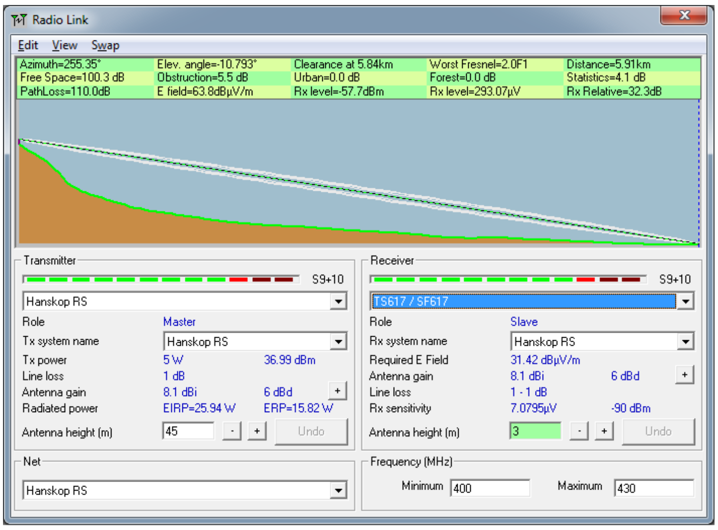
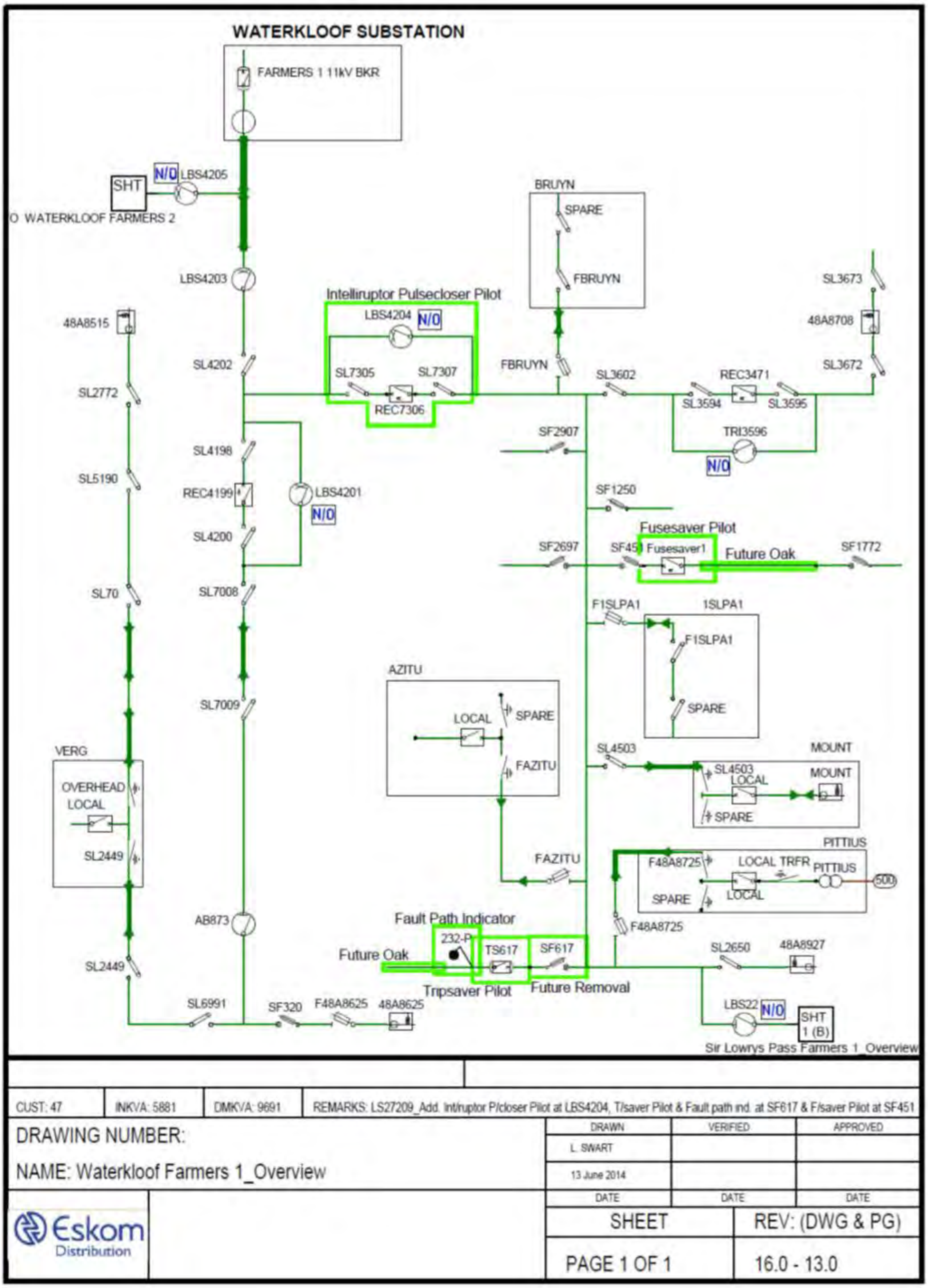
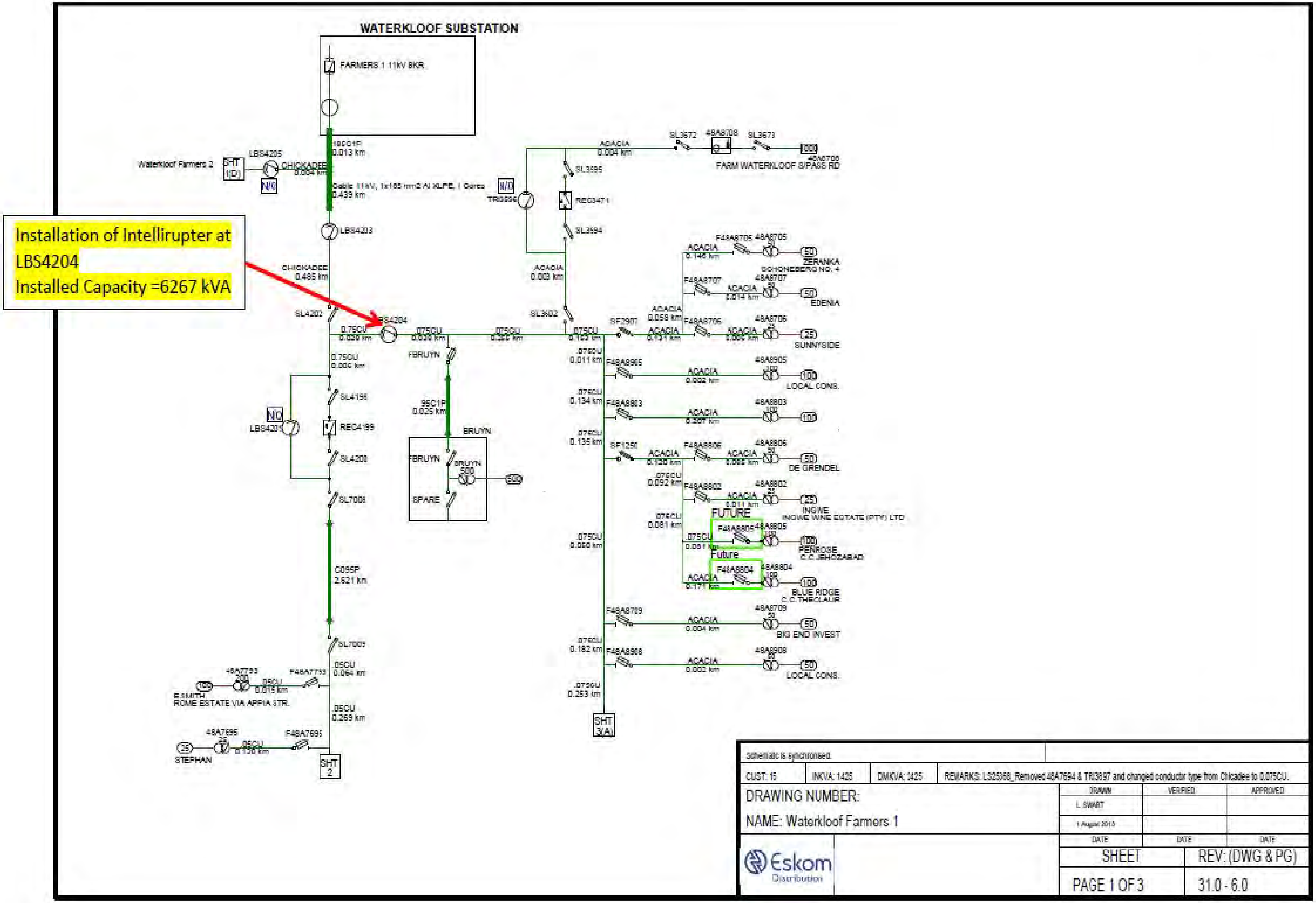


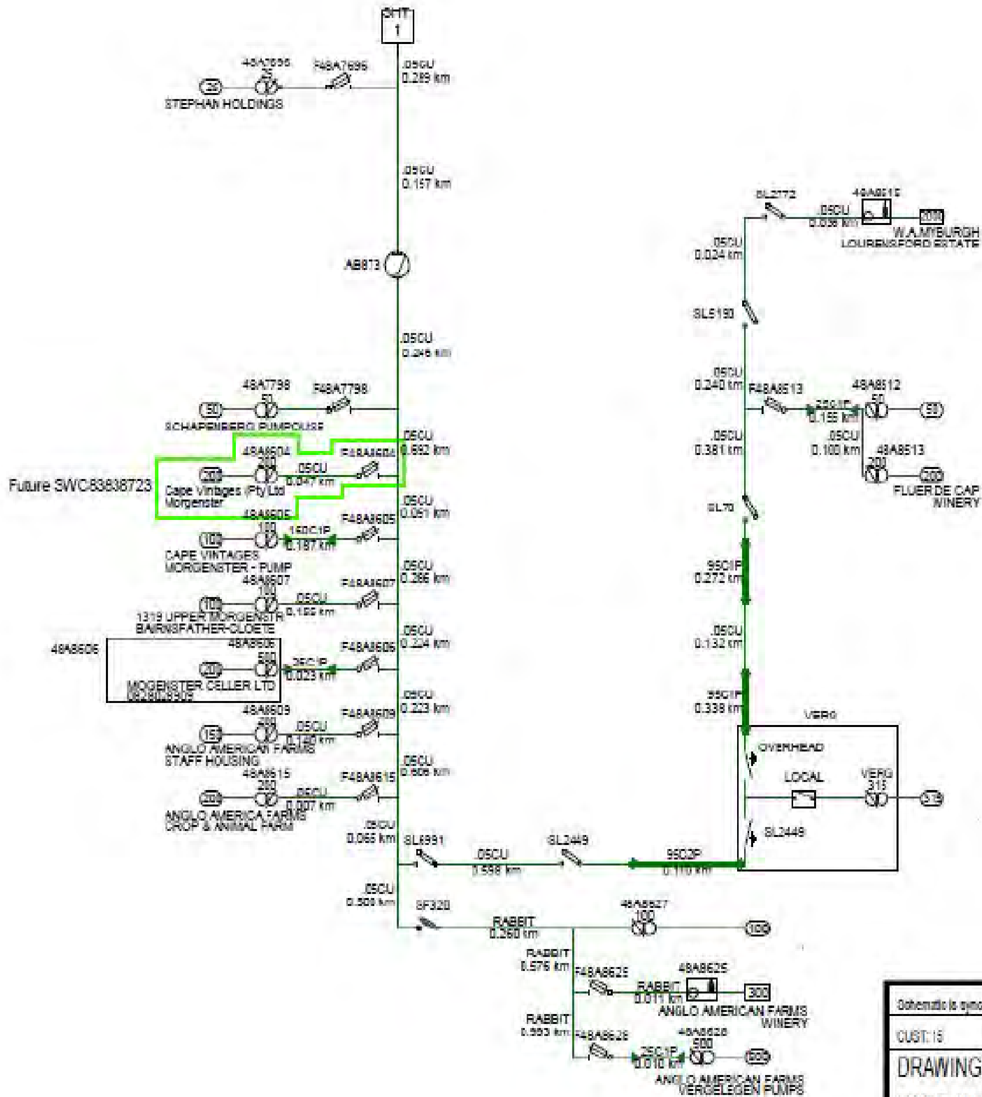
Figure 3: **Section Fuse - SF617**

Appendix D: Single Line Diagram for Waterkloof Farmers 1 11 kV Feeder





Installation of Intellirupter at LBS4204
Installed Capacity =6267 kVA
WATERKLOOF SUBSTATION
FARMERS 1 11KV BKR
Waterkloof Farmers 2
LBS4205
CHICKADEE
N/O
LBS4203
TRI3696
REC3471
SL3695
SL3694
SL3672
SL3673
FARM WATERKLOOF S/PASS RD
ZERANKA
EDENIA
SUNNYSIDE
LOCAL CONS.
DE GRENDEL
FUTURE
Future
PENROSE
BLUE RIDGE
BIG END INVEST
LOCAL CONS.
BRUYN
FBRUYN
SPARE
REC4199
SL4196
SL4200
SL7008
SL7009
STEPHAN
ROME ESTATE VIA APPIA STR.
SHT 2
SHT 3(A)
Schematic is synchronised.
CUST: 15
INKVA: 1425
DMKVA: 1425
REMARKS: LS25368_Removed 48A7694 & TRI3897 and changed conductor type from Chickadee to 0.075CU.
DRAWING NUMBER:
NAME: Waterkloof Farmers 1
DRAWN
VERIFIED
APPROVED
L. SWART
1 August 2013
DATE
Eskom
Distribution
SHEET
REV: (DWG & PG)
PAGE 1 OF 3
31.0 - 6.0



Schematic is synchronised.			
CUST: 15	INKVA: 2540	DMKVA: 4540	REMARKS: LS25368_Added SL6991 and deleted SLP3REG, AB2093, AB2094 & AB2095

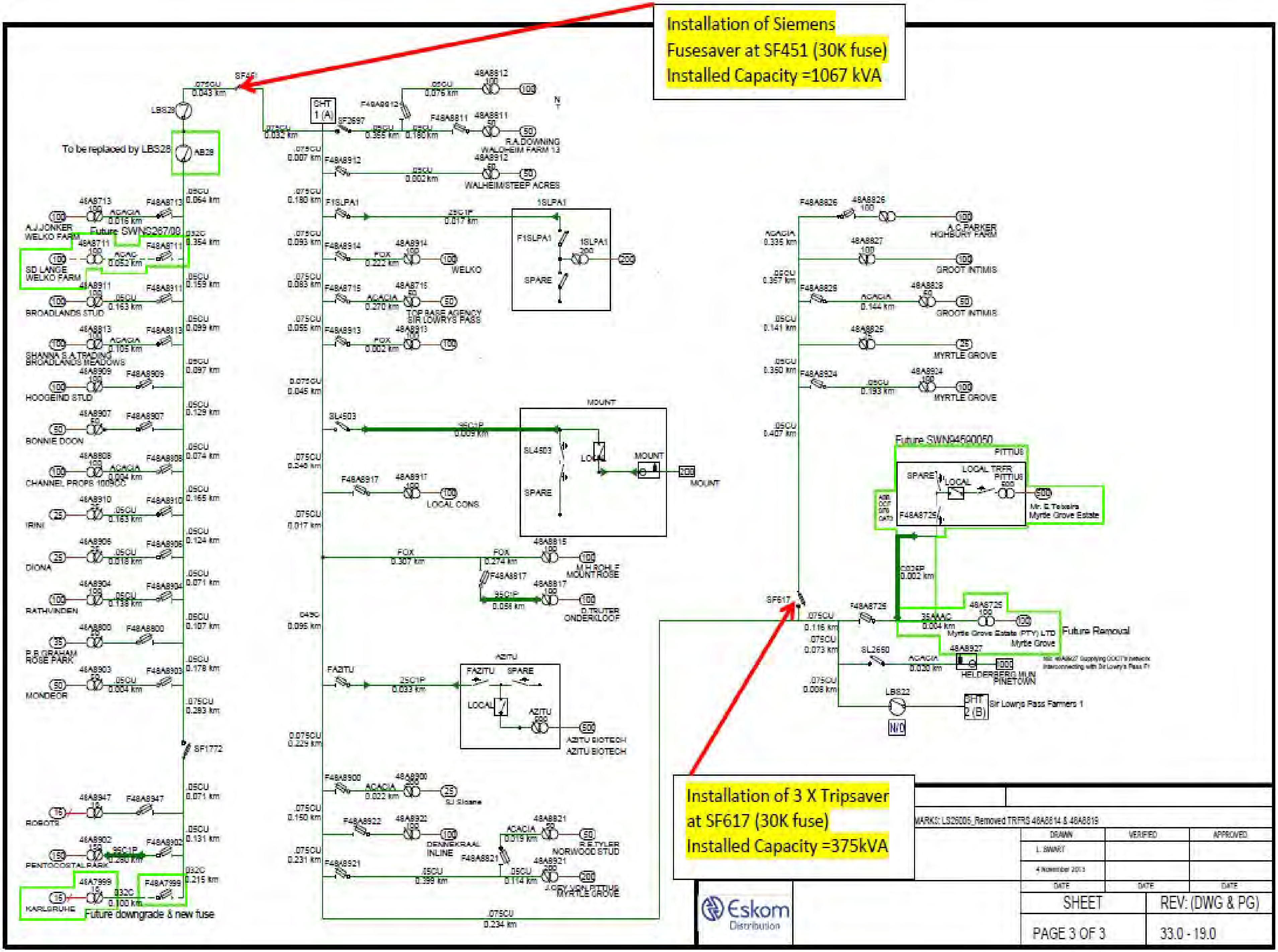
DRAWING NUMBER:

NAME: Waterkloof Farmers 1

DRAWN	VERIFIED	APPROVED
DATE	DATE	DATE

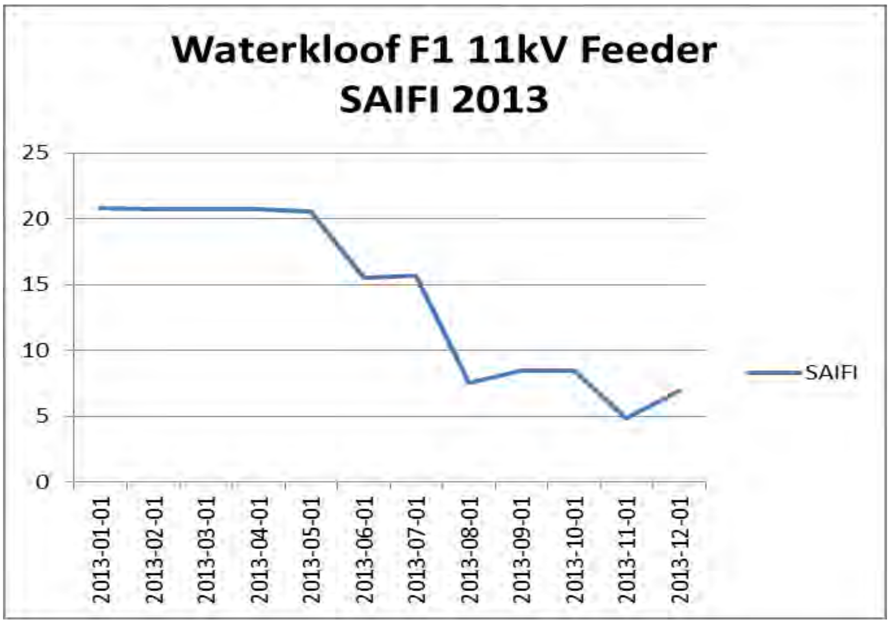
Eskom Distribution

SHEET	REV: (DWG & PG)
PAGE 2 OF 3	30.0 - 4.0


Installation of Siemens
Fusesaver at SF451 (30K fuse)
Installed Capacity =1067 kVA
Installation of 3 X Tripsaver
at SF617 (30K fuse)
Installed Capacity =375kVA
To be replaced by LBS28
Future SWNS267/08
Future SWN94590050
Future Removal
Future downgrade & new fuse
MOUNT
AZITU
PITTIUS
Sir Lowrys Pass Farmers 1
DRAWN
VERIFIED
APPROVED
DATE
Eskom
Distribution
SHEET
REV: (DWG & PG)
PAGE 3 OF 3
33.0 - 19.0

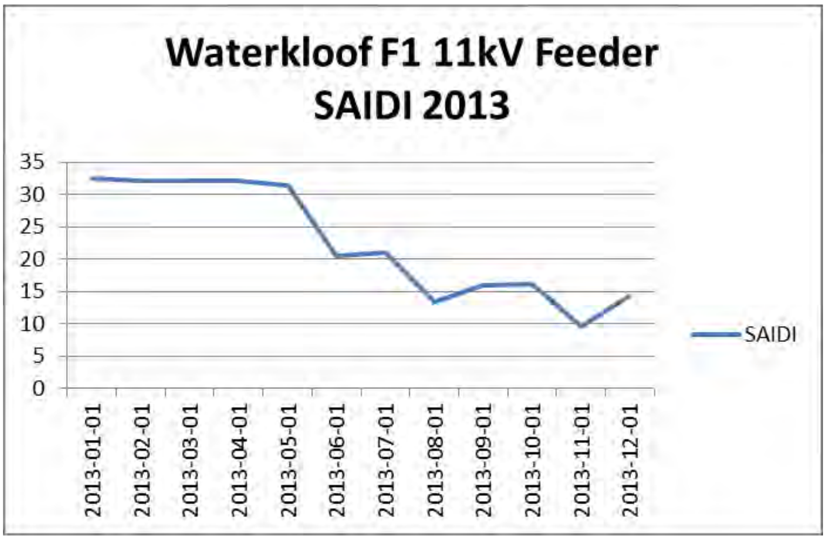
Appendix E: Waterkloof Farmers 1 11 kV - Unplanned SAIFI (2009-2013)

Period	WATERKLOOF / FARMERS 1 11kV FEEDER
01-Dec-09	17,68
01-Jan-10	17,68
01-Feb-10	17,48
01-Mar-10	16,66
01-Apr-10	16,88
01-May-10	17,06
01-Jun-10	16,98
01-Jul-10	16,98
01-Aug-10	16,94
01-Sep-10	13,21
01-Oct-10	11,8
01-Nov-10	4,1
01-Dec-10	4,07
01-Jan-11	4,38
01-Feb-11	4,53
01-Mar-11	4,34
01-Apr-11	4,14
01-May-11	6,16
01-Jun-11	6,16
01-Jul-11	6,22
01-Aug-11	6
01-Sep-11	7,74
01-Oct-11	9,56
01-Nov-11	8,53
01-Dec-11	8,54
01-Jan-12	9,3
01-Feb-12	9,23
01-Mar-12	9,23
01-Apr-12	9,21
01-May-12	7,23
01-Jun-12	12,39
01-Jul-12	14,34
01-Aug-12	22,32
01-Sep-12	21,59
01-Oct-12	19,85
01-Nov-12	23,72
01-Dec-12	21,84
01-Jan-13	20,8
01-Feb-13	20,73
01-Mar-13	20,73
01-Apr-13	20,73
01-May-13	20,58
01-Jun-13	15,52
01-Jul-13	15,68
01-Aug-13	7,57
01-Sep-13	8,53
01-Oct-13	8,57
01-Nov-13	4,92
01-Dec-13	6.95



Appendix F: Waterkloof Farmers 1 11 kV - Unplanned SAIDI (2009-2013)

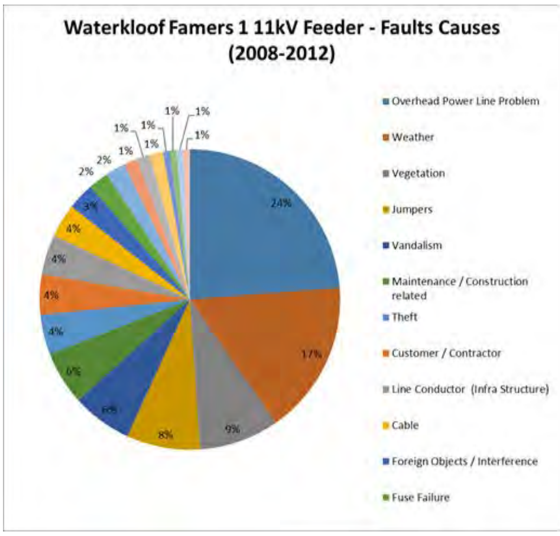
Period	WATERKLOOF / FARMERS 1 11kV FEEDER
01-Dec-09	29,94
01-Jan-10	29,94
01-Feb-10	29,73
01-Mar-10	30,09
01-Apr-10	30,3
01-May-10	32,45
01-Jun-10	32,28
01-Jul-10	32,27
01-Aug-10	31,33
01-Sep-10	24,6
01-Oct-10	9,1
01-Nov-10	5,94
01-Dec-10	5,52
01-Jan-11	5,9
01-Feb-11	7,65
01-Mar-11	7,21
01-Apr-11	7,05
01-May-11	10,89
01-Jun-11	10,89
01-Jul-11	11,04
01-Aug-11	13,61
01-Sep-11	14,86
01-Oct-11	16,63
01-Nov-11	14,9
01-Dec-11	16,15
01-Jan-12	16,99
01-Feb-12	15,7
01-Mar-12	15,7
01-Apr-12	15,65
01-May-12	10,5
01-Jun-12	21,89
01-Jul-12	24,73
01-Aug-12	29,96
01-Sep-12	30,16
01-Oct-12	28,55
01-Nov-12	35,31
01-Dec-12	33,77
01-Jan-13	32,61
01-Feb-13	32,19
01-Mar-13	32,19
01-Apr-13	32,19
01-May-13	31,48
01-Jun-13	20,55
01-Jul-13	21,03
01-Aug-13	13,43
01-Sep-13	16,1
01-Oct-13	16,33
01-Nov-13	9,92
01-Dec-13	14.42

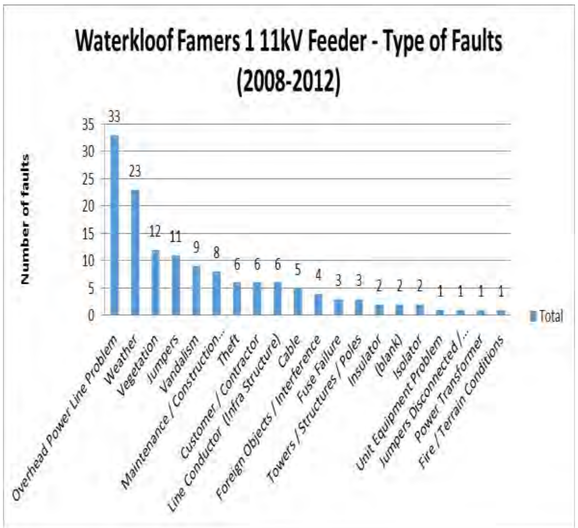


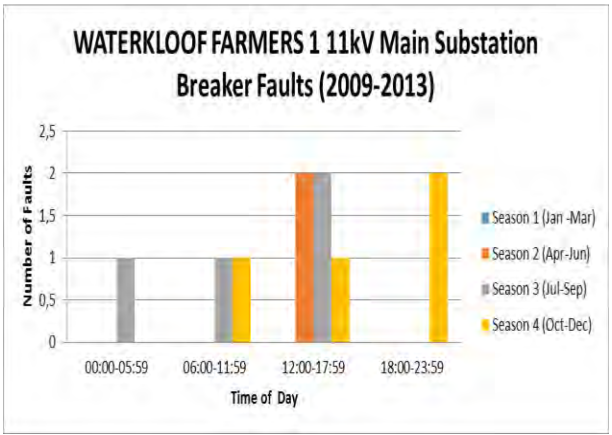
SAIDI 2014

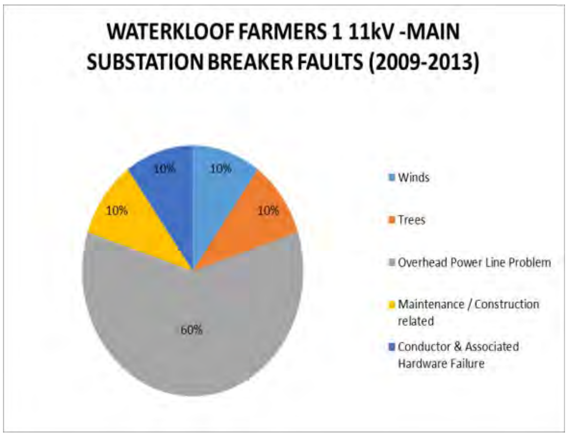
Unplanned Values		SAIDI - Actual	SAIDI - Year	SAIFI - Actual	SAIFI - Year
OHL Feeder Sub	Month				
WATERKLOOF / FARMERS 1 11kV FEEDER(247454265)	NOV2010	2.003	2.003	2.238	2.238
	DEC2010	0.538	2.541	2.274	4.512
	JAN2011	0.419	2.960	0.333	4.845
	FEB2011	1.981	4.941	0.167	5.012
	MAR2011		4.941		5.012
	APR2011	0.017	4.958	0.012	5.024
	MAY2011	6.387	11.345	2.345	7.369
	JUN2011		11.345		7.369
	JUL2011	4.925	16.270	1.167	8.536
	AUG2011	3.327	19.597	0.214	8.750
	SEP2011	1.404	21.001	1.917	10.667
	OCT2011	1.940	22.941	1.988	12.655
	NOV2011		20.938		10.417
	DEC2011	1.849	22.249	2.190	10.333
	JAN2012	1.304	23.134	1.143	11.143
	FEB2012	0.496	21.649	0.083	11.060
	MAR2012		21.649		11.060
	APR2012		21.632		11.048
	MAY2012	0.882	16.128	0.226	8.929
	JUN2012	11.931	28.059	5.405	14.333
	JUL2012	0.141	23.275	0.024	13.190
	AUG2012	7.744	27.691	8.548	21.524
	SEP2012	1.555	27.843	1.071	20.679
	OCT2012	0.162	26.065	0.083	18.774
	NOV2012	6.998	33.063	4.012	22.786
	DEC2012	0.197	31.412	0.167	20.762
	JAN2013	0.066	30.174	0.036	19.655
	FEB2013	0.041	29.718	0.012	19.583
	MAR2013		29.718		19.583
	APR2013		29.718		19.583
	MAY2013	0.125	28.961	0.071	19.429
	JUN2013	0.464	17.493	0.095	14.119
	JUL2013	3.486	20.838	2.179	16.274
	AUG2013	0.649	13.743	0.048	7.774
	SEP2013	4.148	16.337	1.976	8.679
	OCT2013	0.386	16.560	0.119	8.714
	NOV2013	0.362	9.923	0.226	4.929
	DEC2013		9.726		4.762
	JAN2014		9.660		4.726
	FEB2014		9.619		4.714
	MAR2014	9.186	18.805	3.148	7.862
	APR2014	1.281	20.086	2.552	10.414
	MAY2014	3.362	23.323	1.047	11.389
	JUN2014	1.281	24.141	1.035	12.329
	JUL2014	1.294	21.949	0.412	10.562
	AUG2014	0.263	21.563	0.060	10.574
	SEP2014	1.125	18.539	0.417	9.014
	OCT2014	0.235	18.389	0.047	8.942

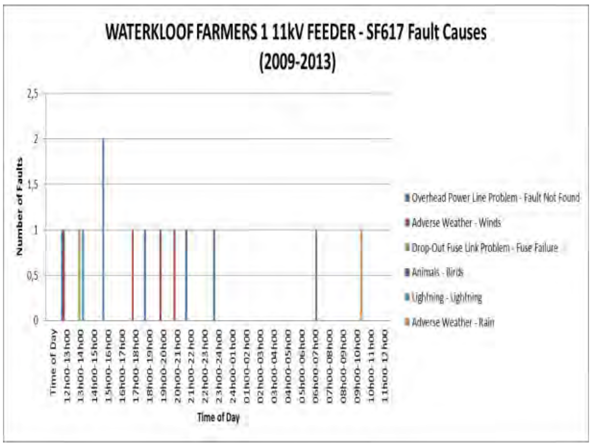
Appendix G: Waterkloof Farmers 1 11 kV Feeder – Historical Data and FMEA Calculations

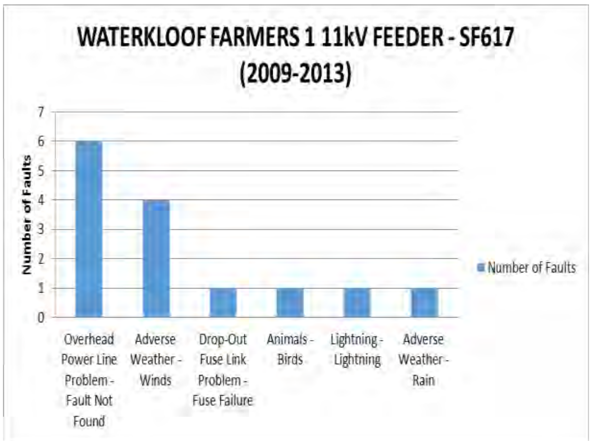


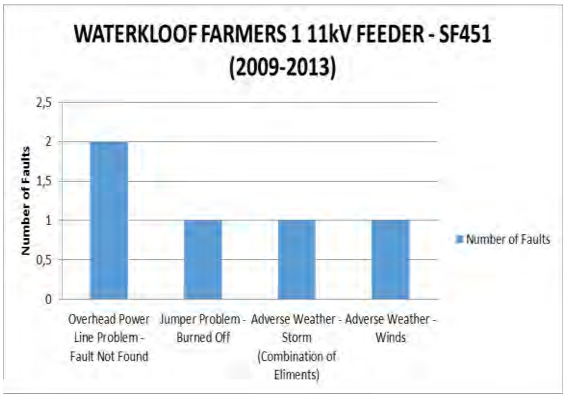


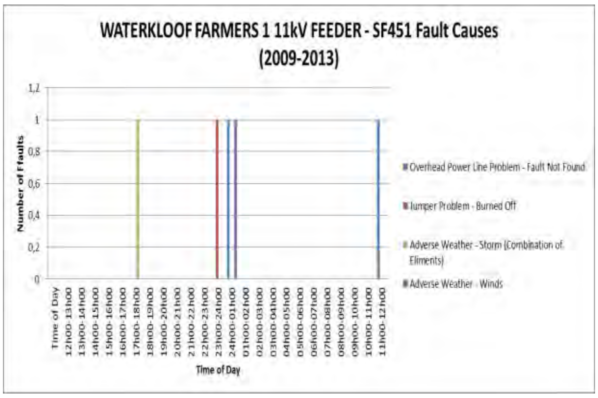


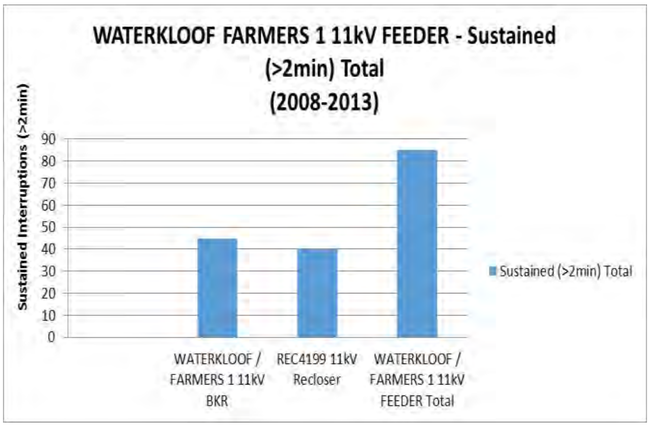


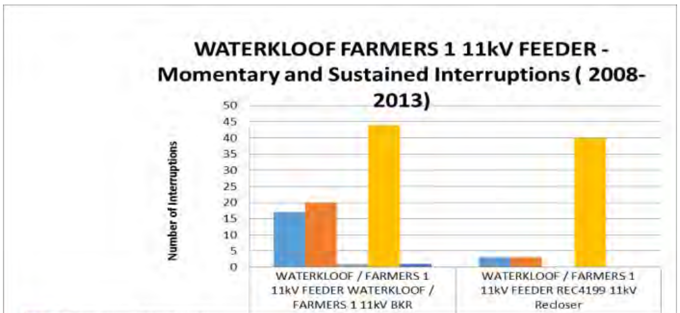






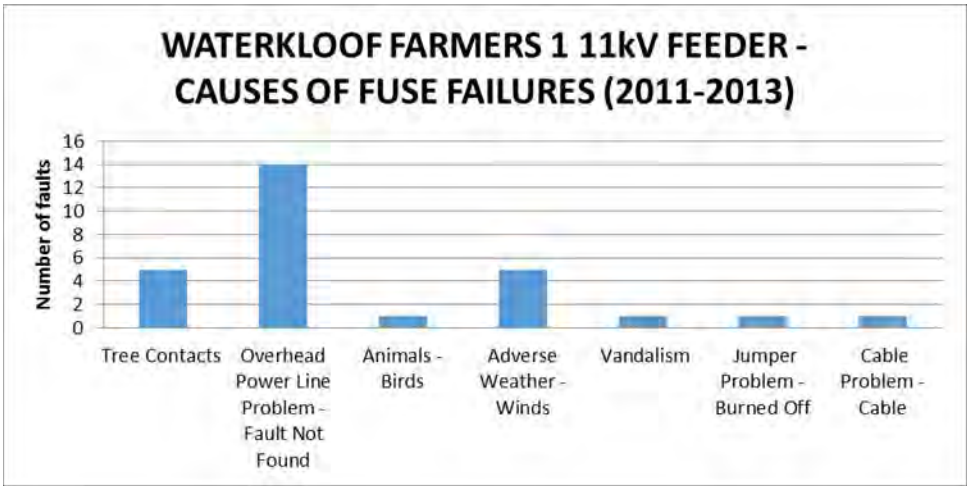


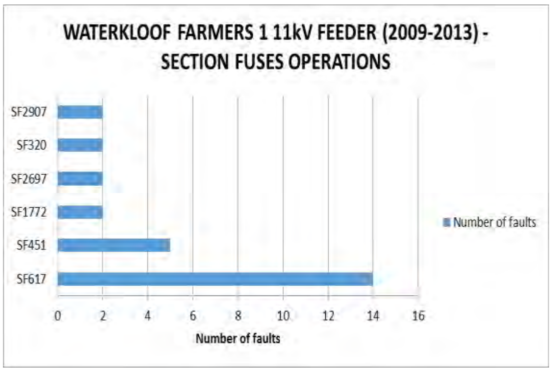


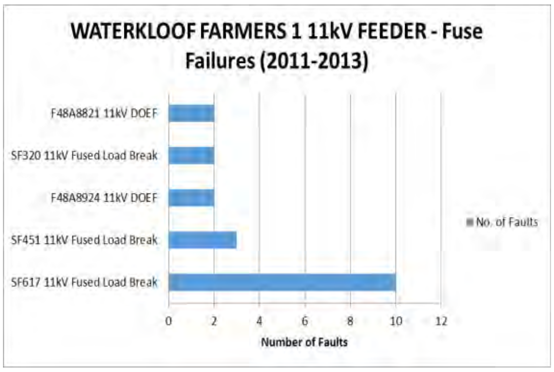


	WATERKLOOF / FARMERS 1 11kV FEEDER WATERKLOOF / FARMERS 1 11kV BKR	WATERKLOOF / FARMERS 1 11kV FEEDER REC4199 11kV Recloser
Momentary (<2min) - Tripped	17	3
Momentary (<2min) - Tripped & ARC	20	3
Momentary (<2min) - Tripped, Closed & Tripped	1	0
Sustained (>2min) - Tripped	44	40
Sustained (>2min) - Tripped, Closed & Tripped	1	0

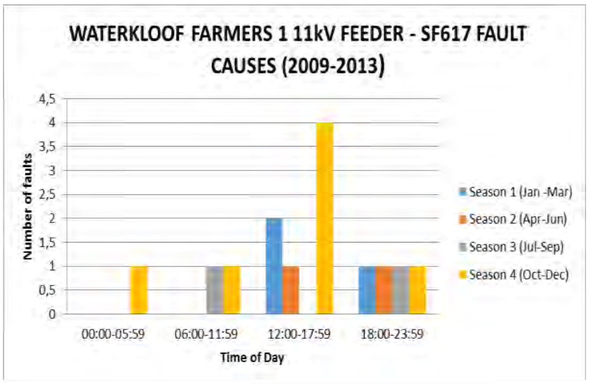
Waterkloof F1 11 kV Feeder Fuse Operations

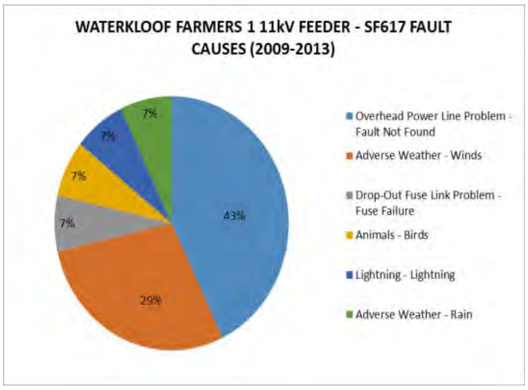


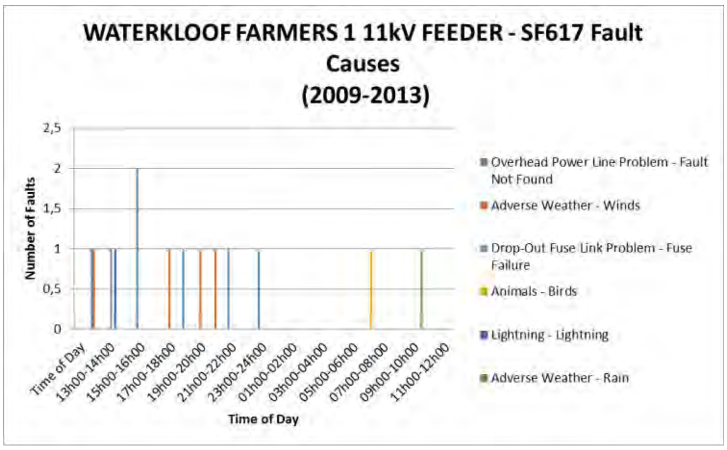




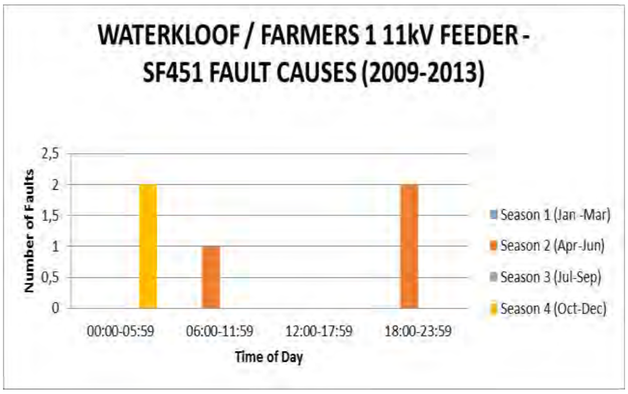
Location : SF617 – Tripsavers : Historical data for SF617 – Installation of Tripsavers

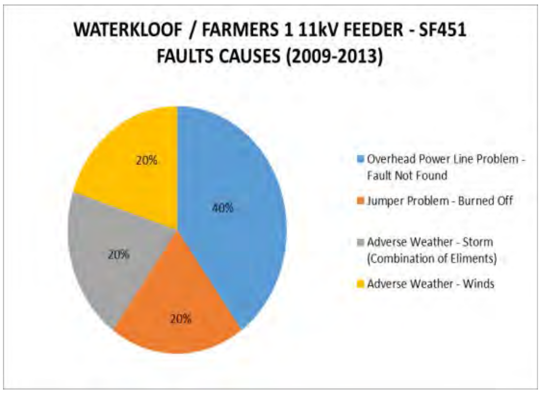


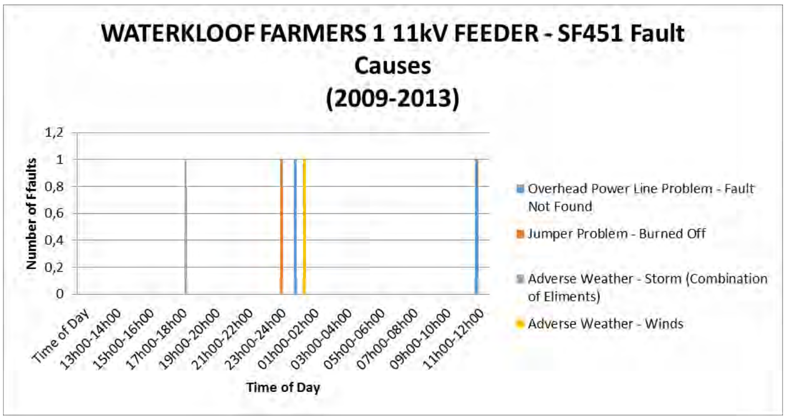




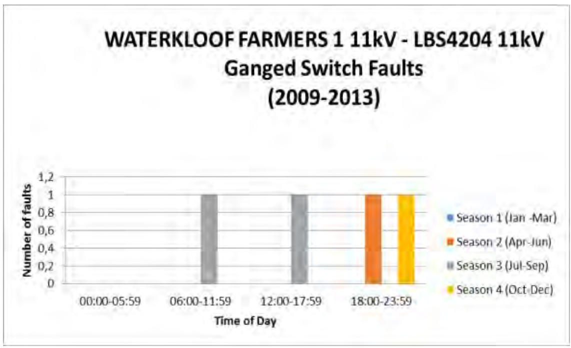
Location: SF451 – Fusesavers Historical data for SF451 – Installation of Fusesavers

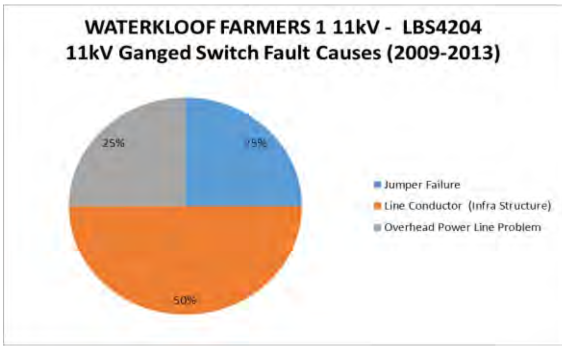






Location: LBS4204 – Intellirupter Pulsecloser - Installation of Intellirupter Pulsecloser





Fault frequency on Waterkloof Feeder

RC_LOC_PARENT	WATERKLOOF / FARMERS 1 11kV FEEDER
MONTH_CHAR	(Multiple Items)
CAUSE_NOFELCA	(Multiple Items)

Row Labels	Sum of OFE_CUSTOMER_INTERRUPTIONS	Sum of FE_CUSTOMER_DURATIONS	Average of DURATION AVG (HOURS)	Count of CAUSEID
48A7798 11kV/400V Two Winding Transformer	2	4,975555556	2,487777778	1
48A8615 11kV/400V Two Winding Transformer	1	2,797222222	2,797222222	1
48A8813 11kV/400V Two Winding Transformer	2	7,838333333	3,919166667	1
48A8826 11kV/400V Two Winding Transformer	3	19,4525	6,484166667	1
48A8917 11kV/400V Two Winding Transformer			0	1
48A8921 11kV/400V Two Winding Transformer			0	1
48A8922 11kV/400V Two Winding Transformer	1	2,648611111	2,648611111	1
F48A8513 11kV DOEF	1	1,890555556	1,890555556	1
F48A8606 11kV DOEF	3	3,433333333	1,144444444	1
F48A8828 11kV DOEF			0	1
F48A8914 11kV DOEF	1	3,212222222	3,212222222	1
LBS4203 11kV Ganged Switch	392	669,2433333	2,593966408	3
REC4199 11kV Recloser	872	373,4911111	3,156503268	4
REC7306 11kV Recloser			0	2
SF320 11kV Fused Load Break	2	2,605555556	1,302777778	1
SF451 11kV Fused Load Break	15	66,61666667	4,441111111	1
SL2449 11kV Solid Cutout	32	70,34722222	3,70248538	1
SL4503 11kV Solid Cutout	2	20,95166667	20,95166667	1
WATERKLOOF / FARMERS 1 11kV FEEDER	765	212,4425	0,277702614	1
Grand Total	**2094**	**1461,946389**	**3,026712901**	**25**

FEEDER	FAULTS	TOTAL_FDR_LENGTH_M	TOTAL_FDR_LENGTH_Km	Faults/100km
WATERKLOOF / FARMERS 1 11kV FEEDER	18	24321,874	24,321874	74,00745518

WMA	FSA	TSA	LOCATI(	DESCRIPTION	OWNER	K	CUST_CI	LPU_CUST_CI	SPU_CUST_CI	PPU_CUST_CI	TOTAL_FDR_LENGTH_M	CABLE_LENGT	LINE_LENGTH_M
Western WMA	Bellville FSA	Somerset We	247454265	WATERKLOOF / FARMERS 1 11kV FEEDER	ESKOM Distribution	11	86	11	73	2	24091.751	4593.653	19498.098

System indices calculations using FMEA

From Event Summary _5 Years - 31 December 2013

λ_{2013} = (Number of Fault per year)/ (year*length of feeder)

= 133/ (5*24.3)

= 1.0947

Line Current Calculations

$I = (KVA * 1000) / (11kV*(3/\sqrt{3}))$

$I_{LBS4204} = (7267*1000) / (11kV*(3/\sqrt{3}))$

$= 381.42A$

$I_{SF451} = (1067*1000) / (11kV*(3/\sqrt{3}))$

$= 56.00A$

$I_{SF617} = (375*1000) / (11kV*(3/\sqrt{3}))$

$= 19.68A$

Historical Data Results: 2009 - 2014

RC_LOC_PARENT	WATERKLOOF / FARMERS 1 11kV FEEDER
MONTH_CHAR	(Multiple Items)
CAUSE_NOFELCA	FAULT

Row Labels	Count of OFE_CUSTOMER_INTERRUPTIONS	Sum of FE_CUSTOMER_DURATIONS	Average of DURATION AVG (HOURS)	Count of CAUSEID
LBS4204 11kV Ganged Switch	4	1322,169167	3,307170489	4
Grand Total	**4**	**1322,169167**	**3,307170489**	**4**

SAIDI	15,37406008
SAIFI	3,069767442
CAIDI	5,00821654

RC_LOC_PARENT	WATERKLOOF / FARMERS 1 11kV FEEDER
MONTH_CHAR	(Multiple Items)
CAUSE_NOFELCA	FAULT

Row Labels	Count of OFE_CUSTOMER_INTERRUPTIONS	Sum of FE_CUSTOMER_DURATIONS	Average of DURATION AVG (HOURS)	Count of CAUSEID
SF451 11kV Fused Load Break	6	392,5102778	4,402374339	6
Grand Total	**6**	**392,5102778**	**4,402374339**	**6**

SAIDI	0,767855989
SAIFI	1,046511628
CAIDI	0,733729056

RC_LOC_PARENT	WATERKLOOF / FARMERS 1 11kV FEEDER
MONTH_CHAR	(Multiple Items)
CAUSE_NOFELCA	FAULT

Row Labels	Sum of OFE_CUSTOMER_INTERRUPTIONS	Sum of FE_CUSTOMER_DURATIONS	Average of DURATION AVG (HOURS)	Count of CAUSEID
SF617 11kV Fused Load Break	84	305,9186111	3,641888228	14
Grand Total	**84**	**305,9186111**	**3,641888228**	**14**

SAIDI	0,254085225
SAIFI	0,976744186
CAIDI	0,260134873

Event Summary _5 Years - 31 December 2013 – Historical Data and Failure Rate Calculations

Table 1: Root causes of the SAIDI variation

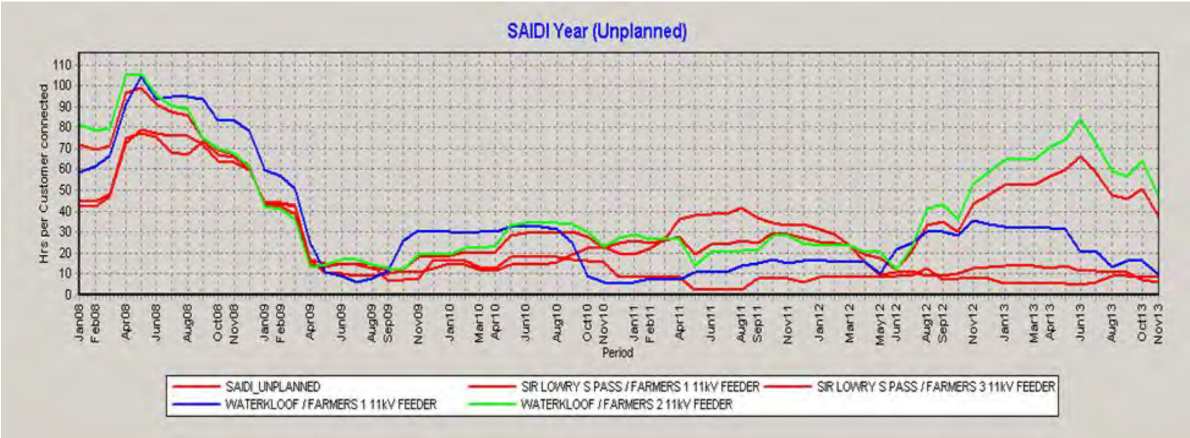
MONTH_CHAR	2013		
CAUSE_NOFELCA	Emergency and Fault		
ROOTCAUSE_PARENT_ CHANGE	WATERKLOOF / FARMERS 1 11kV FEEDER		
TYPE	(All)		
Total number of Feeder Customers	86		
Row Labels	**Count of CAUSEID (number of faults)**	**Sum of FE_CUSTOMER_DURATIONS**	**Sum of FE_CUSTOMER_INTERRUPTIONS**
REC4199 11kV Recloser	2	30,36833333	19
SF617 11kV Fused Load Break	2	18,97694444	12
48A8908 11kV/400V Two Winding Transformer	2	4,968611111	2
SL4202 11kV Solid Cutout	2	348,4672222	166
48A7798 11kV/400V Two Winding Transformer	1	50,44611111	2
48A8902 11kV/400V Two Winding Transformer	1	3,416666667	1
F48A8828 11kV DOEF	1		
48A8804 11kV/400V Two Winding Transformer	1	34,27861111	7
SF320 11kV Fused Load Break	1	4,065555556	2
SL4503 11kV Solid Cutout	1	294,9322222	184
F48A8821 11kV DOEF	1	4,675555556	1
48A8917 11kV/400V Two Winding Transformer	1	23,93222222	4
48A7694 11kV/400V Two Winding Transformer	1		
48A8922 11kV/400V Two Winding Transformer	1	0,597777778	1
Grand Total	**18**	**819,1258333**	**401**

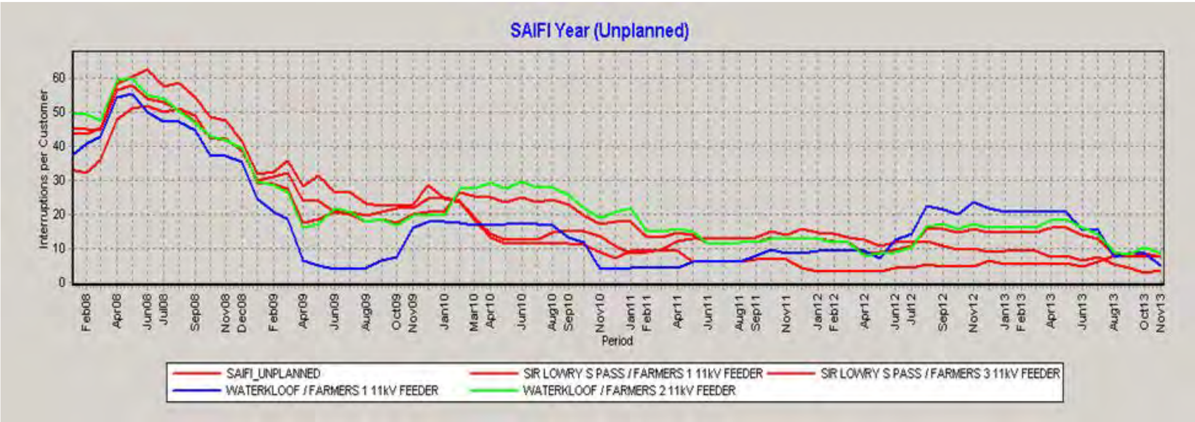
Root causes of the SAIDI differences related to Table 1 are listed in the Table 2.

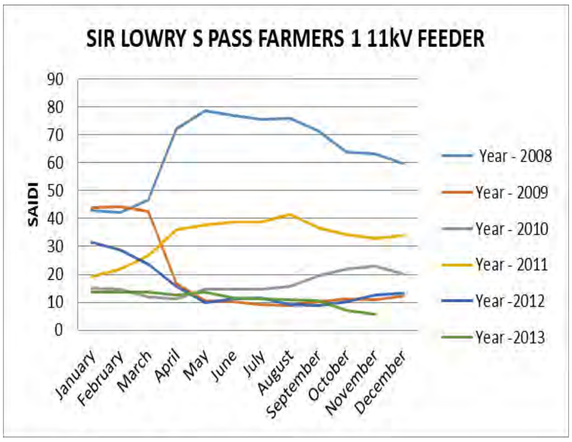
Table 2: Root fault causes of the SAIDI

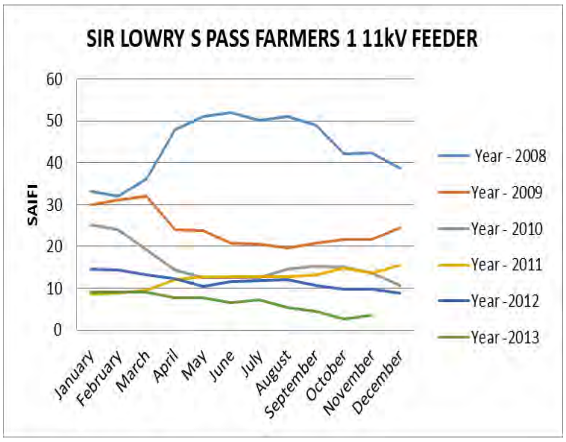
DATE	FAULT CAUSES
October 2013	Birds, Vandalism
November 2013	Overhead Power Line Problem
December 2013	-
January 2014	-
February 2014	-
March 2014	Cable Faulted, Foreign Objects / Interference, Overhead Power Line Problem, Vandalism
April 2014	Birds, Jumper Damaged
May 2014	Fuse Failure, Animals, Conductor & Associated Hardware Failure, Fault On LV Network, Power Transformer failure
June 2014	Fuse Failure, Conductor & Associated Hardware Failure
July 2014	Jumper Failure, Conductor & Associated Hardware Failure
August 2014	Conductor & Associated Hardware Failure, Cable Damaged
September 2014	Conductor & Associated Hardware Failure, Overhead Power Line Problem, Trees, Winds
October 2014	Oil Leak, Vandalism
November 2014	-
December 2014	-

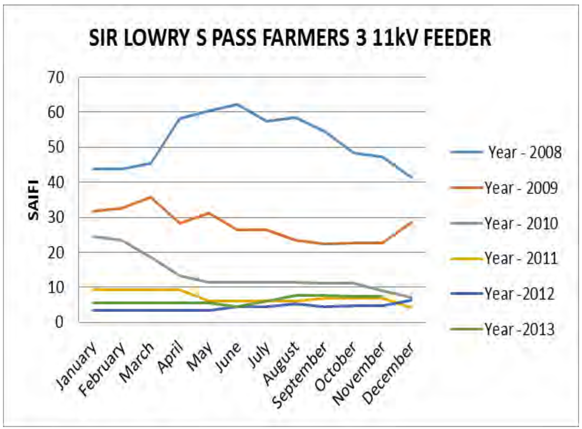
Appendix H: Waterkloof Farmers 1 11 kV Feeder – Reference Group Feeder – SAIDI and SAIFI

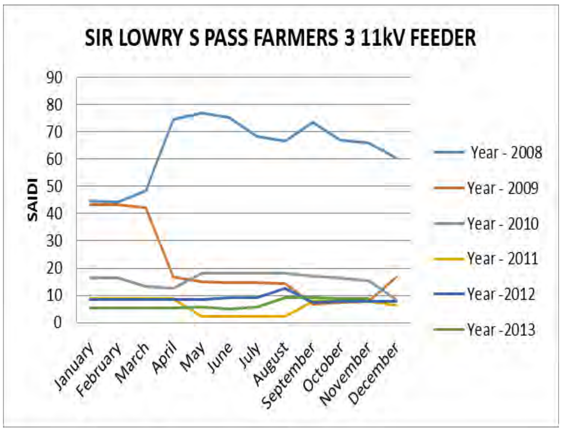


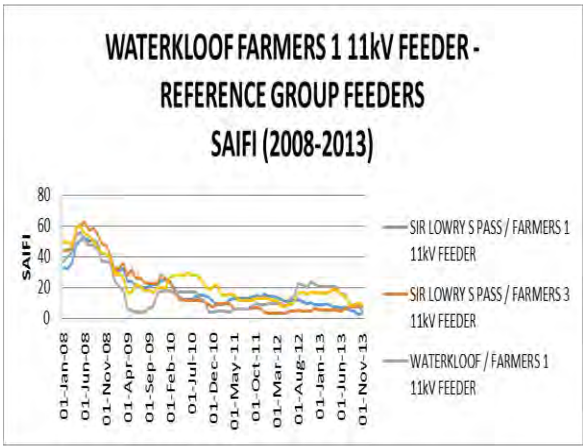


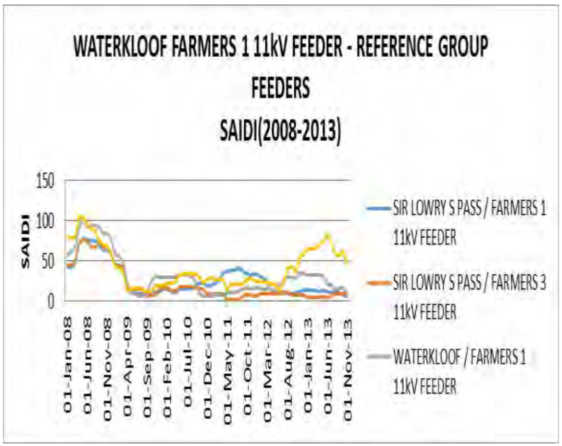


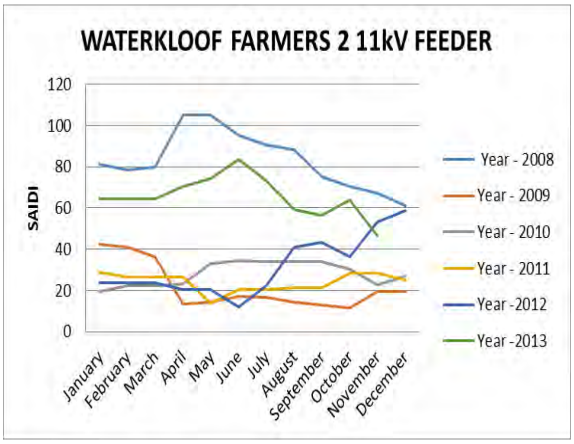


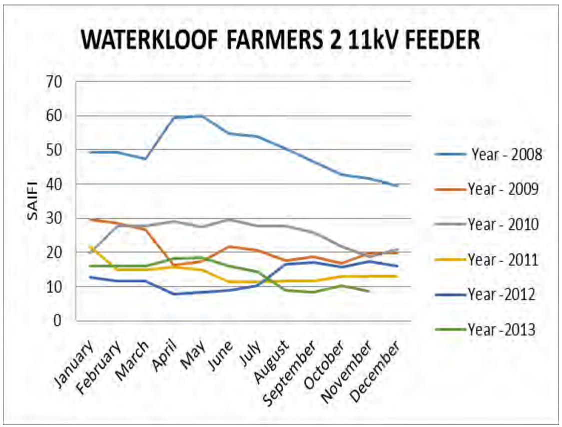

SIR LOWRY S PASS FARMERS 3 11kV FEEDER
SAIFI
Year - 2008
Year - 2009
Year - 2010
Year - 2011
Year -2012
Year -2013
January February March April May June July August September October November December

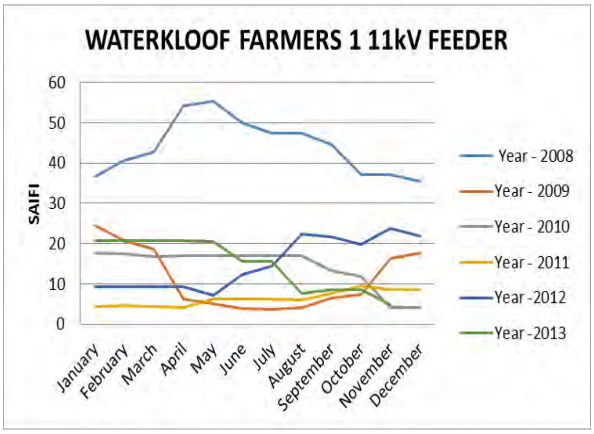

SIR LOWRY S PASS FARMERS 3 11kV FEEDER
SAIDI
Year - 2008
Year - 2009
Year - 2010
Year - 2011
Year -2012
Year -2013
January February March April May June July August September October November December


WATERKLOOF FARMERS 1 11kV FEEDER - REFERENCE GROUP FEEDERS SAIFI (2008-2013)
SAIFI
SIR LOWRY S PASS / FARMERS 1 11kV FEEDER
SIR LOWRY S PASS / FARMERS 3 11kV FEEDER
WATERKLOOF / FARMERS 1 11kV FEEDER


WATERKLOOF FARMERS 1 11kV FEEDER - REFERENCE GROUP FEEDERS SAIDI(2008-2013)
SAIDI
SIR LOWRY S PASS / FARMERS 1 11kV FEEDER
SIR LOWRY S PASS / FARMERS 3 11kV FEEDER
WATERKLOOF / FARMERS 1 11kV FEEDER


WATERKLOOF FARMERS 2 11kV FEEDER
SAIDI
Year - 2008
Year - 2009
Year - 2010
Year - 2011
Year -2012
Year -2013
January February March April May June July August September October November December


WATERKLOOF FARMERS 2 11kV FEEDER
SAIFI
Year - 2008
Year - 2009
Year - 2010
Year - 2011
Year -2012
Year -2013
January February March April May June July August September October November December


WATERKLOOF FARMERS 1 11kV FEEDER
SAIFI
Year - 2008
Year - 2009
Year - 2010
Year - 2011
Year -2012
Year -2013
January February March April May June July August September October November December

Appendix I: Network Description

Waterkloof Faremers 1 [6]

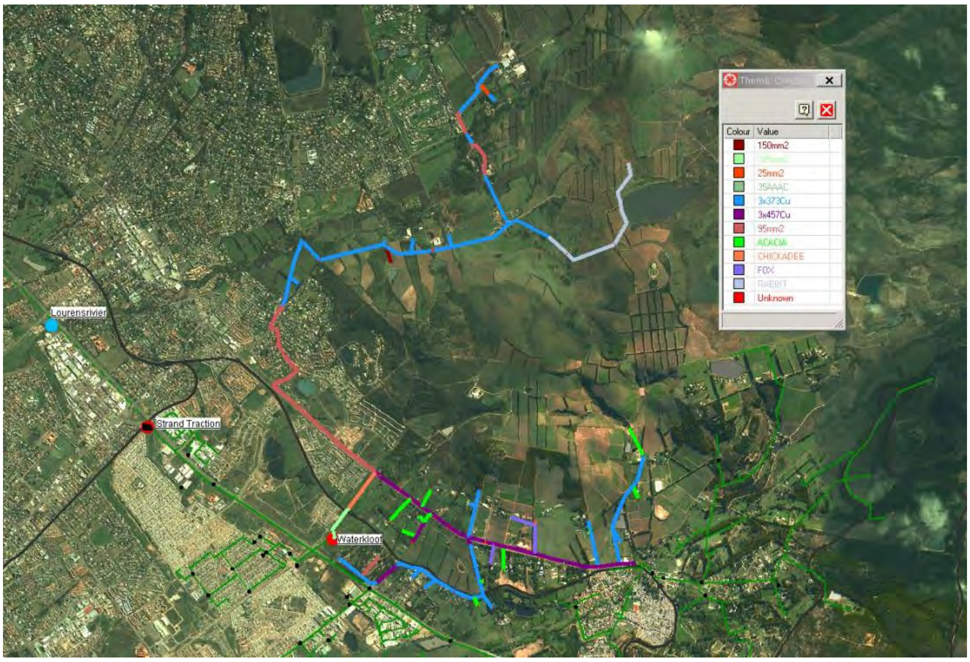
Length

Type	Length
Length of Cables	4593.655 m
Length of Conductors	19675.713 m
Total Length	**24269.367 m**

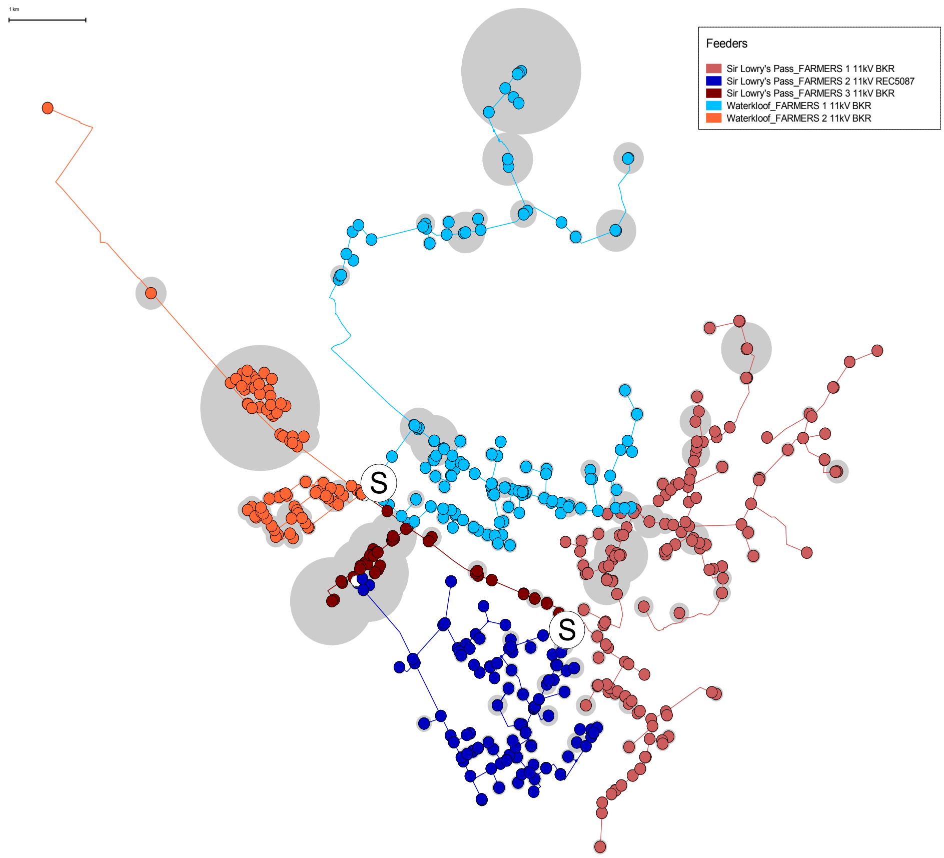
LPU's on Waterkloof / Farmers 1

Customer Name	Property_Description	Feeder	Transform…	NMD	Maximum Load use…	POD
ANGLO AMERICAN FARMS LTD,-	WINERY VERGELEGEN EST,,,1/843/8,I	Waterkloof / Farmers 1	48A8625	300	192	5458487403
FALSE BAY VINEYARDS (PTY) LTD	SIR LOWRY'S PASS RD,WATERKLOOF FARM,, 1	Waterkloof / Farmers 1	48A8708	750	326	4225234124
CITY OF CAPE TOWN METROPOLITAN MUNI	PINETOWN 1/144/2.I;HELDERBERG ADMINIST	Waterkloof / Farmers 1	48A8927	1000	893	2529156781
CITY OF CAPE TOWN METROPOLITAN MUNI	WATER SCHEME PUMP STATION,,ERF NO 820	Waterkloof / Farmers 1	BRUYN	150	251	7037673395
LOURENSFORD ESTATES FARMING ENTERPR	LOURENSFORD EST,,,1/104,I	Waterkloof / Farmers 1	48A8515	2000	1678	6986396220
PRECIOUS PROSPECT TRADING (PTY) LTD	MOUNT RHODES (MOUNT),FARM 918,SIR LOV	Waterkloof / Farmers 1	MOUNT	200	122	5676692779
ANGLO AMERICAN FARMS LTD,-	LOURENSFORD RD,VERGELEGEN FARM,LUBBE	Waterkloof / Farmers 1	48A8615	200	73	7533187669
ANGLO AMERICAN FARMS LTD,-	VERGELEGEN FARM,ROOILAND POMPHUIS,,1	Waterkloof / Farmers 1	48A8628	500	210	7703529841
MORGENSTER (1711) (PTY) LTD	MORGENSTER WINE EST,,,1/2256,I	Waterkloof / Farmers 1	48A8606	200	155	8372930122
VERGELEGEN WINES (PTY) LTD	VERGELEGEN WINE FARM,,,1/2718,I	Waterkloof / Farmers 1	VERG	250	243	7915079590
				5550	4143	75%

Conductors on feeder [6]



Load distribution- DIgSILENT PowerFactory



Appendix J: Digsilent - General Load Data

Name	In Folder	Grid	Number of connec...	Priority	Contracted Active ... MW	Shedding steps	Transferable %	Resulting %	Alternative Supply ... ElmLod,ElmLodlv	Tariff IntTariffenergy,Int...	Scaling factor	Unit	Load Classification
48A8811	48A8811	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8812	48A8812	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8813	48A8813	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8815	48A8815	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8817	48A8817	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8821	48A8821	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8825	48A8825	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8826	48A8826	Grid	3	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8827	48A8827	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8828	48A8828	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8900	48A8900	Grid	4	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8902	48A8902	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8903	48A8903	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8904	48A8904	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8905	48A8905	Grid	3	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8906	48A8906	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8907	48A8907	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8908	48A8908	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8909	48A8909	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8910	48A8910	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8911	48A8911	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8912	48A8912	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8913	48A8913	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8914	48A8914	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8917	48A8917	Grid	4	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8921	48A8921	Grid	3	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8922	48A8922	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8924	48A8924	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8927(1)	48A8927	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
48A8947	48A8947	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
AZITU	AZITU	Grid	2	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
BRUYN	BRUYN	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
MOUNT(2)	MOUNT	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
PITTIUS	PITTIUS	Grid	3	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...
VERG	VERG	Grid	1	0	0.	0	0.	0.		Energy Tariff	1.	/kW	...

Appendix K: Waterkloof Farmers 1 11 kV Feeder- Average Load Factor and Power Factor

01/01/2013 - 31/12/2013

Waterkloof				
Boland	CTS-0000000331			
	11kV Fdr 2 - Farm1			
DATE & TIME	kW	kVAr	kVA	pf
2013/01/01 00:00	1197	635	1355	0
2013/01/01 00:30	1158	576	1293	0.90
2013/01/01 01:00	1025	506	1143	0.90
2013/01/01 01:30	997	536	1132	0.88
2013/01/01 02:00	993	544	1132	0.88
2013/01/01 02:30	966	518	1096	0.88
2013/01/01 03:00	957	528	1093	0.88
2013/01/01 03:30	970	556	1118	0.87
2013/01/01 04:00	964	538	1104	0.87
2013/01/01 04:30	986	547	1128	0.87
2013/01/01 05:00	1089	588	1238	0.88
2013/01/01 05:30	1075	591	1227	0.88
2013/01/01 06:00	1024	595	1184	0.86
2013/01/01 06:30	946	540	1089	0.87
2013/01/01 07:00	1016	604	1182	0.86
2013/01/01 07:30	1029	586	1184	0.87
2013/01/01 08:00	1126	634	1292	0.87
2013/01/01 08:30	1220	624	1370	0.89
2013/01/01 09:00	1259	612	1400	0.90
2013/01/01 09:30	1296	682	1464	0.88
2013/01/01 10:00	1370	692	1535	0.89
2013/01/01 10:30	1428	715	1597	0.89
2013/01/01 11:00	1388	710	1559	0.89
2013/01/01 11:30	1381	695	1546	0.89
2013/01/01 12:00	1357	708	1531	0.89
2013/01/01 12:30	1389	737	1572	0.88
2013/01/01 13:00	1423	744	1606	0.89
2013/01/01 13:30	1314	716	1496	0.88
2013/01/01 14:00	1309	722	1495	0.88
2013/01/01 14:30	1339	755	1537	0.87
2013/01/01 15:00	1388	769	1587	0.87
2013/01/01 15:30	1388	778	1591	0.87
2013/01/01 16:00	1294	731	1486	0.87
2013/01/01 16:30	1170	658	1342	0.87
2013/01/01 17:00	1175	659	1347	0.87
2013/12/15 20:30	1256	561	1376	0.91
2013/12/15 21:00	1265	546	1378	0.92
2013/12/15 21:30	1229	598	1367	0.90
2013/12/15 22:00	1170	563	1298	0.90
2013/12/15 22:30	1116	563	1250	0.89
2013/12/15 23:00	1088	536	1213	0.90
2013/12/15 23:30	1051	560	1191	0.88
2013/12/16 00:00	1003	573	1155	0.87
2013/12/16 00:30	981	581	1140	0.86
2013/12/16 01:00	969	525	1102	0.88
2013/12/16 01:30	922	502	1050	0.88
2013/12/16 02:00	936	521	1071	0.87
2013/12/16 02:30	907	512	1042	0.87
2013/12/16 03:00	897	530	1042	0.86
2013/12/16 03:30	928	529	1068	0.87
2013/12/16 04:00	953	518	1085	0.88
2013/12/16 04:30	944	513	1074	0.88
2013/12/16 05:00	954	500	1077	0.89
2013/12/16 05:30	930	474	1044	0.89
2013/12/16 06:00	982	500	1102	0.89
2013/12/16 06:30	945	489	1064	0.89
2013/12/16 07:00	814	405	909	0.90
2013/12/16 07:30	1098	563	1234	0.89
2013/12/16 08:00	1319	599	1449	0.91
2013/12/16 08:30	1559	650	1689	0.92
2013/12/16 09:00	1770	716	1909	0.93
2013/12/16 09:30	1841	710	1973	0.93
2013/12/16 10:00	1816	698	1946	0.93
2013/12/16 10:30	1626	651	1751	0.93
2013/12/16 11:00	1578	643	1704	0.93
2013/12/16 11:30	1707	680	1837	0.93
2013/12/16 12:00	1701	664	1826	0.93
2013/12/16 12:30	1681	661	1806	0.93
2013/12/16 13:00	1686	635	1802	0.94
2013/12/16 13:30	1713	679	1843	0.93
2013/12/16 14:00	1583	695	1729	0.92
2013/12/16 14:30	1572	705	1723	0.91
2013/12/16 15:00	1574	703	1724	0.91
2013/12/16 15:30	1498	647	1632	0.92
2013/12/16 16:00	1458	630	1588	0.92
2013/12/16 16:30	1442	634	1575	0.92
2013/12/16 17:00	1453	670	1600	0.91
2013/12/16 17:30	1464	676	1613	0.91
2013/12/16 18:00	1444	660	1588	0.91
2013/12/16 18:30	1447	690	1603	0.90
2013/12/16 19:00	1399	683	1557	0.90
2013/12/16 19:30	1359	654	1508	0.90
2013/12/16 20:00	1363	552	1471	0.93
2013/12/16 20:30	1321	602	1452	0.91
2013/12/16 21:00	1325	599	1454	0.91
				0.92

CTS-0000000331		
11kV Fdr 2 - Farm1		
kVA	kWh	LF
2846	1218231	0.58
3946	1208770	0.46
3101	1304477	0.57
2729	1190761	0.61
2509	1195167	0.64
2504	1156431	0.64
2390	1120736	0.63
2553	1215800	0.64
2554	1136957	0.62
2711	1075512	0.53
2264	964769	0.59
2433	512676	0.28
		0.58

Appendix L: Results of the Load Point Indices and System Reliability Indicesof Different Configurations from DIgSILENT

Cost Evaluation of the Different Configurations Tested

Configuration 2: Configuration 1 + FuseSavers added at SF451

Name	In Folder	Grid	Act.Pow. MW	Number of connec....	Tariff IntTariffenergy,Int.....	AID h	LPIT h/a	LPIF 1/a	LPENS MWh/a	ACIF 1/a	ACIT h/a	LPIC $/a	TCIT Ch/a	TMVAIF
A	A	Grid	4,2458	20		1,127442	10,71999	9,5082384	4,551491	9,508238	10,71999	97766,03	214,3997	5,305777
BRUYN (B)	BRUYN (B)	Grid	0,46	1		5,031227	9,96727	1,9810812	0,458494	1,981081	9,96727	9848,46	9,96727	2,758958
C	C	Grid	0,92	1		5,026968	9,980844	1,98546	0,918238	1,98546	9,980844	19723,74	9,980844	5,505747
D	D	Grid	0,115	2		5,02635	11,80089	2,3478057	0,13571	2,347806	11,80089	2915,056	23,60178	0,582003
E	E	Grid	0,529	12		5,019789	15,69255	3,1261374	0,830136	3,126137	15,69255	17831,32	188,3106	2,010653
F	F	Grid	0,138	3		5,023345	13,31158	2,6499429	0,1837	2,649943	13,31158	3945,871	39,93473	0,618774
G	G	Grid	0,98164	15		2,221894	10,22956	4,6039824	1,004175	4,603982	10,22956	21569,67	153,4434	2,533426
H	H	Grid	0,46	5		5,025448	12,21688	2,4310029	0,561976	2,431003	12,21688	12071,25	61,08439	2,24834
I	I	Grid	0,46	6		5,021279	14,59785	2,9071974	0,671501	2,907197	14,59785	14423,84	87,5871	1,880065
J	J	Grid	0,805	11		5,01927	16,11401	3,2104293	1,297178	3,210429	16,11401	27863,38	177,2541	2,979355
K	K	Grid	0,345	6		5,016623	18,67013	3,7216542	0,64412	3,721654	18,67013	13835,69	112,0208	1,10147
L	L	Grid	0,552	3		5,031227	9,96727	1,9810812	0,550193	1,981081	9,96727	11818,15	29,90181	3,31075
M	M	Grid	0,92	1		5,031227	9,96727	1,9810812	0,916989	1,981081	9,96727	19696,92	9,96727	5,517916

Figure 1: **Results of the load point indices for Configuration 2 from DIgSILENT**

$$\textbf{CIC/year} = \sum_{x=A}^{M} U_x L_x C_x \qquad \textbf{(9.1)}$$

The CIC calculation for different load points for Configuration 2 are shown in Figure 2 using equation **(9.1)**

Configuration 2								
Load	λ(f/yr)	r(hrs)	U(hrs/yr)	Average Load (MW)	Average Load (kW)	Unserved Energy (kWh/yr)	COUE(R/kWh)	CIC(R/yr)
A	9,508238	1,12744179	10,71998532	4,1535	4153,5	44525,45903	21,48	956406,8599
BRUYN (B)	1,981081	5,0312272	9,9672696	0,46	460	4584,944016	21,48	98484,59746
C	1,98546	5,026968	9,98084388	0,9	900	8982,759492	21,48	192949,6739
D	2,347806	5,0263495	11,8008921	0,1125	112,5	1327,600361	21,48	28516,85576
E	3,126137	5,0197891	15,6925506	0,529	529	8301,359267	21,48	178313,1971
F	2,649943	5,0233453	13,3115781	0,138	138	1836,997778	21,48	39458,71227
G	4,603982	2,2218938	10,22955972	0,9603	960,3	9823,446199	21,48	211007,6244
H	2,431003	5,0254478	12,2168781	0,46	460	5619,763926	21,48	120712,5291
I	2,907197	5,0212795	14,5978506	0,46	460	6715,011276	21,48	144238,4422
J	3,210429	5,0192696	16,1140101	0,805	805	12971,77813	21,48	278633,7942
K	3,721654	5,0166226	18,6701346	0,345	345	6441,196437	21,48	138356,8995
L	1,981081	5,0312272	9,9672696	0,552	552	5501,932819	21,48	118181,517
M	1,981081	5,0312272	9,9672696	0,92	920	9169,888032	21,48	196969,1949
Total Annual Cost of Interruption								**2702229,898**

Figure 2: **Calculations of the CIC for each load point - Annual cost of interruptions - Configuration 2**

Annual cost of interruptions of feeder for **Configuration 2** = R 2702229.90

Where: *U = λ x r and Unserved energy = U x Average load*

Utility cost for Configuration 2 includes Configuration 1:

Loss of income = R 0.8/kWh x 3618 kVA x 0.92 x 12.991 (SAIDI) = R 34593.06
Investment cost for Fusesaver = R 33800 x 3 = R 101400
Maintenance cost for Fusesaver = 0
Labour cost = 10 % of investment cost for Fusesaver = R 10140

Utility Cost = Loss of income + Investment cost + Maintenance cost + Operation cost

Utility cost = R 34593.06+ R 101400 + R 10140 + R 559071.80 = R 705204.86

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|                  |                                                                    |   DIgSILENT   | Project:                          |
|                  |                                                                    | PowerFactory  |-----------------------------------
|                  |                                                                    |    15.1.4     | Date:  6/30/2015                  |
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| Reliability Assessment                                                                                                              |
|   Method                                     Load flow analysis                                                                    |
|   Network                                    Distribution (Optimal Power Restoration)                                              |
|   Calculation time period                    2015                                                                                  |
|   Consider Maintenance                       Yes                                                                                   |
|   Fault Clearance Breakers                   Use all circuit breakers                                                              |
|   Switching procedures                       Sequential                                                                            |
|   Consider Sectionalizing (Stages 1-3)       No                                                                                    |
|   Time to open remote controlled switches    0.10 min.                                                                             |
|                                                                                                                                     |
| Automatic Contingency Definition                                                                                                    |
|   Selection                                  Whole System                                                                          |
|   Busbars / terminals                        Yes                Common mode                                 No                     |
|   Lines / cables                             Yes                Independent second failures                 No                     |
|   Transformers                               Yes                Double earth faults                         No                     |
|                                                                 Protection/switching failures               No                     |
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| Study Case: Study Case                                                                             | Annex:                  / 1   |
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| System Summary                                                                                                                      |
--------------------------------------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index        :  SAIFI  =   4.752724 1/Ca                                                      |
| Customer Average Interruption Frequency Index      :  CAIFI  =   4.752724 1/Ca                                                      |
| System Average Interruption Duration Index         :  SAIDI  =   12.991     h/Ca                                                    |
| Customer Average Interruption Duration Index       :  CAIDI  =    2.733     h                                                       |
| Average Service Availability Index                 :  ASAI   =    0.9958929464                                                        |
| Average Service Unavailability Index               :  ASUI   =    0.0041070536                                                        |
| Energy Not Supplied                                :  ENS    =   16.521     MWh/a                                                   |
| Average Energy Not Supplied                        :  AENS   =    0.342     MWh/Ca                                                  |
| Average Customer Curtailment Index                 :  ACCI   =    0.944     MWh/Ca                                                  |
| Expected Interruption Cost                         :  EIC    =    0.774     M$/a                                                    |
| Interrupted Energy Assessment Rate                 :  IEAR   =   18.316     $/kWh                                                   |
| System energy shed                                 :  SES    =    0.000     MWh/a                                                   |
| Average System Interruption Frequency Index        :  ASIFI  =   3.769955 1/a                                                       |
| Average System Interruption Duration Index         :  ASIDI  =   13.481247 h/a                                                       |
| Momentary Average Interruption Frequency Index     :  MAIFI  =    0.000000 1/Ca                                                      |
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Figure 3**: Results of the system indices from DIgSILENT PowerFactory to obtain SAIDI for Configuration 2**

Configuration 3: *Configuration 2* + Tripsavers and FPI's added at SF617

Name	In Folder	Grid	Act.Pow. MW	Number of connec....	Tariff IntTariffenergy,Int.....	AID h	LPIT h/a	LPIF 1/a	LPENS MWh/a	ACIF 1/a	ACIT h/a	LPIC $/a	TCIT Ch/a	TMVAIF
A	A	Grid	4,2458	20		1,127442	10,71999	9,5082384	4,551491	9,508238	10,71999	97766,03	214,3997	5,305777
BRUYN (B)	BRUYN (B)	Grid	0,46	1		5,031227	9,96727	1,9810812	0,458494	1,981081	9,96727	9848,46	9,96727	2,758958
C	C	Grid	0,92	1		5,026968	9,980844	1,98546	0,918238	1,98546	9,980844	19723,74	9,980844	5,505747
D	D	Grid	0,115	2		5,02635	11,80089	2,3478057	0,13571	2,347806	11,80089	2915,056	23,60178	0,582003
E	E	Grid	0,529	12		5,019789	15,69255	3,1261374	0,830136	3,126137	15,69255	17831,32	188,3106	2,010653
F	F	Grid	0,138	3		5,023345	13,31158	2,6499429	0,1837	2,649943	13,31158	3945,871	39,93473	0,618774
G	G	Grid	0,98164	15		2,221894	10,22956	4,6039824	1,004175	4,603982	10,22956	21569,67	153,4434	2,533426
H	H	Grid	0,46	5		5,025448	12,21688	2,4310029	0,561976	2,431003	12,21688	12071,25	61,08439	2,24834
I	I	Grid	0,46	6		5,021279	14,59785	2,9071974	0,671501	2,907197	14,59785	14423,84	87,5871	1,880065
J	J	Grid	0,805	11		5,01927	16,11401	3,2104293	1,297178	3,210429	16,11401	27863,38	177,2541	2,979355
K	K	Grid	0,345	6		2,724951	10,14133	3,7216542	0,349876	3,721654	10,14133	7515,332	60,84796	1,10147
L	L	Grid	0,552	3		5,031227	9,96727	1,9810812	0,550193	1,981081	9,96727	11818,15	29,90181	3,31075
M	M	Grid	0,92	1		5,031227	9,96727	1,9810812	0,916989	1,981081	9,96727	19696,92	9,96727	5,517916

Figure 4: **Results of the load point indices for Configuration 3 from DIgSILENT**

The CIC calculation for different load points for Configuration 3 are shown in Figure 5 using equation **(9.1)**

Configuration 3								
Load	**λ(f/yr)**	**r(hrs)**	**U(hrs/yr)**	**Average Load (MW)**	**Average Load (kW)**	**Unserved Energy (kWh/yr)**	**COUE(R/kWh)**	**CIC(R/yr)**
A	9,508238	1,12744179	10,71998532	4,1535	4153,5	44525,45903	21,48	956406,8599
BRUYN (B)	1,981081	5,0312272	9,9672696	0,46	460	4584,944016	21,48	98484,59746
C	1,98546	5,026968	9,98084388	0,9	900	8982,759492	21,48	192949,6739
D	2,347806	5,0263495	11,8008921	0,1125	112,5	1327,600361	21,48	28516,85576
E	3,126137	5,0197891	15,6925506	0,529	529	8301,359267	21,48	178313,1971
F	2,649943	5,0233453	13,3115781	0,138	138	1836,997778	21,48	39458,71227
G	4,603982	2,2218938	10,22955972	0,9603	960,3	9823,446199	21,48	211007,6244
H	2,431003	5,0254478	12,2168781	0,46	460	5619,763926	21,48	120712,5291
I	2,907197	5,0212795	14,5978506	0,46	460	6715,011276	21,48	144238,4422
J	3,210429	5,0192696	16,1140101	0,805	805	12971,77813	21,48	278633,7942
K	3,721654	2,724951421	10,1413269	0,345	345	3498,757781	21,48	75153,31713
L	1,981081	5,0312272	9,9672696	0,552	552	5501,932819	21,48	118181,517
M	1,981081	5,0312272	9,9672696	0,92	920	9169,888032	21,48	196969,1949
Total Annual Cost of Interruption								**2639026,315**

Figure 5: **Calculations of the CIC for each load point - Annual cost of interruptions - Configuration 3**

Annual cost of interruptions of feeder for **Configuration 3** = R 2639026.32

Where: $U = \lambda \, x \, r$ *and Unserved energy = U x Average load*

Utility cost for Configuration 3 includes Configuration 2:

Loss of income = R 0.8/kWh x 3618kVA x 0.92 x 12.4 (SAIDI) = R 33019.32
Investment cost for Tripsaver and FPI = (R 30000+R 32300) x 3 = R 186900
Maintenance cost for Tripsaver and FPI = 0
Labour cost = 10 % of investment cost for Trisaver and FPI = R 18690

Utility Cost = Loss of income + Investment cost + Maintenance cost + Operation cost

Utility cost = R 33019.32 + R 186900 + 0 + R 18690 + R 705204.86 = R 943814.18

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|                 |                                                                  |   DIgSILENT    | Project:                       |
|                 |                                                                  | PowerFactory   |--------------------------------
|                 |                                                                  |    15.1.4      | Date:  6/30/2015               |
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| Reliability Assessment                                                                                                             |
|   Method                                      Load flow analysis                                                                   |
|   Network                                     Distribution (Optimal Power Restoration)                                             |
|   Calculation time period                     2015                                                                                 |
|   Consider Maintenance                        Yes                                                                                  |
|   Fault Clearance Breakers                    Use all circuit breakers                                                             |
|   Switching procedures                        Sequential                                                                           |
|   Consider Sectionalizing (Stages 1-3)        No                                                                                   |
|   Time to open remote controlled switches     0.10 min.                                                                            |
|                                                                                                                                    |
| Automatic Contingency Definition                                                                                                   |
|   Selection                                   Whole System                                                                         |
|   Busbars / terminals                         Yes                   Common mode                                 No                |
|   Lines / cables                              Yes                   Independent second failures                 No                |
|   Transformers                                Yes                   Double earth faults                         No                |
|                                                                     Protection/switching failures               No                |
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| Study Case: Study Case                                                                         | Annex:                     / 1  |
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| System Summary                                                                                                                     |
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| System Average Interruption Frequency Index          :  SAIFI  =   4.752724 1/Ca                                                   |
| Customer Average Interruption Frequency Index        :  CAIFI  =   4.752724 1/Ca                                                   |
| System Average Interruption Duration Index           :  SAIDI  =   12.426    h/Ca                                                  |
| Customer Average Interruption Duration Index         :  CAIDI  =    2.6145     h                                                    |
| Average Service Availability Index                   :  ASAI   =    0.9958929464                                                      |
| Average Service Unavailability Index                 :  ASUI   =    0.0041070536                                                      |
| Energy Not Supplied                                  :  ENS    =   16.218     MWh/a                                                 |
| Average Energy Not Supplied                          :  AENS   =    0.287     MWh/Ca                                                |
| Average Customer Curtailment Index                   :  ACCI   =    0.944     MWh/Ca                                                |
| Expected Interruption Cost                           :  EIC    =    0.774     M$/a                                                  |
| Interrupted Energy Assessment Rate                   :  IEAR   =   17.627     $/kWh                                                 |
| System energy shed                                   :  SES    =    0.000     MWh/a                                                 |
| Average System Interruption Frequency Index          :  ASIFI  =   3.769955 1/a                                                    |
| Average System Interruption Duration Index           :  ASIDI  =  13.134153 h/a                                                    |
| Momentary Average Interruption Frequency Index       :  MAIFI  =    0.000000 1/Ca                                                   |
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```

Figure 6: **Results of the system indices to obtain SAIDI for Configuration 3**

Configuration 4: Configuration 3 + Intellirupter Pulsecloser added at **LBS 4204**

Name	In Folder	Grid	Act.Pow. MW	Number of connec....	Tariff IntTariffenergy,Int.....	AID h	LPIT h/a	LPIF 1/a	LPENS MWh/a	ACIF 1/a	ACIT h/a	LPIC $/a	TCIT Ch/a	TMVAIF
A	A	Grid	4,2458	20		1,127442	10,71999	9,5082384	4,551491	9,508238	10,71999	97766,03	214,3997	5,305777
BRUYN (B)	BRUYN (B)	Grid	0,46	1		1,563972	3,098356	1,9810812	0,142524	1,981081	3,098356	3061,423	3,098356	2,758958
C	C	Grid	0,92	1		1,568848	3,114885	1,98546	0,286569	1,98546	3,114885	6155,512	3,114885	5,505747
D	D	Grid	0,115	2		2,100676	4,931978	2,3478057	0,056718	2,347806	4,931978	1218,297	9,863956	0,582003
E	E	Grid	0,529	12		2,822536	8,823637	3,1261374	0,46677	3,126137	8,823637	10026,23	105,8836	2,010653
F	F	Grid	0,138	3		2,431246	6,442664	2,6499429	0,088909	2,649943	6,442664	1909,76	19,32799	0,618774
G	G	Grid	0,98164	15		0,729943	3,360646	4,6039824	0,329894	4,603982	3,360646	7086,132	50,40968	2,533426
H	H	Grid	0,46	5		2,1999	5,347964	2,4310029	0,246006	2,431003	5,347964	5284,216	26,73982	2,24834
I	I	Grid	0,46	6		2,658552	7,728937	2,9071974	0,355531	2,907197	7,728937	7636,808	46,37362	1,880065
J	J	Grid	0,805	11		2,879707	9,245096	3,2104293	0,74423	3,210429	9,245096	15986,07	101,6961	2,979355
K	K	Grid	0,345	6		0,87929	3,272413	3,7216542	0,112898	3,721654	3,272413	2425,054	19,63448	1,10147
L	L	Grid	0,552	3		1,563972	3,098356	1,9810812	0,171029	1,981081	3,098356	3673,708	9,295067	3,31075
M	M	Grid	0,92	1		1,563972	3,098356	1,9810812	0,285049	1,981081	3,098356	6122,846	3,098356	5,517916

Figure 7: **Results of the load point indices for Configuration 4 from DIgSILENT**

The CIC calculation for different load points for Configuration 4 are shown in Figure 8 using equation **(9.1)**

Configuration 4								
Load	**λ(f/yr)**	**r(hrs)**	**U(hrs/yr)**	**Average Load (MW)**	**Average Load (kW)**	**Unserved Energy (kWh/yr)**	**COUE(R/kWh)**	**CIC(R/yr)**
A	9.508238	1.12744179	10.71998532	4.1535	4153.5	44525.45903	21.48	956406.8599
BRUYN (B)	1.981081	1.563971992	3.09835551	0.46	460	1425.243535	21.48	30614.23112
C	1.98546	1.568848267	3.11488548	0.9	900	2803.396932	21.48	60216.9661
D	2.347806	2.100675541	4.93197801	0.1125	112.5	554.8475261	21.48	11918.12486
E	3.126137	2.82253637	8.82363651	0.529	529	4667.703714	21.48	100262.2758
F	2.649943	2.431246353	6.44266401	0.138	138	889.0876334	21.48	19097.60237
G	4.603982	0.729943197	3.36064563	0.9603	960.3	3227.227998	21.48	69320.85741
H	2.431003	2.1999003	5.34796401	0.46	460	2460.063445	21.48	52842.16279
I	2.907197	2.65855236	7.72893651	0.46	460	3555.310795	21.48	76368.07587
J	3.210429	2.879707088	9.24509601	0.805	805	7442.302288	21.48	159860.6531
K	3.721654	0.879289863	3.27241281	0.345	345	1128.982419	21.48	24250.54237
L	1.981081	1.563971992	3.09835551	0.552	552	1710.292242	21.48	36737.07735
M	1.981081	1.563971992	3.09835551	0.92	920	2850.487069	21.48	61228.46225
Total Annual Cost of Interruption								**1659123.891**

Figure 8: **Calculations of the CIC for each load point - Annual cost of interruptions - Configuration 4**

Annual cost of interruptions of feeder for **Configuration 4** = R 1659123.89

Where: *$U = \lambda \times r$ and Unserved energy = U x Average load*

Utility cost for Configuration 4 includes Configuration 3:

Loss of income = R 0.8/kWh x 3618kVA x 0.92 x 7.13 (SAIDI) = R 18986.11
Investment cost for Intellirupter Pulsecloser = R 345600
Maintenance cost for Intellirupter Pulsecloser = 0
Labour cost = 10 % of investment cost for Intellirupter Pulsecloser = R 34560

Utility Cost = Loss of income + Investment cost + Maintenance cost + Operation cost

Utility cost = R 18986.11+ R 345600 + R 34560 + R 943814.18 = R 1342960.29

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|                                                          |  DIgSILENT   | Project:
|                                                          | PowerFactory |
|                                                          |   15.1.4     | Date:  6/30/2015
| Reliability Assessment
|   Method                                   Load flow analysis
|   Network                                  Distribution (Optimal Power Restoration)
|   Calculation time period                  2015
|   Consider Maintenance                     Yes
|   Fault Clearance Breakers                 Use all circuit breakers
|   Switching procedures                     Sequential
|   Consider Sectionalizing (Stages 1-3)     No
|   Time to open remote controlled switches  0.10 min.
|
| Automatic Contingency Definition
|   Selection                                Whole System
|   Busbars / terminals                      Yes         Common mode                        No
|   Lines / cables                           Yes         Independent second failures        No
|   Transformers                             Yes         Double earth faults                No
|                                                        Protection/switching failures      No
| Study Case: Study Case                                                  | Annex:           / 1
| System Summary
| System Average Interruption Frequency Index      :  SAIFI  =   4.752724  1/Ca
| Customer Average Interruption Frequency Index    :  CAIFI  =   4.752724  1/Ca
| System Average Interruption Duration Index       :  SAIDI  =    7.134    h/Ca
| Customer Average Interruption Duration Index     :  CAIDI  =    1.501    h
| Average Service Availability Index               :  ASAI   =    0.9991314654
| Average Service Unavailability Index             :  ASUI   =    0.0008685346
| Energy Not Supplied                              :  ENS    =    8.081    MWh/a
| Average Energy Not Supplied                      :  AENS   =    0.094    MWh/Ca
| Average Customer Curtailment Index               :  ACCI   =    0.192    MWh/Ca
| Expected Interruption Cost                       :  EIC    =    0.123    M$/a
| Interrupted Energy Assessment Rate               :  IEAR   =   15.217    $/kWh
| System energy shed                               :  SES    =    0.000    MWh/a
| Average System Interruption Frequency Index      :  ASIFI  =    3.769955 1/a
| Average System Interruption Duration Index       :  ASIDI  =    7.392628 h/a
| Momentary Average Interruption Frequency Index   :  MAIFI  =    0.000000 1/Ca
```

Figure 9: **Results of the system indices to obtain SAIDI for Configuration 4**

Appendix M: Last Fault Data – FuseSaver

Phase	DateTime	Name	Duration
A-RED	2014-12-19 14:47	Outage	0.418992
A-RED	2014-12-19 14:47	Line Current On	
A-RED	2014-12-19 14:47	Line Current Off	
C-BLU	2014-12-19 14:47	Outage	0.418991
C-BLU	2014-12-19 14:47	Line Current On	
C-BLU	2014-12-19 14:47	Line Current Off	
B-WHT	2014-12-19 14:47	Outage	0.418991
B-WHT	2014-12-19 14:47	Line Current On	
B-WHT	2014-12-19 14:47	Line Current Off	
A-RED	2014-12-08 10:00	Outage	0.419998
A-RED	2014-12-08 10:00	Line Current On	
A-RED	2014-12-08 10:00	Line Current Off	
C-BLU	2014-12-08 10:00	Outage	0.418991
C-BLU	2014-12-08 10:00	Line Current On	
C-BLU	2014-12-08 10:00	Line Current Off	
B-WHT	2014-12-08 10:00	Outage	0.418991
B-WHT	2014-12-08 10:00	Line Current On	
B-WHT	2014-12-08 10:00	Line Current Off	
C-BLU	2014-12-07 10:01	Outage	0.418991
C-BLU	2014-12-07 10:01	Line Current On	
C-BLU	2014-12-07 10:01	Line Current Off	
A-RED	2014-12-07 10:01	Outage	0.418991
A-RED	2014-12-07 10:01	Line Current On	
A-RED	2014-12-07 10:01	Line Current Off	
B-WHT	2014-12-07 10:01	Outage	0.418991
B-WHT	2014-12-07 10:01	Line Current On	
B-WHT	2014-12-07 10:01	Line Current Off	
C-BLU	2014-12-06 16:12	Outage	0.418991
C-BLU	2014-12-06 16:12	Line Current On	
C-BLU	2014-12-06 16:12	Line Current Off	
A-RED	2014-12-06 16:12	Outage	0.418991
A-RED	2014-12-06 16:12	Line Current On	
A-RED	2014-12-06 16:12	Line Current Off	
B-WHT	2014-12-06 16:12	Outage	0.418991
B-WHT	2014-12-06 16:12	Line Current On	
B-WHT	2014-12-06 16:12	Line Current Off	
B-WHT	2014-12-06 10:07	Outage	0.418991
B-WHT	2014-12-06 10:07	Line Current On	
B-WHT	2014-12-06 10:07	Line Current Off	
C-BLU	2014-12-06 10:07	Outage	0.418991
C-BLU	2014-12-06 10:07	Line Current On	
C-BLU	2014-12-06 10:07	Line Current Off	
A-RED	2014-12-06 10:07	Outage	0.418991
A-RED	2014-12-06 10:07	Line Current On	
A-RED	2014-12-06 10:07	Line Current Off	
C-BLU	2014-12-05 13:31	Outage	0.418991
C-BLU	2014-12-05 13:31	Line Current On	
C-BLU	2014-12-05 13:31	Line Current Off	
A-RED	2014-12-05 13:31	Outage	0.418991
A-RED	2014-12-05 13:31	Line Current On	
A-RED	2014-12-05 13:31	Line Current Off	
B-WHT	2014-12-05 13:31	Outage	0.418991
B-WHT	2014-12-05 13:31	Line Current On	
B-WHT	2014-12-05 13:31	Line Current Off	
B-WHT	2014-11-29 10:04	Outage	0.418991
B-WHT	2014-11-29 10:04	Line Current On	
B-WHT	2014-11-29 10:04	Line Current Off	
C-BLU	2014-11-29 10:04	Outage	0.418991
C-BLU	2014-11-29 10:04	Line Current On	
C-BLU	2014-11-29 10:04	Line Current Off	
A-RED	2014-11-29 10:04	Outage	0.418991
A-RED	2014-11-29 10:04	Line Current On	
A-RED	2014-11-29 10:04	Line Current Off	
C-BLU	2014-11-26 17:36	Outage	0.418991
C-BLU	2014-11-26 17:36	Line Current On	
C-BLU	2014-11-26 17:36	Line Current Off	
B-WHT	2014-11-26 17:36	Outage	0.418991
B-WHT	2014-11-26 17:36	Line Current On	
B-WHT	2014-11-26 17:36	Line Current Off	
A-RED	2014-11-26 17:36	Outage	0.418991
A-RED	2014-11-26 17:36	Line Current On	
A-RED	2014-11-26 17:36	Line Current Off	
C-BLU	2014-11-22 10:00	Outage	0.418991
C-BLU	2014-11-22 10:00	Line Current On	
C-BLU	2014-11-22 10:00	Line Current Off	
A-RED	2014-11-22 10:00	Outage	0.418991
A-RED	2014-11-22 10:00	Line Current On	
A-RED	2014-11-22 10:00	Line Current Off	
B-WHT	2014-11-22 10:00	Outage	0.418991
B-WHT	2014-11-22 10:00	Line Current On	
B-WHT	2014-11-22 10:00	Line Current Off	
A-RED	2014-11-02 10:02	Outage	0.418991
A-RED	2014-11-02 10:02	Line Current On	
A-RED	2014-11-02 10:02	Line Current Off	
B-WHT	2014-11-02 10:02	Outage	0.418991
B-WHT	2014-11-02 10:02	Line Current On	
B-WHT	2014-11-02 10:02	Line Current Off	
C-BLU	2014-11-02 10:02	Outage	0.418992
C-BLU	2014-11-02 10:02	Line Current On	
C-BLU	2014-11-02 10:02	Line Current Off	

Appendix N: Network Reliability Equivalent for Distribution Test System Feeder (RBTS Bus 6) Feeder 4 and Waterkloof Farmers 1 11 kV

Distribution Test system (RBTS Bus 6) Feeder 4

Customer Data, Feeder Types and Lengths

Customer Data [60]

Number of Load Points	*Load Points*	*Customer Type*	*Load Level per Load Point, MW*		*Number of Customers*
			Peak	*Average*	
Bus 6					
3	1 3 9	residential	0.3171	0.1775	138
4	2 4 11 19	residential	0.3229	0.1808	126
2	5 6	residential	0.3864	0.2163	118
5	7 8 10 18 23	residential	0.2964	0.1659	147
3	12 13 22	residential	0.3698	0.2070	132
4	25 28 31 36	residential	0.2776	0.1554	79
4	27 29 33 39	residential	0.2831	0.1585	76
2	14 17	commercial	0.8500	0.4697	10
1	15	small	1.9670	1.6391	1
1	16	small	1.0830	0.9025	1
2	32 37	farm	0.5025	0.1929	1
3	20 30 34	farm	0.6517	0.2501	1
2	21 35	farm	0.6860	0.2633	1
2	24 40	farm	0.7965	0.3057	1
2	26 38	farm	0.7375	0.2831	1
Total			***20.0000***	***10.7155***	***2938***

Feeder Types and Lengths [60]

Feeder Type	*Length (km)*	*Feeder Section Numbers*
Bus 6		
1	*0.6*	*2 3 8 9 12 13 17 19 20 24 25 28 31 34 41 47*
2	*0.75*	*1 5 6 7 10 14 15 22 23 26 27 30 33 43 61*
3	*0.8*	*4 11 16 18 21 29 32 35 55*
4	*0.9*	*38 44*
5	*1.6*	*37 39 42 49 54 62*
6	*2.5*	*36 40 52 57 60*
7	*2.8*	*35 46 50 56 59 64*
8	*3.2*	*45 51 53 58 63*
9	*3.5*	*48*

Main section data, Line: Λ = 0.065 (f/km.yr)

Main Section	Length (km)	λ(f/yr)	r(hrs)	s(hrs)	Line: λ = 0,065 (f/km.yr)
35	0.8	0.052	5	1	
36	2.5	0.1625	5	1	
37	1.6	0.104	5	1	
38	0.9	0.0585	5	1	
39	1.6	0.104	5	1	
40	2.5	0.1625	5	1	
42	1.6	0.104	5	1	
44	0.9	0.0585	5	1	
45	3.2	0.208	5	1	
46	2.8	0.182	5	1	
48	3.5	0.2275	5	1	
49	1.6	0.104	5	1	
59	2.8	0.182	5	1	
59	2.8	0.182	5	1	

Lateral Section, Sub-Feeders and Transformer Data

Component Sections	Length (km)	λ(f/yr)	r(hrs)	s(hrs)	Line: λ = 0,065 (f/km.yr)
41	0.6	0.039	5	1	
43	0.75	0.04875	5	1	
47	0.6	0.039	5	1	
F5	13.3	0.8645	5	1	
F6	8.5	0.5525	5	1	
F7	12.9	0.8385	5	1	
Transformers		0.015	10	1	

Number of customers

LOAD POINTS	Number of Customers
LP18	147
LP19	126
LP20	1
LP21	1
LP22	132
LP23	147
LP24	1
LP25	79
LP26	1
LP27	76
Reliability-network equivalent - Feeder 5	158
Reliability-network equivalent - Feeder 6	156
Reliability-network equivalent - Feeder 7	158
Total	**1183**

Data for the lateral sections, Bus 6

Node	Lateral Section (i)	Fuse	Transf	Failure Rate of Lateral section λL (occ./yr)	Repair Time for lateral section RL (hr)	Switching Time Rs (hr)	Failure Rate of Transformer λT (occ/yr)	Repair time for Transformer RT (hr)
1	1	1	1	0.039	5	1	0.015	10
2	2	1	1	0.052	5	1	0.015	10
3	3	1	1	0.04875	5	1	0.015	10
4	4	1	1	0.039	5	1	0.015	10
5	5	1	1	0.04875	5	1	0.015	10
6	6	1	1	0.039	5	1	0.015	10
7	7	1	1	0.04875	5	1	0.015	10
8	8	1	1	0.052	5	1	0.015	10
9	9	1	1	0.052	5	1	0.015	10
10	10	1	1	0.039	5	1	0.015	10
11	11	1	1	0.04875	5	1	0.015	10
12	12	1	1	0.039	5	1	0.015	10
13	13	1	1	0.04875	5	1	0.015	10
14	14	1	0	0.039	5	1	0	0
15	15	1	0	0.04875	5	1	0	0
16	16	1	0	0.052	5	1	0	0
17	17	1	0	0.039	5	1	0	0
18	18	1	1	0	0	1	0.015	10
19	19	1	1	0	0	1	0.015	10
20	20	1	1	0	0	1	0.015	10
21	21	1	1	0	0	1	0.015	10
22	22	1	1	0	0	1	0.015	10
23	23	1	1	0.039	5	1	0.015	10
24	24	1	1	0.04875	5	1	0.015	10
26	25	1	1	0	0	1	0.015	10
27	26	1	1	0.039	5	1	0.015	10
28	27	1	1	0	0	1	0.015	10
30	28	1	1	0	0	1	0.015	10
31	29	1	1	0	0	1	0.015	10
32	30	1	1	0	0	1	0.015	10
33	31	1	1	0	0	1	0.015	10
34	32	1	1	0.052	5	1	0.015	10
35	33	1	1	0	0	1	0.015	10
36	34	1	1	0	0	1	0.015	10
37	35	1	1	0	0	1	0.015	10
38	36	1	1	0	0	1	0.015	10
39	37	1	1	0.04875	5	1	0.015	10
40	38	1	1	0	0	1	0.015	10
41	39	1	1	0	0	1	0.015	10
42	40	1	1	0	0	1	0.015	10

Data for the load points, Bus 6

Load Point	Node	Lateral Section	Load (MW)	NumCust	Type
1	1	1	0.3171	138	R
2	2	2	0.3229	126	R
3	3	3	0.3171	138	R
4	4	4	0.3229	126	R
5	5	5	0.3864	118	R
6	6	6	0.3864	118	R
7	7	7	0.2964	147	R
8	8	8	0.2964	147	R
9	9	9	0.3171	138	R
10	10	10	0.2964	147	R
11	11	11	0.3229	126	R
12	12	12	0.3698	132	R
13	13	13	0.3698	132	R
14	14	14	0.8500	10	C
15	15	15	1.9670	1	I
16	16	16	1.0830	1	I
17	17	17	0.8500	10	C
18	18	18	0.2964	147	R
19	19	19	0.3229	126	R
20	20	20	0.6517	1	A
21	21	21	0.6860	1	A
22	22	22	0.3698	132	R
23	23	23	0.2964	147	R
24	24	24	0.7965	1	A
30	32	30	0.6517	1	A
31	33	31	0.2776	79	R
32	34	32	0.5025	1	A
33	35	33	0.2831	76	R
34	36	34	0.6517	1	A
35	37	35	0.6860	1	A
36	38	36	0.2776	79	R
37	39	37	0.5025	1	A
38	40	38	0.7375	1	A
39	41	39	0.2831	76	R
40	42	40	0.7965	1	A

Where,
R = Residential customers
A = Agricultural customers
C = Commercial customers
I = Industrial customers

Comparison of load point indices for Bus 6

Load Point (i)	Failure Rate (Occ./yr)		Ave. Repair Time (hr/Occ.)		Unavailability (hr/yr)	
	(A)	(S)	(A)	(S)	(A)	(S)
1	0.33010	0.33162	2.47168	2.45385	0.81590	0.81375
2	0.34310	0.34388	2.45439	2.44876	0.84210	0.84208
3	0.33985	0.34284	2.54421	2.56967	0.86465	0.88099
4	0.33010	0.33382	2.47168	2.48771	0.81590	0.83045
5	0.33985	0.34126	2.43004	2.44324	0.82585	0.83378
6	0.33010	0.33300	2.51166	2.47339	0.82910	0.82364
7	0.36915	0.37024	2.31654	2.34894	0.85515	0.86967
8	0.37240	0.37072	2.44415	2.44042	0.91020	0.90471
9	0.37240	0.37142	2.33996	2.33755	0.87140	0.86821
10	0.35940	0.35854	2.24374	2.25329	0.80640	0.80789
11	0.36915	0.36974	2.45740	2.47989	0.90715	0.91691
12	0.35940	0.35844	2.35170	2.36412	0.84520	0.84740
13	0.36915	0.36816	2.31654	2.32934	0.85515	0.85757
14	0.22740	0.22864	2.54266	2.60060	0.57820	0.59460
15	0.23715	0.23622	3.52077	3.56628	0.83495	0.84243
16	0.24040	0.23970	4.18968	4.23888	1.00720	1.01606
17	0.22740	0.22702	5.00000	5.00907	1.13700	1.13716
18	1.67250	1.67376	3.31928	3.31656	5.55150	5.55113
19	1.67250	1.67356	3.31928	3.31285	5.55150	5.54425
20	1.67250	1.67278	3.31928	3.31078	5.55150	5.53821
21	1.67250	1.67376	3.31928	3.32237	5.55150	5.56085
22	1.67250	1.67344	3.31928	3.31169	5.55150	5.54191
23	1.71150	1.71422	3.35758	3.35375	5.74650	5.74907
24	1.72125	1.72302	3.36688	3.36085	5.79525	5.79081
25	1.67250	1.67366	5.04484	5.05702	8.43750	8.46374
26	1.71150	1.71146	5.04382	5.06023	8.63250	8.66038
27	1.67250	1.67370	5.04484	5.05654	8.43750	8.46313
28	2.22500	2.22838	5.03371	5.03971	11.20000	11.23040
29	2.22500	2.22912	5.03371	5.04401	11.20000	11.24370
30	2.22500	2.23090	5.03371	5.04572	11.20000	11.25650
31	2.53700	2.53782	3.89200	3.88528	9.87400	9.86014
32	2.58900	2.58776	3.91425	3.90164	10.13400	10.09650
33	2.52200	2.53672	3.85567	3.87980	9.72400	9.84197
34	2.52200	2.53562	3.85567	3.88120	9.72400	9.84124
35	2.52200	2.53628	3.85567	3.87767	9.72400	9.83486
36	2.51100	2.51708	5.02987	5.02658	12.63000	12.65230
37	2.55975	2.56686	5.02930	5.03432	12.87375	12.92240
38	2.49600	2.51728	5.00000	5.03099	12.48000	12.66440
39	2.51100	2.51750	5.02987	5.03174	12.63000	12.66740
40	2.49600	2.51702	5.00000	5.02880	12.48000	12.65760

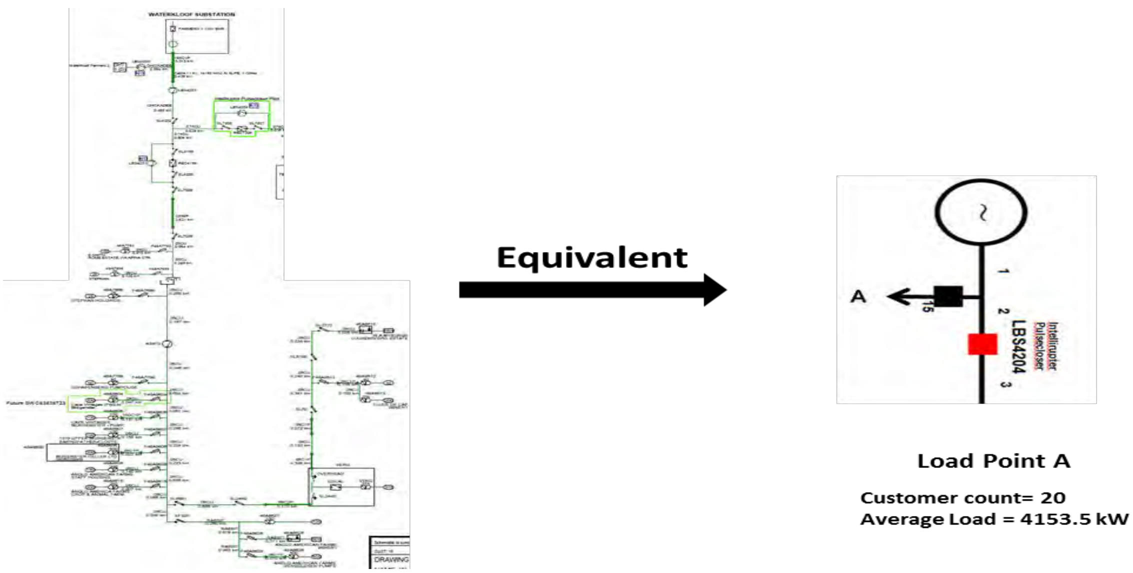
Comparison of system indices for Bus 6

		Feeder 1	Feeder 2	Feeder 3	Feeder 4	System
SAIFI	(A)	0.335511	0.367299	0.228434	1.976799	1.006066
	(S)	0.337655	0.366951	0.228845	1.979710	1.007680
SAIDI	(A)	0.832602	0.863826	0.863370	8.214516	3.815494
	(S)	0.836577	0.865891	0.869573	8.234640	3.825360
CAIDI	(A)	2.481594	2.351836	3.779517	4.155464	3.792490
	(S)	2.477609	2.359691	3.799834	4.159518	3.796205

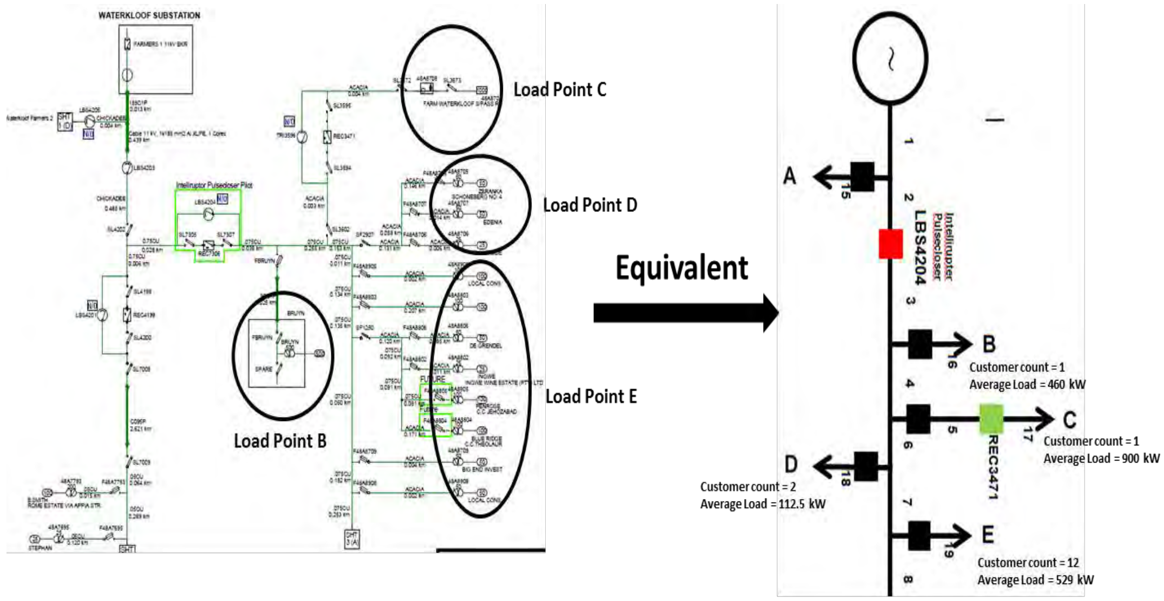
<u>Waterkloof Farmers 1 11 kV Feeder</u>

The successive lateral section equivalents for Waterkloof Farmers 1 11kV Feeder are shown below.

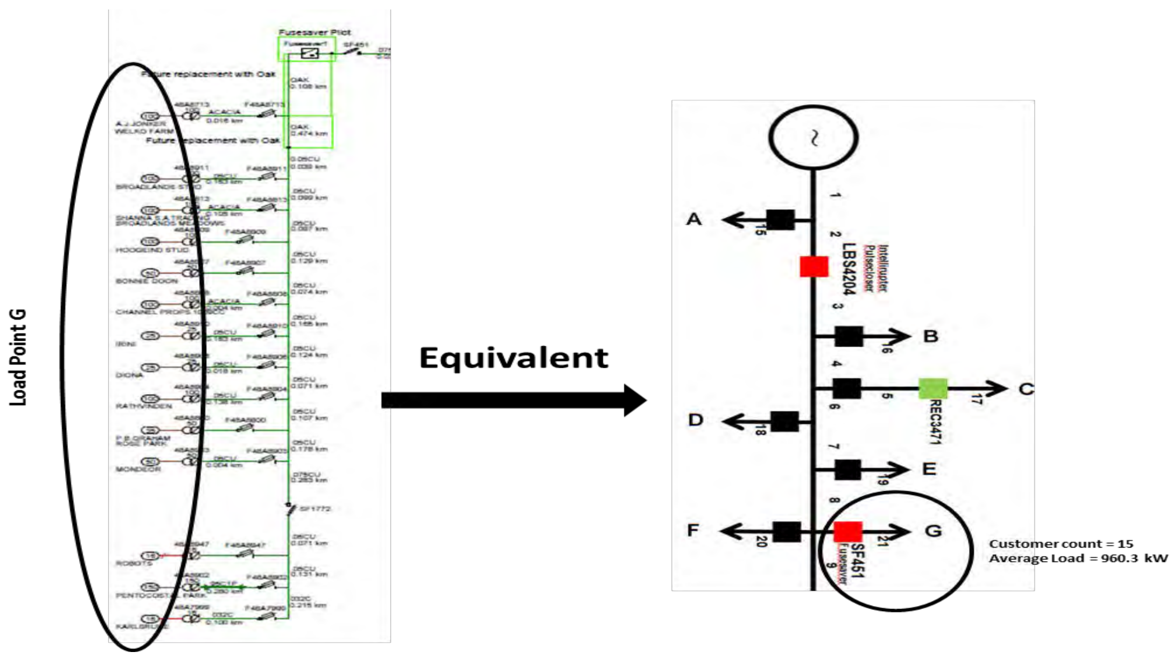
Load Point A



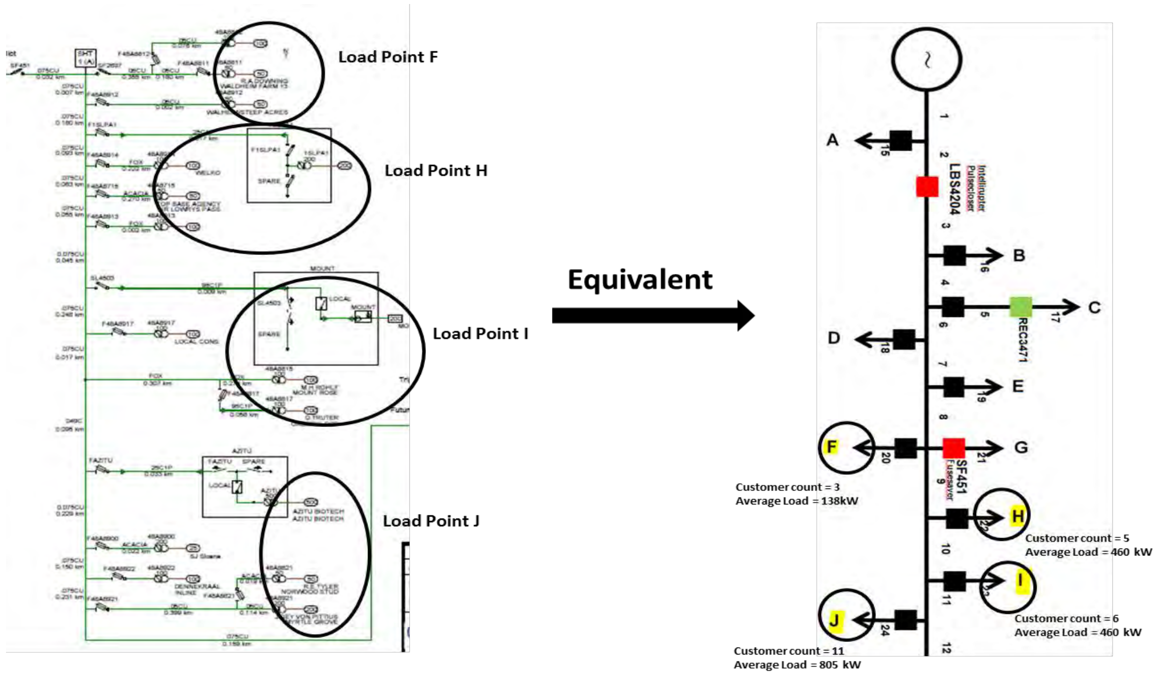
Load Points B, C, D and E



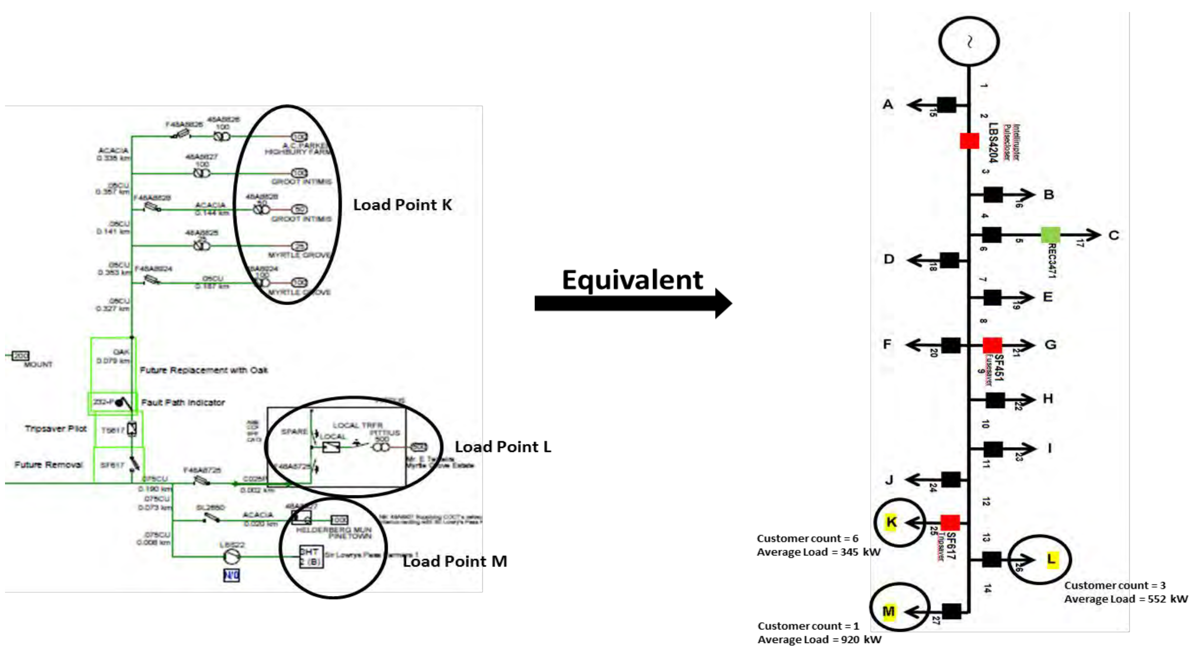
Load Point G



Load Points F, H, I and J

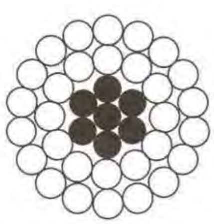
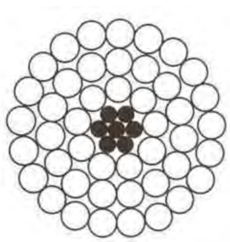


Load Points K, L and M



Appendix O: Conductor Reference Table

ACSR

Physical representation	Name	Current Rating (A) 50°C	Current Rating (A) 70°C	Overall diameter (mm)	Total area (mm^2)	Stranding & wire diameter (mm)	Unit weight (N/m)	UTS (kN)
 3Al/4St	Magpie	33	58	6.35	24.71	3/4/2.118	1.40	18.57
	Squirrel	106	149	6.33	24.48	6/1/2.11	0.84	8.02
	Fox	148	210	8.37	42.80	6/1/2.79	1.46	13.10
	Rabbit	186	-	10.05	61.70	6/1/3.35	2.10	18.5
6Al/1St	Mink	209	297	10.98	73.65	6/1/3.66	2.52	21.90
	Raccoon	238	-	12.27	91.97	6/1/4.09	3.14	27.20
	Hare	292	408	14.16	122.48	6/1/4.72	4.19	36.00
	Chickadee	433	625	18.87	212.09	18/1/3.77	6.31	44.90
18Al/1St	Kingbird	590	855	23.88	340.96	18/1/4.78	10.08	69.80
	Wolf	378	548	18.13	194.94	30/7/2.59	7.16	69.20
	Bear	529	770	23.45	326.12	30/7/3.35	11.97	112.00
30Al/7St	Goat	607	884	25.97	399.98	30/7/3.71	14.72	136.00
 45Al/7St	Tern	611	911	27.00	431.60	45/3.38 + 7/2.25	13.15	98.70

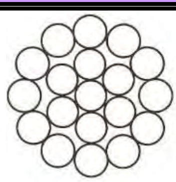
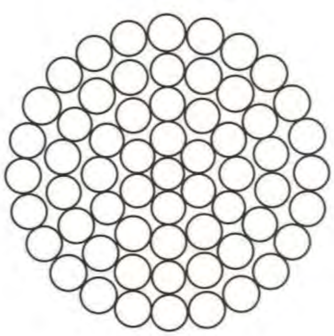
ACAR

Physical representation	Name	Current Rating (A) 50°C	Current Rating (A) 70°C	Overall diameter (mm)	Total area (mm^2)	Stranding & wire diameter (mm)	Unit weight (N/m)	UTS (kN)
12Al/7St	Code 250	-	-	21.00	264.49	12/7/4.21	7.13	63.92

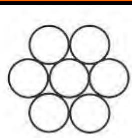
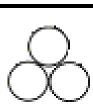
AAAC

Physical representation	Name	Current Rating (A)		Overall diameter (mm)	Total area (mm^2)	Stranding & wire diameter (mm)	Unit weight (N/m)	UTS (kN)
		50°C	70°C					
 7Al	Acacia	114	160	6.24	23.79	7/2.08	0.65	6.69
	35	163	229	8.31	42.18	7/2.77	1.13	11.86
	Pine	227	320	10.83	71.65	7/3.61	1.92	20.20
	Oak	312	443	13.95	118.90	7/4.65	3.19	33.33
 37Al	Sycamore	583	829	22.61	303.20	37/3.23	8.19	85.00
	Upas	557	740	24.71	362.10	37/3.53	9.78	101.67

AAC

Physical representation	Name	Current Rating (A) 50°C	Current Rating (A) 70°C	Overall diameter (mm)	Total area (mm^2)	Stranding & wire diameter (mm)	Unit weight (N/m)	UTS (kN)
 19Al	Hornet	-	-	16.25	157.62	19/3.25	4.27	26.00
c.f. above	Centipede	-	-	26.46	415.22	37/3.78	11.28	67.20
 61Al	Bull	-	-	38.25	865.36	61/4.24	23.54	139.00

Cu

Physical representation	Name	Current Rating(A) at 50°C	Overall diameter (mm)	Total area (mm^2)	Stranding & wire diameter (mm)	Unit weight (N/m)	UTS (kN)	Replacement conductor (greased)
 7Cu	0.15 Cu	352.2	12.63	97.44	7/4.21	8.59	38.0	Chickadee
	0.1 Cu	279.9	10.36	65.60	7/3.45	5.77	26.1	Oak
	0.06 Cu	197	7.92	38.36	7/2.64	3.37	15.7	Pine
	0.075 Cu		8.84	47.73	7/2.95	4.20	19.4	Oak
 3Cu	0.05 Cu	188	8.04	32.85	3/3.73	2.89	12.9	Pine
	0.025 Cu	124.1	5.67	16.44	3/2.64	1.45	6.8	35

Appendix P: Planning and Designing of Intellirupter Pulsecloser Structure, FuseSaver and Tripsaver

Structure of Drawings

A special structure was designed and planned for the Intellirupter Pulsecloser. Visual 400 A isolating links was designed on either side of the Intellirupter for the incoming and outgoing solid cut-outs isolation purposes. A load break switch was included in the design as a by-pass in the event of mal-functioning of the devise.

The structure was made up of

- Strain A- Frame or Delta Wood X- Arm
- Bypass (Load Break Switch)
- Intellirupter Pulsecloser
- Jumpers to be Covered
- Pole 9m Min. 160mm Top Diameter
- Pole 12m Min. 180mm Top Diameter for conductors up to Mink
- Pole 12m 200mm Top Diameter for bigger conductors.
- Make use of 400 A links for the incoming and outgoing solid cut-outs
- Support centre Intellirupter Pulsecloser jumpers with post insulator.
- Use top groove ties attach jumpers to insulator
- Special anti-climbing device is required in high risk areas.

Figure 1 explains the structure of the Intellirupter Pulsecloser.

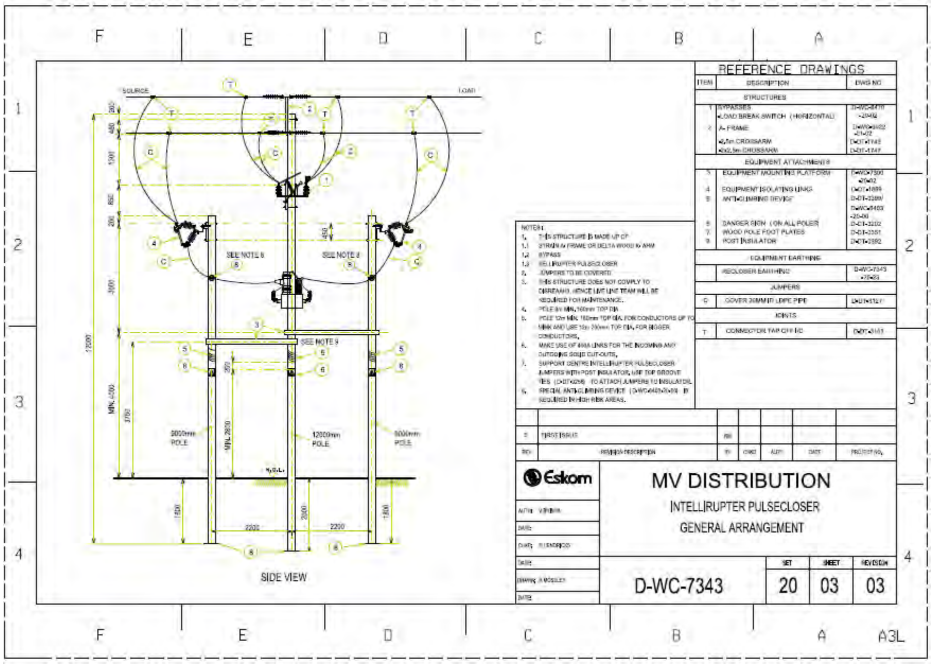


Figure 1: **Intellirupter Pulsecloser Structure [6]**

Designing and Planning of the ENS drawing for the Pilot feeder

The Intelliruptor Pulsecloser, Tripsaver, FuseSaver and Fault Path Indicators were added to the locations indicated on the drawings below:

Intellirupter Pulsecloser at Existing LBS4204

The physical operation of the Pulsecloser is basically similar to that of a recloser, therefore the Intellirupter and two sets of links were added at the existing LBS4204 and the normal recloser symbols were used for Intelliruptor. A short note "Intelliruptor Pulsecloser" Pilot was included on the drawing.

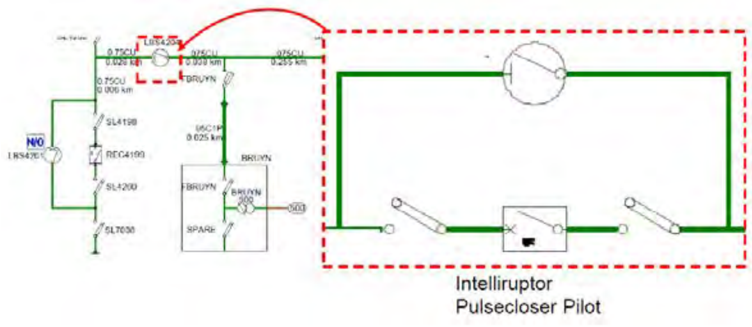


Figure 2: **Intelliruptor Pulsecloser symbol on ENS**

Tripsaver at SF617

The Tripsaver also drops out the same way a fuse does, and for operating purposes it can be opened in the same way as a fuse. The SF617 was replaced with a symbol for rackable breaker and the note "Tripsaver Pilot" was added to the drawing.

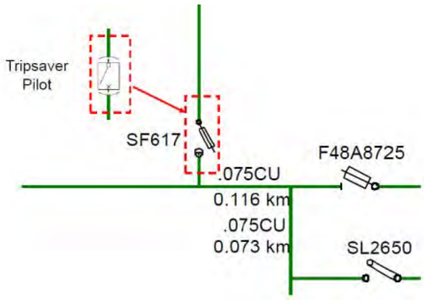


Figure 3: **The Tripsaver symbol on ENS**

FuseSaver at SF451

The FuseSaver is basically a breaker and hence it can also be indicated as a recloser symbol with a note. The Recloser symbol was included directly after SF451 (use same coordinates as SF451) and the note: "FuseSaver Pilot" was included on the drawing.

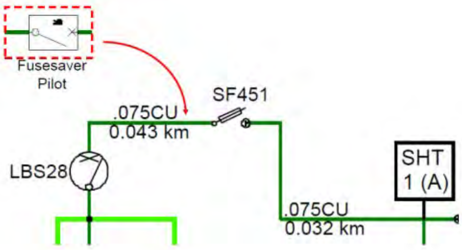


Figure 4: **The FuseSaver symbol on ENS**

Appendix Q: Installation – Tripsavers and FPI's

Figure 1: **Overhead crew members from Eskom Western Cape Operating Unit distribution, install a Tripsaver Dropout Recloser as part of the pilot project – Waterkloof F1 11 kV Feeder**

Figure 2: **Workmen ready to close a Tripsaver into an operational circuit**