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Investigation into the Issues Associated with closing an automated Normally Open (N/O) point on three Medium Voltage (MV) Networks where Fault Location, Isolation and Service Restoration (FLISR) is planned

Dissertation

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Abstract

The design of Medium Voltage (MV) Overhead Lines (OHLs) in the electricity distribution industry is often radial in nature which makes back-feeding difficult and these networks are often long which increases their exposure to faults. This has resulted in poor network reliability. Customers are mainly affected by faults on the MV network, to which particular attention has to be paid. Permanent faults have negative impact on customers since they experience outages or interruptions. The impact on customers increases when these outages are long. The network reliability is reducing and the cost to customers is increasing. Customers are demanding higher levels of quality of supply from the distribution network. As the global energy study is working on achieving the seventh Sustainable Development Goal (SDG 7), it is important to have a reliable power supply to improve socioeconomic development to customers and this will be a stepping stone in achieving other SDGs. Digitalization is one of the factors affecting electricity networks towards a clean energy future and automatic service restoration is one of the most important strategies for Distribution Automation (DA). Therefore it is necessary to implement self-healing Smart Grid technologies. One such solution is Fault Location, Isolation and Service Restoration (FLISR). The main drive towards FLISR is to improve Eskom's network performance, improve electricity sales, flexibility and accessibility and reduce impact on the economy of outages as well as to support trends towards a more sustainable energy supply. This research investigates various ways to implement FLISR and it focuses on case studies on real distribution networks and looks at the issues associated with closing a remotely controlled or automatically operated Normally Open (N/O) point for back-feeding. The complete algorithm and procedure of auto-restoration are discussed. The results on case studies discussed in this dissertation show that a remotely controlled N/O point can be installed without constraining the network to reduce restoration time following a fault. This is assured by not violating network's electrical requirements such as voltage levels and feeder thermal loading.

Declaration

I declare that this dissertation is my own work except as indicated in the references and acknowledgements. It is submitted in fulfilment of the requirements for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Signed at University of the Witwatersrand, Johannesburg

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List of Abbreviations

Abbreviation/ Acronym	Description
FLISR	Fault Location, Isolation and Service Restoration
N/O	Normally Open
MV	Medium Voltage
LV	Low Voltage
SDG	Sustainable Development Goal
OHL	Overhead Line
DA	Distribution Automation
DG	Distributed Generation
MOU	Mpumalanga Operating Unit
RTU	Remote Terminal Unit
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
KPI	Key Performance Indicator
IBR	Incentive Based Regulation
NERSA	National Energy Regulator of South Africa
SCADA	System Control And Data Acquisition
ARC	Automatic Reclosing
FPI	Fault Path Indicator
DMS	Distribution Management System
AMS	Advanced Metering System
OMS	Outage Management System
GIS	Geographic Information System
ORHVS	Operation Regulation of High Voltage System
NRS	National Rationalised Specification
MVA	Mega-ampere (unit of apparent power)
kVA	kilovolt-ampere (unit of apparent power)
kV	kilovolt (unit of voltage)
PEM	Project Evaluation Model

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1. Introduction

1.1. Background

A smart grid aims to perform automated action in restoring power back to customers after an unplanned outage has occurred. This feature of the system is also known as self-healing. Self-healing performs self-adjustments during the abnormal operation state and performs self-restoration to the customers by identifying and reacting to the interruption with minimal human intervention. The objective of self-healing is to restore supply to customers, making the system highly dependable, reliable and efficient. There are still many faults occurring in distribution systems due to various factors such as lightning and trees on the line. These faults will cause short-term to long-term power outages for customers and may lead to significant inconvenience and economic losses. There is therefore a need for fast detecting, isolating and repairing these faults to have and maintain reliable power system operation. Thus the concept of a self-healing power grid gains more recognition as a solution to mitigate inconvenience and economic losses caused by interruptions in the power grid.

A Fault Location, Isolation and Service Restoration (FLISR) tool is an important technology to implement self-healing. This involves self-reconfiguration of MV feeders when a fault occurs on a certain section of a feeder. FLISR will help in reducing the impact of a fault on customers, thereby improving network performance. Numerous technologies, such as fault detection, communication, protective relaying and remote control are involved in feeder automation. Self-healing schemes operate without or with limited Network Control (manual remote control) and Work Team (manual local control) intervention. FLISR quickly restores supply to customers on unfaulted sections of the feeder that lie beyond the faulted section, long before Work Teams arrive on site to locate the fault. For FLISR to restore supply to unfaulted sections of the feeder there is a need for the feeder to have multiple sources of supply. It is important to note that FLISR does not avoid outages but reduces their impact on customers when they do occur. Automated fault location and fault isolation are relatively easy to achieve. However, automated supply restoration has many obstacles and a lot of research has been done in this area [1], however technical and non-technical issues associated with automatic restoration have not been covered. This dissertation will also focus on those issues.

Whenever faults occur in distribution networks the affected part of the system has to be isolated. During this course of action, healthy parts of the system get de-energized. Service restoration is used to restore supply to those customers who lose supply. As the size of the network increases, the problem faced by Work Teams increases. Restoring supply in less time is the main challenge. More effective restoration plans are necessary for these large and complex networks. Initially the main objective of restoration was to restore supply to customers as soon as possible, but with increasing size and complexity of networks, objectives like minimization of power loss, minimization of extent of out-of-service area were also included in later research work with electrical and topological constraints. Now, the penetration of Distributed Generation (DG) is increasing in networks, because of its important benefits of use of renewable energy sources to generate electricity, enhancement of power quality and reliability, cost reduction and power loss minimization. Various new methods and software have been developed for testing and deploying system restoration strategies for distribution networks [2].

Service restoration can be treated as a temporary system reconfiguration problem, which is done by changing the status of switches present in the system. These switches are sectionalizing switches (normally closed) and tie switches (normally open). The service restoration problem is an optimization problem because of the presence of a very large number of switches in the system. With conventional methods like load flow, it is impossible to perform all of the calculations related to each of the switching sequences. So the final objective of service restoration is to find optimal switching sequences for the network [2]. This dissertation presents an approach to performing autonomous power restoration on a mesh distribution network. In this approach, a solution is developed to close the N/O points remotely. It discusses safety measures that must be taken to prevent damage to human and equipment before closing a N/O point remotely. Chapter 1 is an introduction detailing the content of the report, research questions, proposed research and expected deliverables. Chapter 2 discusses the Distribution network reliability, the benefits of the FLISR towards electricity utilities and the FLISR module. It elaborates on the equipment needed for the functionality of the FLISR, the FLISR process and the FLISR architectures. The main focus of this report is discussed on Chapter 3, the automatic supply restoration which proposed the algorithm to be followed when remotely closing the N/O point. Thereafter, the issues associated with closing a remotely controlled N/O point are discussed on Chapter 4. Case studies are introduced and performed on chapter 5 and 6 respectively to introduce the automatic supply restoration on real MV Distribution networks. Chapter 7 then concludes the investigation and also gives considerations to future work.

1.2. Research Questions

The main research question associated with this research project is:

When planning FLISR on MV networks, what are the issues (technical and non-technical) associated with closing N/O points remotely?

The above main research question will be addressed through consideration of each of the following secondary research questions:

1. What data or information is needed before closing a N/O point remotely?
2. Assuming the above data or information is available, under what conditions would closing the N/O point not be allowed?
3. What simulation studies should be done to decide on whether closing a N/O point remotely is allowed or not allowed?

Issues related to closing N/O points will be discussed and automated N/O points will be modeled, simulated and implemented on two overhead MV feeders and one underground MV cable feeder.

1.3. Scope and Limitations

The outcomes of this research will be to install automated N/O points to implement FLISR on two poorly performing rural feeders and on a poorly performing urban cable ring in Eskom's distribution network.

Proposed Research:

- Investigation into the data, equipment and network characteristics required to implement FLISR.
    - Investigating the issues associated with closing N/O points remotely.
    - Implementing FLISR on three real feeders in the Mpumalanga Operating Unit (MOU) so that the issues associated with closing N/O points remotely can be investigated.

Expected Deliverables:

- Implementation of FLISR on two poorly performing overhead MV feeders and on an urban cable ring network in Eskom.

2. Fault Location, Isolation and Service Restoration

2.1. Introduction to FLISR

FLISR aims to reduce the duration of outages, frequency of outages and operational expenditure while improving overall network performance. The electrical distribution network is affected periodically by faults on some of its elements (such as the lines and transformers). While the presence of automation within the distribution network, such as circuit breakers, automatic reclosers and remotely operated switches can eliminate certain faults automatically, other faults require operator intervention, which can cause several hours of downtime.

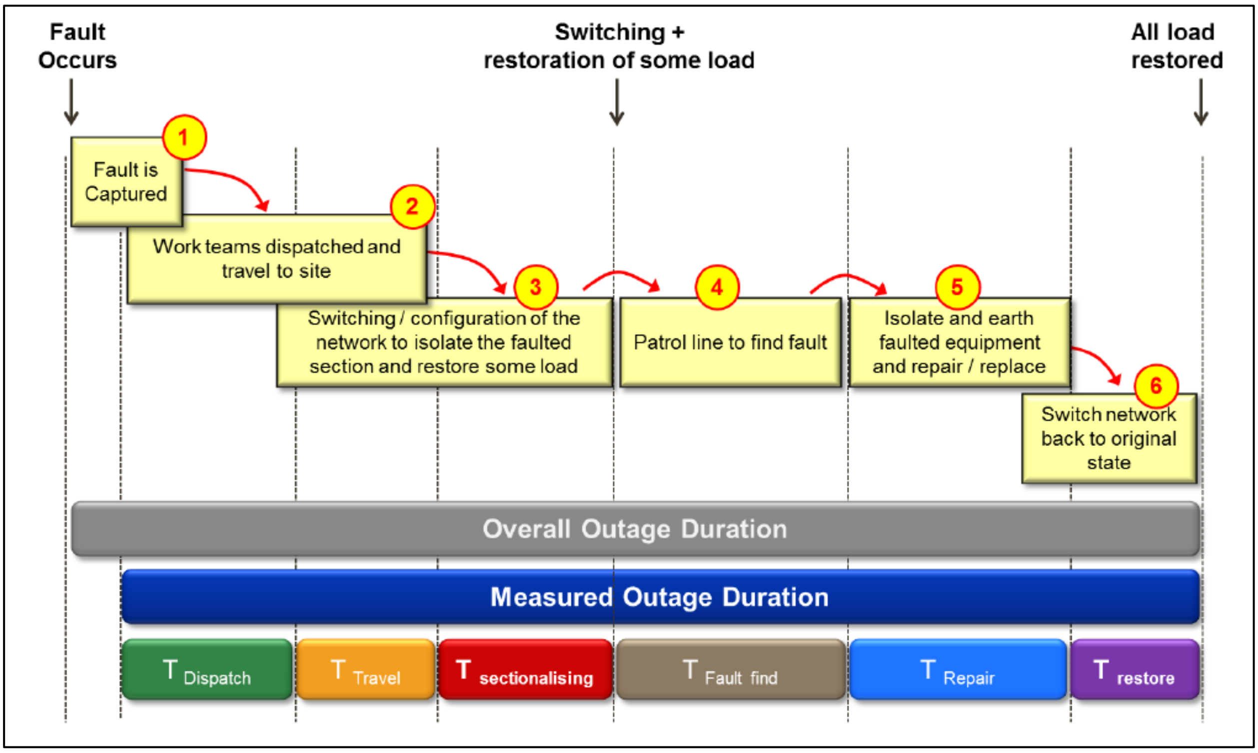

Figure 2.1: Process to restore supply after a fault has occurred [3]

Currently, restoration takes a long time because switching operations are done manually. When a fault occurs and customers experience supply loss, they phone and report the outage. The Network Controller from the control centre then dispatches a Work Team to the field. The Work Team determines the fault location and then implements the switching to isolate the faulted section and restore supply to quickly restorable customers as seen on Figure 2.1. This practice for supply restoration normally takes several hours to complete, depending on how quickly customers report the supply outage and how quickly the Work Team can locate the fault point and perform the power restoration [1]. When a fault occurs, the restoration time is divided into:

- **Time to dispatch the Work Team**: The time for a call to be logged onto the system through a customer reporting an interruption or through Remote Terminal Unit (RTU) alarms and the Work Team is advised about the fault.
- **Time for the Work Team to travel to site**
- **Time to sectionalise the portion of the feeder with a fault**: The Work Team performs switching (opening and closing of breakers and disconnectors) at different locations along the network with the aim of isolating the faulted part of the network. Customers are partially restored during this period through back-feeding and network reconfiguration.

- **Time to find a fault:** After isolation of the faulted section, the Work Team then performs visual inspection with the aim to identify the faulted equipment.
- **Time to repair the fault**
- **Time to restore supply:** After replacing or repairing the faulted equipment the network is returned to its original state.

This extends the outage time and thereby increases the duration that customers are without supply i.e. increasing the System Average Interruption Duration Index (SAIDI – see section 2.2 below). If the time between repairs and switching can be reduced, then the outage duration will also be reduced resulting in a lower SAIDI and increased customer satisfaction. With the implementation of FLISR, the Work Teams do not need to visit the apparatus or switchgear for switching and therefore the travel time is reduced. FLISR will remotely locate the fault, isolate the fault and restore supply to quickly restorable customers within the duration of less than three minutes so that the interruption to the quickly restorable customers does not increase the SAIDI (interruptions of less than three minutes are excluded from the calculation of the SAIDI).

2.2. Distribution Network Reliability Indices

The performance of distribution networks can be evaluated by different indices. These indices are a measure of the reliability and availability of supply experienced by customers. The two basic categories of network reliability indices are customer-based indices and load-based indices. Customer-based indices quantify the loss of supply in terms of the frequency, duration, the amount of installed equipment affected such as transformers and the number of customers affected by outages occurring on the network [4]. Load-based indices record the frequency and duration of interruption of the load. The indices considered in this study are the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). SAIDI measures the average amount of time that the customers are without supply over customers served and it is defined by the equation 2.1:

$$SAIDI = \frac{\sum(Number\ of\ customers\ affected\ \times Duration)}{Total\ number\ of\ Customers\ Served} \dots\dots\dots\dots(2.1)$$

The summation is for all the sustained interruptions (>3min) in a year. The SAIDI can be decreased (improved reliability) by decreasing the number of interruptions or by decreasing the duration of these interruptions (to less than three minutes). Since both of these reflect reliability improvements, a decrease in SAIDI indicates an improvement in reliability.

The SAIFI measures the total number of interruptions experienced by customers per customer served and is defined by the equation 2.2:

$$SAIFI = \frac{\sum(Number\ of\ customers\ affected\ \times number\ of\ Interruptions)}{Total\ number\ of\ Customers\ Served} \dots\dots\dots(2.2)$$

The summation is for all the sustained interruptions (>3min) in a year. SAIFI is a measure of how many sustained interruptions an average customer will experience annually. The SAIFI can be decreased (improved reliability) by decreasing the number of sustained interruptions experienced by customers.

The advantages of the network reliability Key Performance Indicators (KPI) (SAIDI and SAIFI) are [5]:

- Forecasting and trend analysis on the network performance. Appropriate performance improvement plans can be implemented.
- The predicted performance can also be evaluated against actual performance. Sustainable (long term) performance levels can be introduced into the electrical utility.
- Appropriate performance target setting and Incentive Based Regulation (IBR) and monitoring.
- The customer expectations and experiences can be compared against the actual performance (measured).
- Rapid (<3min) restoration is not recorded and therefore it does not affect the SAIDI and SAIFI.

2.3. Distribution Network Reliability

MV networks have the highest impact on reliability because more customers are affected by faults on these networks. The difficulty with network is that it is extensive and could have line lengths that exceed 100 km [4]. Thus, when improving the network reliability, it is important to focus more on MV networks.

Reliability also depends on numerous aspects such as location (urban or rural), environment, network topology and the type of equipment installed. So attention should be given to these factors when building distribution networks in order to ensure good reliability. Improving reliability is a main objective of the electric power industry and can reduce economic losses, reduce lost productivity, and increase customer satisfaction. The objectives of improving reliability in MV networks are [10]:

- Maintain continuity of supply to customers.
- Reduce the frequency and duration of sustained supply interruptions (i.e. SAIDI and SAIFI).
- Minimize customers affected by sustained interruptions.
- Determine the causes of sustained interruptions in order to take corrective actions to reduce them.
- Analyse and improve performance.

2.4. Benefits of FLISR to Power Utilities

FLISR performs self-healing and quick recovery from faults. When a permanent fault occurs, the customers affected by the fault may be categorized into two groups: those that will have to wait until the faulted section has been repaired and those whose supply has been interrupted, but can be restored through the main or alternate supplies by means of switching and isolating the healthy section from the faulted feeder section. In most cases the second group of customers is larger than the first group. When performing system operations manually, the fault isolation and service restoration activities can only be done after the fault has been located. FLISR is able to restore service to customers in less than three minutes, resulting in significant reliability improvement compared to traditional manual switching.

By implementing remote closing of the N/O point, the following will be the benefits for Eskom.

- Minimise the number of customers affected by a sustained fault which will ultimately minimise the number of customer-hours interrupted (SAIDI).
- Facilitate the decision to close the automated N/O point and hence restore many customers before the three minutes limit thereby improving both the SAIDI and the SAIFI to the values required by the National Energy Regulator of South Africa (NERSA).

- Reduce the number of customers affected by a sustained fault by automatically isolating the faulted location and restoring service to the remaining customers by transferring them to adjacent circuits.

According to the technical and financial issues of the existing distribution network case studies discussed in Chapter 5, FLISR is selected as the most significant and beneficial solution to be implemented on such networks. The idea behind FLISR is to achieve the self-healing grid and reliability improvement, where the service for all customers is restored automatically after a few minutes (<3 min) from fault occurrence. The information required for FLISR is gathered from the field devices and processed in a control station. The main objectives of the FLISR are as follows:

- Detect the fault quickly, locate the faulted section accurately and estimate probable fault location.
- Isolate only the faulted section in the faulted feeder.
- Restore the service as quickly as possible to the maximum number of customers.

From the previous discussion, FLISR presents a solution for many challenges that the distribution network Work Teams face today. Applying FLISR on the proposed distribution networks will not require a complete replacement of the power equipment. Retrofitting will be marked by adding the appropriate smart devices for communication and data acquisition.

2.5. Features enabling FLISR

There are numerous distribution devices that are used to improve the safety and reliability of the distribution network. This section will review some of these devices and how they take part during FLISR operation. Self-restoration of power distribution systems is conducted through smart protective and switching devices that automatically isolate faulted sections and transfer quickly restorable customers to an alternate source when their normal supply has been lost. Features that enable the functioning of FLISR are as follows:

2.5.1. Fault Path Indicators (FPIs)

One solution to assist Work Teams to locate a fault and separate healthy sections of a feeder is the installation of FPIs at strategic points along a feeder. FPIs exist for both overhead and underground cable networks. The FPIs operate by monitoring the current at a specific point on the feeder [6]. They will be incorporated into the System Control and Data Acquisition (SCADA) for remote monitoring. Upon detecting a fault downstream of the FPI, it will flash its LED or signal to SCADA to indicate when it sees a downstream fault. The Work Teams will know that the fault is downstream of that FPI [7]. The FLISR will be assisted by the FPI to locate the fault. According to [6], at least a 20 minute improvement on sectionalising time on the network with FPIs is achieved. The benefits of the FPI are realized when installed on long networks with a high number of customers rather than networks with fewer customers [7].

2.5.2. Automatic Reclosers

Automatic reclosing devices are designed to trip and reclose for transient (short duration) faults. Automatic reclosers are electrically operated devices that can sense over-current (O/C), earth-fault (E/F) or sensitive earth-fault (SE/F) conditions. Subject to protection coordination settings, the automatic recloser will trip and automatically reclose. If the fault remains (sustained fault), the recloser will go through a fixed sequence of trip and reclose cycles after which it will lockout. When the recloser is in the lockout state the faulted section will be isolated from the supply and human involvement is required to close the recloser. Most automatic reclosers have three trips to lockout [4].

Automatic reclosers nowadays are capable of sophisticated protection, communication, automation and analytical functionality. With an abundance of processing power at their disposal, utilities have the flexibility to use the recloser as a stand-alone unit in a remote location, or to integrate several units into sophisticated substation automation systems. Whatever the application, the reclosers are flexible enough to evolve with the utility requirements. Reclosers monitor current, voltage, frequency and the power flow direction. During a fault, only the recloser that is closest to the fault will trip by coordinating the automatic reclosers. This is important for the successful implementation of reclosers.

It is possible to operate the network in either manual operation mode where the operator has to manually perform the reconfiguration of the network or in an automated operation mode where the reclosers perform the entire task automatically. In manual operation mode, the following action are taken after the recloser immediately upstream of the fault automatically trips, recloses to lockout and remains open. The operator determines the location of the fault from the automatic recloser status and/or additional FPIs, opens the next automatic recloser downstream of the fault (that did not see the fault occurs assuming that there is no back-feeding in place) to isolate the faulted section, reconfigures the protection settings in expectation of restoration of supply from alternative source and closes the N/O point to restore power downstream of the faulted section. Power is restored to the healthy parts of the network and it is possible for the dispatcher to despatch the Work Teams to the faulted section of the feeder. Once the entire feeder is healthy, the operator can open the N/O point, reconfigure and close the automatic reclosers to restore the network to the normal configuration. In loop automation operation mode it is important to note that protection is the first and foremost function of the automatic reclosers. A more sophisticated automatic recloser is required to perform both protection and automation functions [4]. In addition to these the reclosers have to measure power flow and measure voltage on both sides of the open recloser.

In an automated network the following actions will take place when a sustained fault occurs:

- The automatic recloser immediately upstream of the fault automatically trips, recloses to lockout and remains open.
- The faulted section is isolated.
- Automatic reclosers downstream of the fault automatically change their protection settings in anticipation of power flow in the opposite direction.
- The N/O point recloser closes automatically. This will automatically restore power to the healthy parts of the network. The dispatcher can now dispatch Work Teams to the faulted section of the network. It is also possible for the loop automation system to restore the original configuration when the fault is cleared.

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 restored to the network soon after a trip. Automatic reclosing devices are therefore specifically designed to trip and successfully reclose after transient fault conditions.

2.5.3. Sectionalizers and Automated Feeder Switches

Sectionalizers are electrically operated devices that are used in conjunction with an upstream recloser to isolate a sustained fault. The device isolates the faulted section before the recloser finishes a sequence of automatic reclosing and locks out. Automated feeder switches improve the reliability of the network by reducing the outage duration, frequency of interruptions as well as reducing the impact on the affected customer. The FLISR will use these devices to isolate the fault from the healthy part of the feeder.

2.5.4. Remotely operated N/O points

Medium voltage distribution rings are usually fitted with N/O points splitting the ring into two separate feeders. The purpose of the N/O point is to ensure selectivity for protection systems and reduce the impact of faults by limiting the number of customers that are affected when the protection operates. However, on the downside, the N/O points might indirectly incur additional grid losses by preventing optimal power flow. With power flow that shows strongly dynamic behaviour throughout the day, the optimal location for the N/O point would continuously change, as ideally the current flowing through each feeder should be roughly equal. Following a fault, N/O points can be closed so that the supply can be restored to quickly restorable customers. The idea is to isolate the faulted section and reconnect the healthy part of the system as soon as possible. To achieve back-feed power restoration, healthy portions of the feeder that have lost power are restored through their N/O points from neighbouring sources [1]. The restoration of supply will be quicker and does not directly depend on the fault repair time. The back-feed restoration should not overload any part of the back-feeding network. Communications may be desirable in order to monitor the status of the network at several key points to assist Work Teams. In a manual recloser system the feeder upstream from the fault is unaffected by communication problems but communications are required to reconfigure the downstream portion of the network and to control the N/O point. Chapter 3 focuses more on this topic.

2.6. The FLISR process

When the network is operated without FLISR, part of the feeder will experience an outage until Work Teams arrive on site for manual operation. Figure 2.2 illustrates restoration time activities during an outage, from the occurrence of the fault until the feeder is returned to a normal state [8]. When a fault occurs, a customer phones to report the fault or a breaker trips. Then Work Teams must travel to the approximate fault location identified by protective relays and FPIs and locate the fault by patrolling the suspected faulted portion of the feeder. Once the Work Teams manage to locate the fault, they isolate the faulted section and perform manual switching to restore supply to as many customers as possible. After that they repair the fault and restore supply to the rest of the customers. Based on the typical restoration time without FLISR, customers connected to healthy portions of the feeder can experience an outage lasting several minutes to hours as can be seen in Figure 2.2.

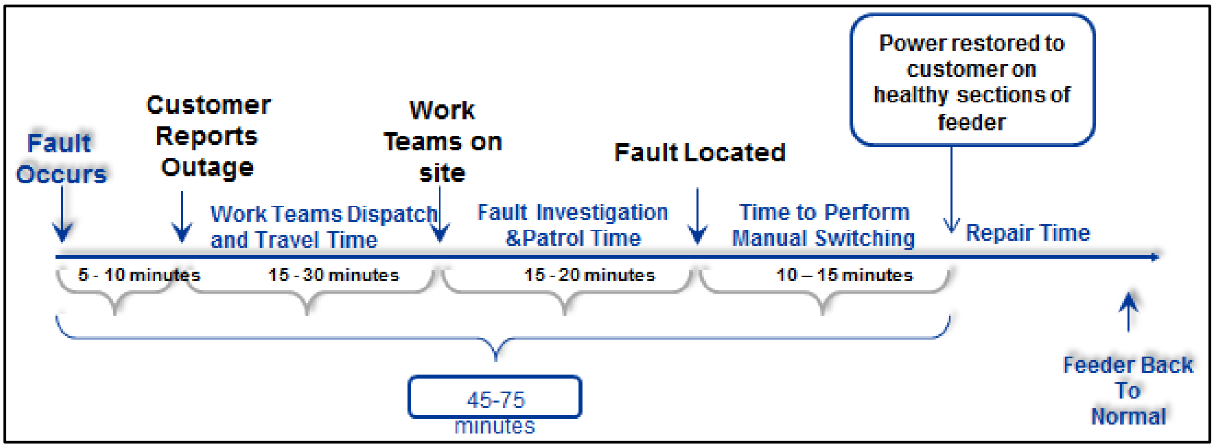

Figure 2.2: Outage time for a distribution network without FLISR [8].

With FLISR as can be seen in Figure 2.3, FLISR can reduce the outage duration for the same customers to one minute or less. When a fault occurs, FPIs immediately report the fault (via the SCADA) to the FLISR. Before performing any operations, the FLISR will allow protection and control schemes such as automatic reclosers time to operate. If automatic reclosing is not successful because of a permanent fault, then the FLISR will be triggered. The FLISR will then automatically detect that a fault has occurred, locate the fault between two switches, open the switches that surround the faulted section to isolate the faulted section of the feeder, and then close other switches (where possible) to restore supply to the healthy sections of the feeder.

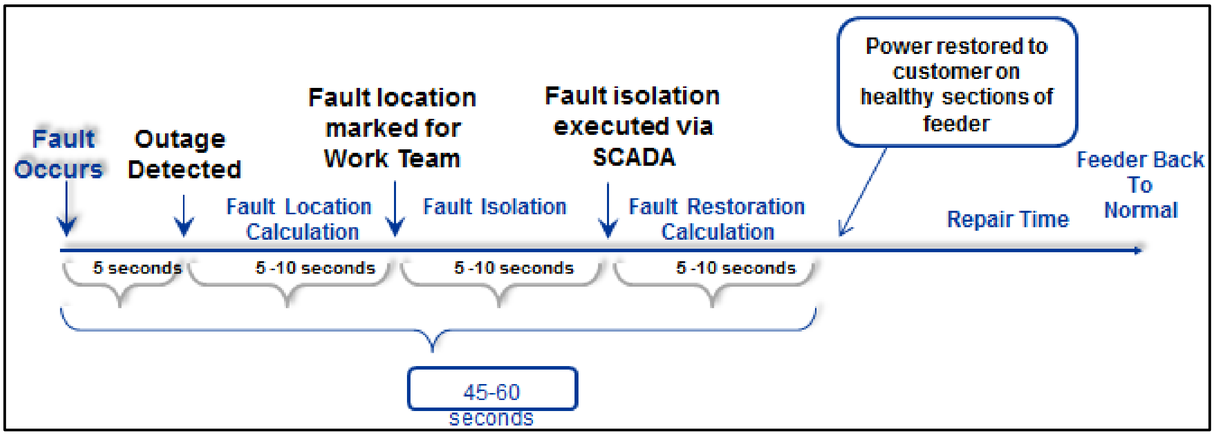

Figure 2.3: Outage Time for a distribution network with FLISR [8].

All of these actions are completed without manual intervention [8]. The FLISR steps are detailed below:

2.6.1. **Fault Detection**: The FLISR operates as a result of a permanent fault on the feeder. It should not operate when a feeder becomes de-energized due to manual switching activities or due to an emergency that triggers under-frequency or under-voltage load shedding. Therefore, fault detectors are essential to activate the FLISR when a permanent fault is detected. Automatic reclosers trip and lockout to provide a signal to trigger the FLISR. After the recloser locks out, the faulted section on the tripped feeder needs to be located [9].

2.6.2. **Fault Location**: The next step is to determine the portion of the feeder that contains the fault. A FPI determines if fault current has recently passed through the FPI and indicates this by flashing its LED (and indicates this to the SCADA). This indicates that there is a fault located downstream of the FPI. The FLISR uses the FPI status indications and automatic recloser operations to determine what section is faulted. The faulted section is bounded by one FPI that has a fault indication and one or more FPIs that did not see the fault [8].

2.6.3. **Fault Isolation**: The FLISR then issues control commands (via the SCADA) to open the feeder switches needed to isolate the faulted section of the feeder based on the Fault Location analysis described in 2.6.2 above. The FLISR waits for the automatic reclosing sequence to be completed before it operates. This is done to ensure that feeder reconfiguration by the FLISR is only performed as a result of a permanent fault.

2.6.4. **Service Restoration**: Once the faulted section of the feeder is isolated, the FLISR will restore supply to as many customers as possible via the original supply and alternative sources. After isolation and before restoration, capability estimations need to be carried out to determine if back-feeding is possible [9]. Any portion of the feeder that is upstream of the faulted section can have its supply restored from the original source without any capacity calculations. However, to restore downstream feeder sections, the feeder should have a back-feeding source with sufficient capacity to carry the additional customers being transferred. If sufficient capacity exists, then the N/O point is closed to allow back-feeding to restore supply. If there is insufficient capacity, then the portion of the feeder in question will remain de-energized until Work Teams arrive on site. All of the above actions can be completed in less than one minute with no manual intervention when using FLISR [8].

2.7. FLISR Architectures

The various architectures of FLISR deployment are:

- Centralized FLISR (C-FLISR)
- De-Centralized FLISR (DC-FLISR)
- Distributed FLISR (D-FLISR)

The centralized approach may be implemented as one of the applications of the Distribution Management System (DMS) or Distribution SCADA. Feeder optimization can be achieved at the highest possible level with more complex switching logic and effective load distribution. However, each switch controller needs to communicate with the control centre directly and this may require a high bandwidth communication network, as well as accurate load model information. The response time of the complete automation system may be comparatively high [9]. This research will focus on the centralized FLISR approach to be implemented in case studies.

On the other hand, the DC-FLISR system is deployed at the substation level using a single or a redundant automation device installed in each substation. The remote I/O modules installed at each switch/recloser location need to be connected to the distribution substation automation device over a communication network. As compared to the C-FLISR, the DC-FLISR system is faster with lower bandwidth requirements. The achieved solution may not be the best one but it is easy and less expensive to deploy [9].

The distributed approach (D-FLISR) uses controlled devices at each switch or automatic recloser location and these devices communicate amongst each other to determine where the fault has occurred and to determine the appropriate switching actions necessary for the restoration. As the intelligent devices (controllers) are distributed, the reliability of the scheme is higher. However, this requires a controller, instead of remote I/O units, at each switch location [9].

Today the concept of Distribution Automation (DA) is evolving into a DMS, which is a decision support system to help operators monitor and control the entire distribution network in an optimal manner while improving safety and reliability. The DMS will assist, not replace, the operating personnel who will continue playing an essential role in managing the operation of the distribution system. While some DMS control applications are fully automatic, this does not eliminate the need for operator oversight of all operations. A primary DMS objective is to optimize distribution system performance by "squeezing" as much capability as possible out of existing assets. This is a major new responsibility for control room operators, who have focused on maintaining workforce safety and "keeping the lights on." Adding this new operating responsibility is one of the most significant DMS implementation challenges, often requiring new control room procedures, extensive training and certification, and additional technical support. The DMS consists of three major components: distribution SCADA, advanced distribution applications, and external interfaces [8]. Figure 2.4 illustrates how these three pieces fit together [8].

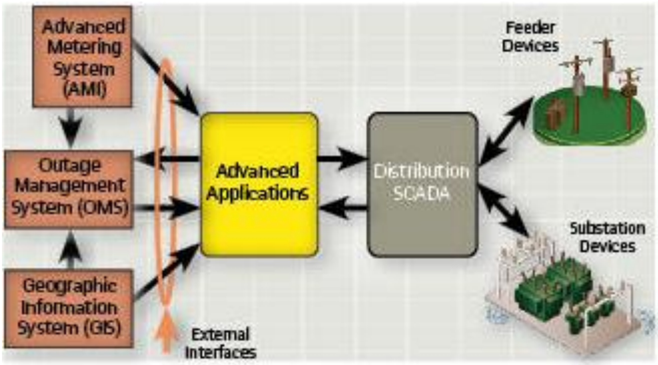

Figure 2.4: DMS pieces [8]

These technologies work together to automate power restoration, reducing both the duration and impact of power interruptions while minimising maintenance and operational costs. The impact on customers affected by the outage is also minimised through automatic restoration of supply to unaffected sections of the network. Where back-feed capabilities are available, the supply to affected customers is also restored by transferring them to an alternative supply. The minimised number of affected customers and the associated lower customer minutes of interruption are the primary benefits of reliability improvement in a power distribution system.

2.8. FLISR Impact on Existing Protection and Control Functionalities

FLISR should coordinate with existing protection and control functionalities already installed in the network. So the following issues regarding existing protection should be kept in mind:

- Protection such as recloser relays and circuit breakers must operate to indicate that a permanent fault has occurred on the distribution network. The protection system must be able to inform FLISR of any sustained fault detected.
- The FLISR should not operate until existing protective relays have completed their necessary operations, such as automatic reclosing. The FLISR should operate for permanent faults that have caused automatic recloser trip and lockout.
- Connecting a large portion of a faulted feeder to an alternative feeder may increase the length of the alternative feeder by a considerable amount. Protective relays on the alternative feeder must be able to see faults on the entire feeder after re-configuration. This means that there should be protection settings to cater for back-feeding. It may be necessary for FLISR to assign an alternate protection settings group during feeder re-configuration [8].

3. Automatic Supply Restoration: Remotely Closed N/O point.

3.1. Introduction

The idea of the remotely closed N/O point is for the system to act as soon as possible in a fault condition in order to restore supply to customers. The automation of distribution systems with the installation of remotely controlled or automated switches plays an important role in reducing the time to restore supply to customers. These devices have been shown to be economically viable due to the growth of a large number of automation equipment suppliers and new communication technologies. In this chapter, a methodology for the automatic restoration of supply in distribution systems by means of remotely controlled N/O points is presented.

3.2. Methodology for remote closing of N/O points to restore supply.

When a sustained fault occurs downstream of an automatic recloser REC-1 in Figure 3.1 the short circuit current will be flagged remotely in the SCADA system. REC-1 follows its reclose sequence and locks out automatically to isolate the sustained fault.

When a sustained fault occurs upstream of REC-1, loads downstream of REC-1 should not see a sustained interruption so REC-1 is opened remotely and either N/O-1 or N/O-2 is closed to transfer customers downstream of REC-1 to the adjacent feeder FD-2 or FD-3.

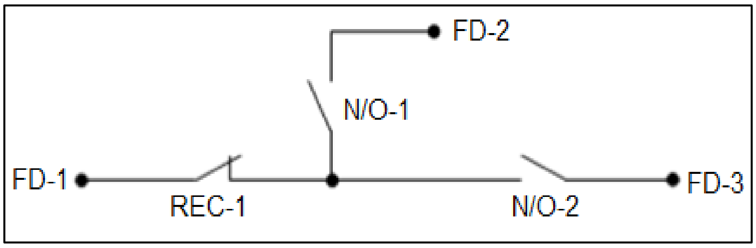

Figure 3.1: Example of switches in a distribution network

The technical and operational feasibility of load transfers using remotely controlled N/O points is verified by simulations. If there is more than one option of load transfer (e.g. to FD-2 or FD-3), the best option will be chosen based on the availability of spare capacity without violating voltage and conductor thermal limits. After this analysis, the FLISR tool automatically sends the necessary commands to close the respective N/O point.

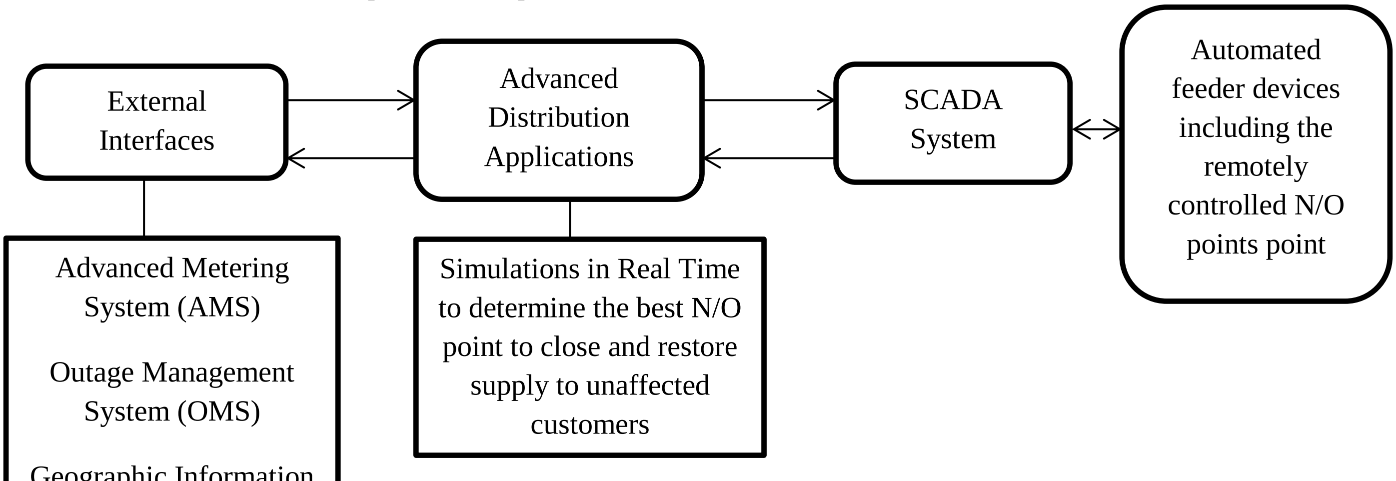

Figure 3.2: Architecture of the developed auto-restoration system [8]

3.2. Back-feeding Interconnectors

The transfer of power to an alternative source is viable if the following operating criteria are not violated during normal and N-1 contingency conditions [10]:

- Thermal overload: Continuous ratings of lines, cables or transformers are not exceeded.
- Undervoltage: No busbar voltage is allowed to fall below statutory or contracted limits (e.g. minimum of 0.925 p.u. and maximum of 1.05 p.u. as prescribed by NERSA NRS 048-2)

In utility networks high reliability of supply is of fundamental importance as any major interruption of supply causes major inconvenience to the customers, can lead to life threatening situations and for the industrial customers may pose severe technical and production problems. In such situations, the electricity utility incurs a large loss in revenue. Therefore, interconnected networks capable of supplying each customer via alternative routes have high ranking and radial networks have low ranking with respect to network reliability and flexibility.

The N-1 contingency scenario is usually set for urban MV cable networks regardless of the feeder length and customer load. However, there is no explicit requirement for redundancy in overhead MV networks. Redundancy in overhead MV networks should only be implemented when it can be economically justified [10].

If two interconnectors can both back-feed the same or similar amount of load and can be justified, then the selection of the preferred interconnector also needs to consider the line length exposure to faults.

3.2.1. Selecting the Best Interconnector

In order to identify the best interconnector, the steps are:

- Identify different interconnection options.
- Calculate the amount of load that can be back-fed by each interconnector.
- Select the interconnector with the highest amount of customer load back-fed that does not overload the equipment or cause under-voltages.
- Exclude the interconnectors that have high exposure to faults.

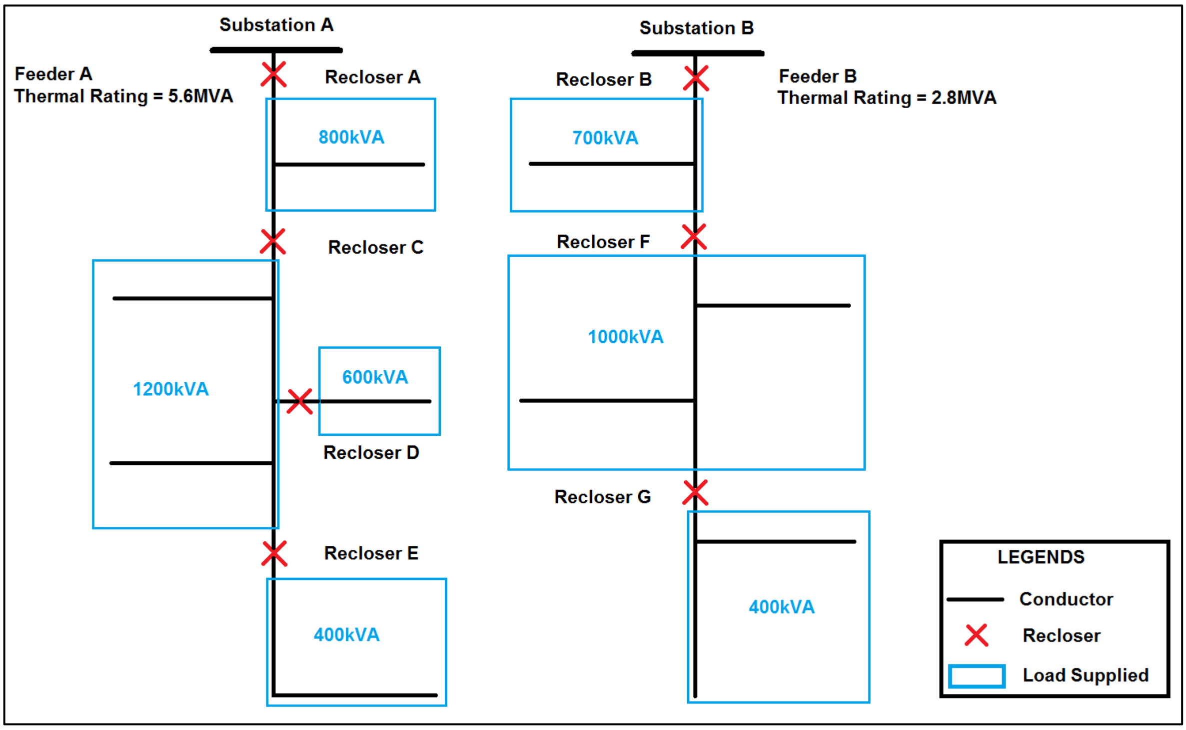

Figure 3.3: Example of two feeders with potential of back-feeding each other

Figure 3.3 shows two overhead MV feeders with the potential for back-feeding. For this example, assume that the thermal ratings of the feeders are the only constraint for back-feeding, i.e. voltage limits are not an issue. However, for the case studies in this dissertation, both thermal and voltage limit constraints are considered. Figure 3.4 shows different possible interconnectors that are capable of providing back-feeding.

Step 1: Identifying all possible interconnection options

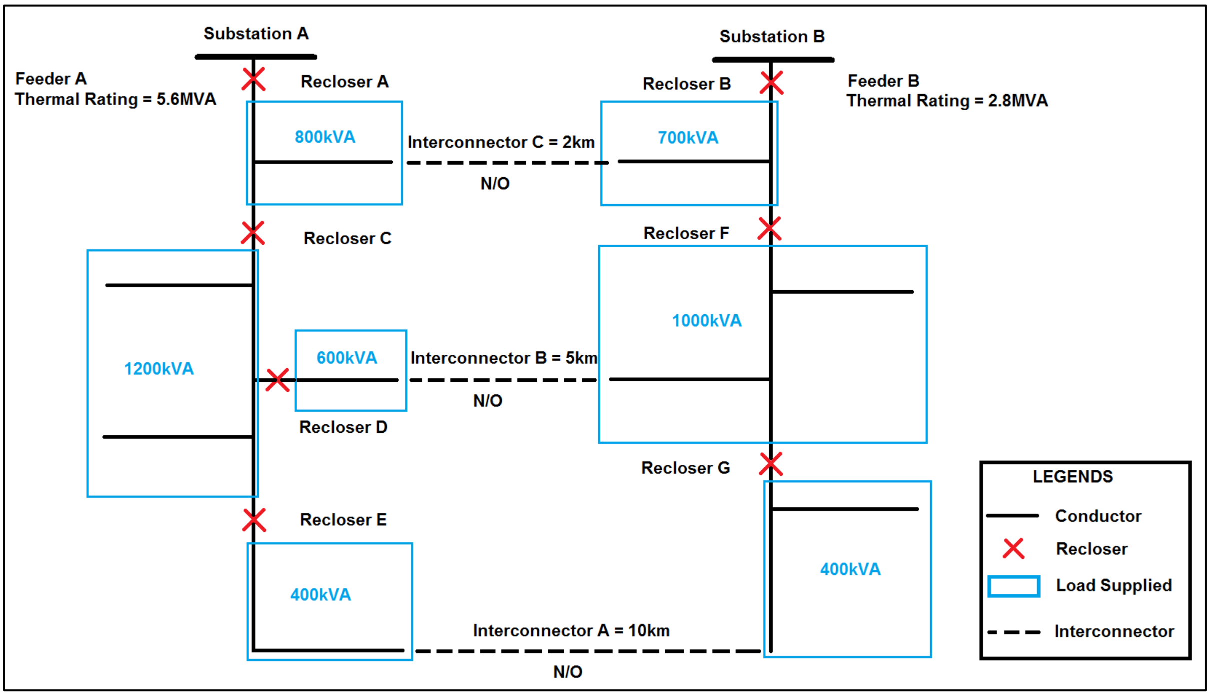

Figure 3.4: Possible interconnection options

Step 2: Calculating load that can be back-fed

- Interconnector A

For a fault on Feeder A downstream of Recloser A (tripping Recloser A) using interconnector A as the back-feeding arrangement, Recloser E on Feeder A has to be opened to prevent Feeder B from exceeding its thermal capacity limit. This means that Feeder B can at a maximum only supply 400 kVA of Feeder A under back-feeding conditions. If Feeder A is back-feeding Feeder B due to the loss of supply from Substation B, Feeder A can supply the whole of Feeder B (i.e. 2100 kVA) without exceeding the thermal limits of Feeder A.

- Interconnector B

For a fault on Feeder A downstream of Recloser A and upstream of Recloser D using Interconnector B as the back-feeding arrangement Recloser D on Feeder A has to be opened to prevent Feeder B from being overloaded. The maximum load that Feeder B can therefore back-feed to Feeder A is 600 kVA. If Feeder A is back-feeding Feeder B due to the loss of supply from Substation B, Feeder A can supply the whole of Feeder B (i.e. 2100 kVA) without exceeding the thermal limits of Feeder A.

- Interconnector C

For a fault downstream of Recloser C on Feeder A the load on the first section of Feeder A is too large for Feeder B, so no back-feeding is possible. Feeder B therefore cannot back-feed Feeder A via Interconnector C. However, if Feeder A is back-feeding Feeder B due to supply from Substation B being unavailable, Feeder A can supply the whole of Feeder B (i.e. 2100 kVA) without exceeding the thermal limits of Feeder A.

Step 3: Establish which interconnectors are the most suitable

From step 2, the total load that can be back-fed by the different interconnection options is as follows: ·

- Interconnector A (10 km) = 2,500 kVA
- Interconnector B (5 km) = 2,700 kVA
- Interconnector C (2 km) = 2,100 kVA

The sum of peak loads restored by each interconnector versus the length of the interconnector is economically justifiable for all interconnectors as clearly demonstrated on Figure A.1 in the Appendix A. A short (in km) interconnector that can back-feed most load is said to be economically justifiable.

Step 4: Selection of the optimum interconnector

It can be seen that Interconnector B can back-feed the most load. Interconnector A can back-feed a similar amount of load and is most suitable. At this point the selection should consider the likelihood of the interconnectors being used based on the line length exposure that is mitigated by the interconnectors. However line length exposure was not considered in this example and Interconnector B is selected as the optimum interconnector purely on the basis that it can back-feed the most load.

Step 5: Considering additional interconnectors

In order to select additional interconnectors it is assumed that Interconnector B has been constructed. Steps 1 to 4 are repeated to calculate the load that can be back-fed by the remaining interconnecting options for scenarios when Interconnector B cannot be used.

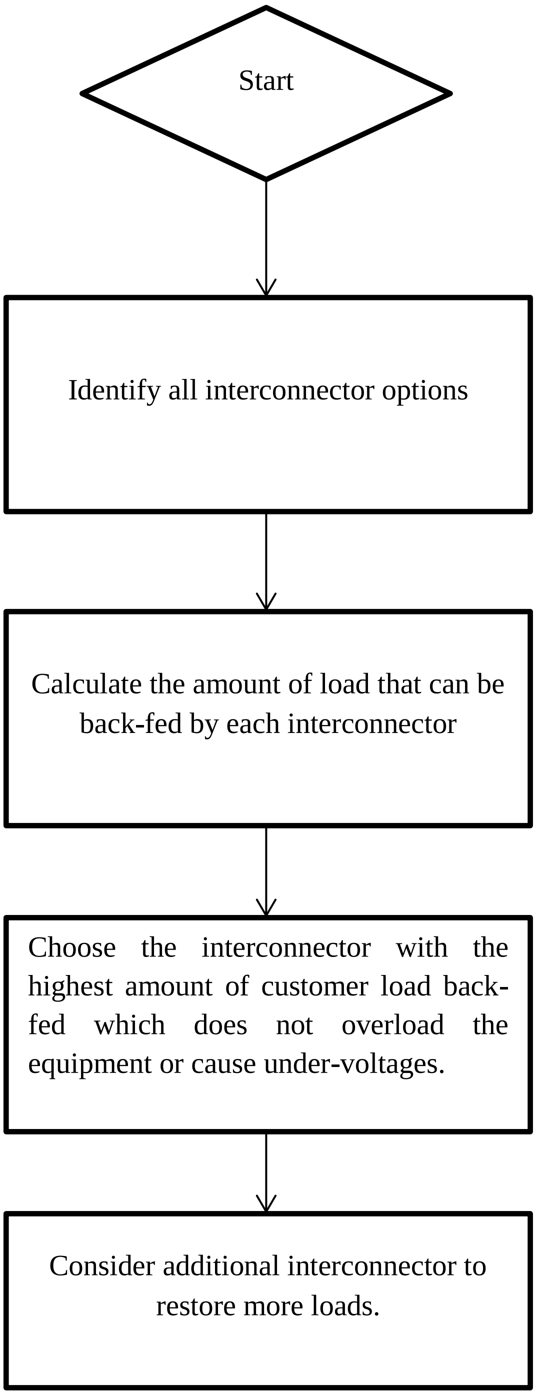

Figure 3.5: Choosing the best interconnector algorithm

3.3. The Automatic Restoration Process

After a fault the restoration strategy should restore supply quickly to the maximum number of customers. In order to do this, voltage and current measurements must be obtained from various points of the network for analysis pre-outage and post-outage. If a downstream N/O point is closed to back-feed the lost load on the original feeder, the back-feeding feeder will supply more power over a greater distance and run the risk of (i) voltage regulation issues towards the end of the newly back-feeding feeder and (ii) current violations at the primary substation end of the back-feeding feeder [11].

The upstream restoration is straightforward and can be achieved by:

- Opening the upstream switch closest to the faulted section
- Closing the main switch at the primary substation.

The downstream restoration involves transferring of unfaulted sections to possible neighbouring feeders by back-feeding through N/O points.

In order to choose the best back-feeding N/O points, simulations are required to:

- Choose the feeder that could give the highest number of customers that could be restored
- Determine the maximum extent of back-feeding possible without either voltage or current violations [11].

Prior to closing the N/O point and restoring customers in unfaulted sections, the following safety checks are required.

- Determine pre-fault load on the unfaulted section of line.
- Compare pre-fault load to capacity and determine if the alternate source can handle the un-faulted section load.

3.3.1. Supply Restoration Algorithm

The basic assumptions for the algorithm are as follows, modified from [11], [12]:

- The substations are assumed to have a fixed capacity
- Loads are considered to be constant power.

Following a fault the algorithm in Figure 3.6 searches for all N/O points that could provide back-feeding capabilities. The steps involved are:

Step 1: Searches amongst all the switches downstream of the fault until reaching N/O points and assumes that all of them are in the open state.

Step 2: Considers how many customers experiencing an outage could be restored by closing each N/O point.

Step 3: Performs a load flow study for the different back-feeding interconnector alternatives to determine if the back-feeding substation and feeder conductors have the necessary spare capacity (which depends on the time of the day). It also checks if voltage and conductor thermal levels are within the limits.

Step 4: Selects the best interconnector which has a higher spare capacity and is not overloading the feeder conductor.

Step 5: The remaining customers experiencing an outage would be supplied by searching amongst the remaining back-feeding points repeating steps 1 to 5 and choose the second best interconnector.

Step 6: Recording the number of quickly restored customers. These customers are excluded in the calculations of SAIDI and SAIFI.

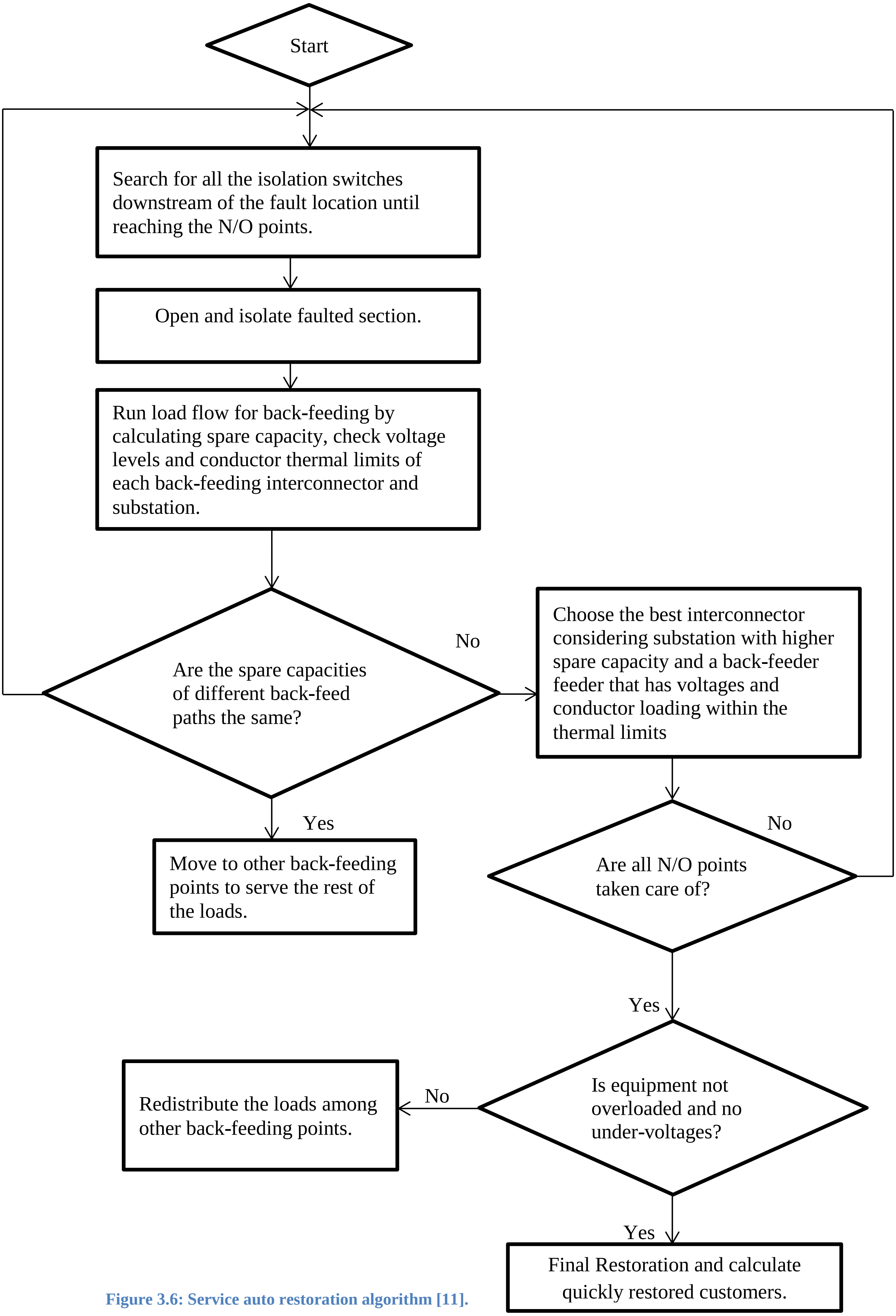

Figure 3.6: Service auto restoration algorithm [11].

4. Equipment and Human Safety and Security issues associated with closing a N/O point remotely

4.1. Introduction

It is important to understand the state of the network before remotely closing the N/O point for automatic restoration. There are issues that need to be taken into consideration before performing an automatic supply restoration in order to ensure safety of personnel and equipment.

4.2. Safety and Work Processes

The safety of workers, the general public and equipment must not be compromised. This imposes the biggest challenge for deploying any remotely controlled system. New automation systems often require new work processes [5]. Utility personnel must be well trained to safely operate and maintain the new automated distribution system.

Safety related issues include [5]:

- Requirements for a visible gap for disconnect switches.
- No automatic closures after 2 minutes have elapsed following the initial fault to protect Work Teams.
- System disabled during maintenance (live line) work, typically locally and remotely.
- Each algorithm has several safety checks before any operation occurs.
    - Communications Status - verify that all necessary devices are on-line and communicating.
    - Switch Position - verify that each appropriate line switch is in the appropriate position.
    - Voltages - check that the appropriate feeders are energized.
    - Feeder Breaker Position - verify the faulted feeder breaker is in its opened position and is opened only by a relay, not by SCADA or by the breaker control handle.

4.3. Line Phasing

Phasing must be checked during the initial commissioning of the N/O point. The phasing must be the same for the back-feeding feeder and the back-fed feeder.

4.4. Protection settings coordination

Faults occurring in the distribution system must be sensed quickly and immediately isolated to prevent hazards to the general public and utility personnel. Protective relays are used to sense fault conditions caused by fault in the distribution system and the use of proper schemes and settings can help to maximize sensitivity and selectivity. For automatic or remote back-feeding, protection relays should be able to protect when the supply is coming from the alternate source. When feeder automation is used in a looped network, it is necessary to consider using reclosers and sectionalisers with capabilities such as directional protection and loop automation. Some permanent faults can be equipment failures or cables damaged by excavation equipment.

Connecting a large portion of a faulted feeder to an alternative feeder may increase the length of the alternative feeder by a considerable amount. With full directional capabilities the reclosers and sectionalisers are configured for protection with power flowing in either the forward or reverse direction. This allows the utility to remotely close the N/O point in the event of a fault without having to reconfigure the other switchgear in the feeder. It is therefore important to focus on the communications link to the N/O point and by ensuring that reliable power restoration will always be possible.

The ability to have several relay settings groups that can be selected automatically to meet the needs of the system is one of the most useful features of automatic restoration. Switchgear status can be used to switch to appropriate setting groups [13].

4.5. Back-feeding source spare capacity

The back-feeding source must be capable of taking the load of the quickly restorable customers before closing the N/O point. The capacity as well as the number of source feeders that supply a substation impacts the availability of supply to the customers supplied from that substation. Reliability of supply can be improved by adding a second source to a substation either via a second feeder in parallel to the existing feeder, or by closing the loop between two substations that are not connected. In cases where a substation has two source feeders but only a portion of the load can be back-fed due to thermal or voltage limits, full redundancy can be achieved by increasing the capacity of the feeder that is the constraint.

4.6. Conductor thermal rating

The conductor used for the original feeder should be the same as the conductor for the feeder that will take up the load. The conductor thermal rating and the feeder voltage drop both limit the loads that a feeder can supply. The check of equipment loading and thermal limits is important to determine whether load transfers can safely take place.

The power transfer on overhead lines affects the sag of the conductor and hence the height of the conductor above the ground. This in turn affects the safety of the public. The determination of the allowable power transfer is thus not only a function of the properties of the conductor but also of the safety to the public.

According to the Eskom Conductor Current Rating Distribution Standard DST-240-100176272 [13], ratings are calculated for normal and emergency conditions at 75ºC and 90ºC. The lines were then templated at 50ºC according to an Internal Eskom Directive, IED 15/6/1-1 1970. This means that if the conductor temperature reaches 50ºC, the height of the conductor above the ground would be at the minimum height prescribed by law [13]. It is necessary to use equipment more efficiently ensuring that thermal ratings are not over the prescribed limits. In the cases where the electrical requirements such as the conductor thermal loading, reliability strategies can be implemented as shown on Table A.1 in Appendix A.

4.7. Fault Isolation

Inadequate or inaccessible isolating links can substantially increase the duration of outages. The number and location of isolating links shall be determined when designing for an automatic supply restoration. The faulted apparatus must be isolated from all possible sources of supply. According to Eskom’s Operating Regulations for High Voltage System (ORHVS), an authorized person physically carries out the switching, linking, safety testing and earthing in order to make the apparatus safe to work on. Isolation of the faulted equipment must be done before closing the N/O points and isolators must leave a visible gap when open. This means that the time to find a fault should be minimal in order to quickly isolate the faulted section and remotely restore power to quickly restorable customers via remotely controlled N/O points. In order to minimize the time to find a fault, more reclosers and FPIs on every tee-off should be strategically installed. The status of the network must be known.

A person cannot close any switch or breaker without permission from the Network Control Centre. The implementation of a supervisory remotely controlled N/O point instead of a manually operated

N/O point will reduce the restoration time because there will be no time required for Work Teams to travel to the N/O point to close it. The N/O point will be remotely closed by the Network Controller.

4.8. Voltage Limits

MV distribution feeders have to comply with the voltage regulation standards required by the National Energy Regulator of South Africa (NRS-048) as well as the Distribution Voltage Regulation and Apportionment Limits Standard DST_34-542. Therefore, before and after closing a remotely controlled N/O point it is important to ensure that the MV distribution network operates within the set voltage regulation standards as the first step in reliability planning. The maximum number of customers that can be supplied per MV feeder, without exceeding the voltage regulation limits defined by NRS-048 and DST_34-542, is determined by:

- Network voltage e.g. 11 kV or 22 kV
- Backbone length of the feeder
- Line type (cable vs. overhead) as described on Table A.2 in Appendix A
- Maximum allowable voltage drop
- Maximum allowable loading

5. Case Studies

DIgSILENT PowerFactory software was used for load flow studies.

The following were performed on pilot feeders:

- The three case study networks in the MOU were modelled with and without FLISR being implemented (for the FLISR case the scenarios where the N/O point is allowed to be closed or not were modelled).
- The planned FLISR solution was presented to the stakeholders in the Eskom MOU i.e. Network Planning, Plant, Project, Distribution Management System (DMS)/SCADA and Land Development departments to get approval for this project to be implemented on real Eskom MV lines.
- Training of Network Controllers and Work Teams on Loop Automation concepts was done so they can do manual Loop Automation which will help to prepare them for FLISR operation.

The case studies discussed in this chapter are conventional distribution networks i.e. those without automated N/O points.

5.1. Case Study 1: Balfour Munic/Siyathemba 1 and 2 22 kV Overhead Line Feeders

The performance of the distribution network before the implementation of FLISR and after the implementation of FLISR was investigated. Feeders were chosen as case studies based on intelligent devices that allow the implementation of the FLISR.

The first case study was the Balfour Munic/Siyathemba 22 kV feeder. This feeder was chosen based on its poor performance and good back-feeding capabilities. This feeder features on the SAIDI and SAIFI Top 100 worst performing feeder list for the MOU. The feeder ranks as number 20 in the Operating Unit, number 15 in the Ermelo Zone and number 2 in the Secunda Sector as a poorly performing feeder. This feeder has experienced an excessive number of trips and long customer duration outages.

5.1.1. Feeder Characteristics

The Balfour Munic/Siyathemba 22 kV feeder has been split into two feeders; the Balfour Munic/Siyathemba 1 22 kV feeder and the Balfour Munic/Siyathemba 2 22 kV feeder. Both these feeders are on the top 100 worst performing feeders in the MOU.

The Balfour Munic/Siyathemba 1 22 kV OHL Feeder

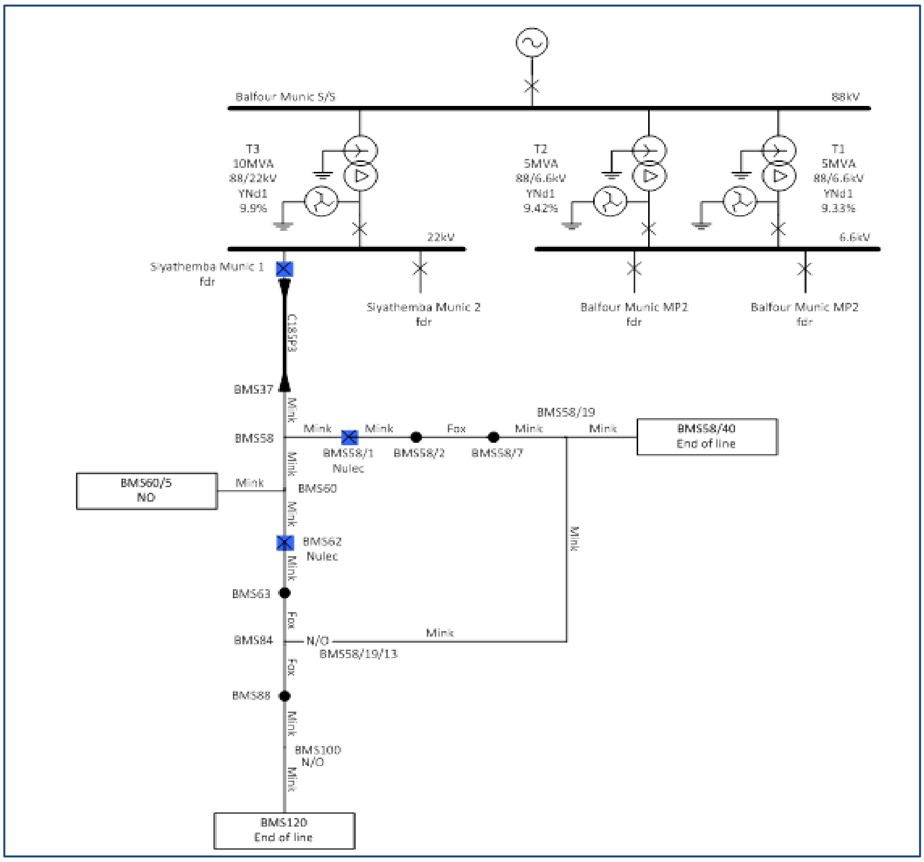

Figure 5.1: The Balfour Munic/Siyathemba 1 22 kV OHL Feeder

The Balfour Munic/Siyathemba 2 22 kV OHL Feeder

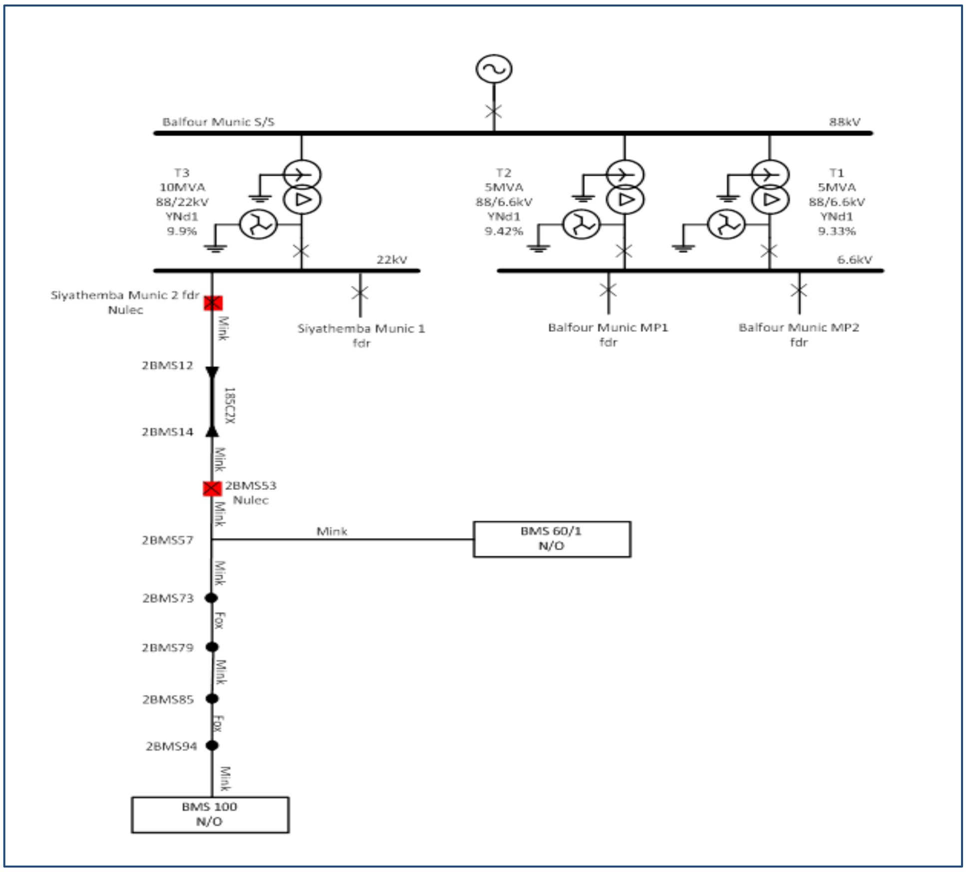

Figure 5.2: The Balfour Munic/Siyathemba 2 22 kV OHL Feeder

Figure 5.1 and Figure 5.2 show the positioning of the Nulec reclosers, sectionalizers and N/O points. The Balfour Munic/Siyathemba 1 22 kV feeder has three Nulec reclosers, 79 sectionalizers and two N/O points as shown from the feeder characteristics on Table 5.1. The Balfour Munic/Siyathemba 2 22 kV OHL feeder has two Nulec reclosers, 64 sectionalizers and two N/O points which are used for back-feeding.

Table 5.1: Balfour Munic/Siyathemba 1 and 2 22 kV OHL Feeders Characteristics

Feeder	Customers	Isolators	Transformers	Reclosers	Line length	SAIDI	SAIFI
Balfour Munic/Siyathemba 1 22 kV feeder	2801	79	39	3	18.58 km	74.9 hr	53.11
Balfour Munic/Siyathemba 2 22 kV feeder	1343	64	39	2	14.12 km	72.8 hr	37.99

5.1.2. Feeder Performance

The Balfour Munic/Siyathemba 1 22 kV feeder had a SAIDI of 74.91 hours against the target of 27.89 hours with 2801 customers. The Balfour Munic/Siyathemba 2 22 kV feeder had a SAIDI of 72.8 hours against the target of 24.04 hours with 1343 customers. Table 5.2 shows the impact of faults per recloser on customers.

Table 5.2: Faults contribution per recloser

Breaker	No. of Faults	Fault Contribution (%)	Customer Interruption	Customer Interruption Contribution (%)
Balfour Munic/Siyathemba 1 22 kV OHL				
BMS58/1 22 kV Recloser	26	54%	38139	46%
BMS62 22 kV Recloser	14	29%	15705	19%
BMS1 22 kV Recloser	8	17%	28601	35%
Balfour Munic/Siyathemba 2 22 kV OHL				
2BMS1 22 kV Recloser	2	13%	2683	13%
2BMS53 22 kV Recloser	13	87%	17439	87%

On the Balfour Munic/Siyathemba 1 22 kV feeder, the BMS58/1 Nulec recloser experienced a lot of faults that affected many more customers than other reclosers. On the Balfour Munic/Siyathemba 2 22 kV feeder, the 2BMS53 Nulec recloser experienced almost 90% of the faults. More customers experienced outages beyond this recloser. N/O points will be automated so that FLISR will quickly restore supply to all customers not affected and thereby reduce the SAIDI. This will be done by replacing N/O points with supervisory circuit breakers so that they can be operated remotely by the Network Controller or FLISR tool.

5.1.3. Applying FLISR features on the Balfour Munic/Siyathemba 22 kV Feeders

In order for the FLISR to function on the Balfour Munic/Siyathemba 22 kV feeders, many field devices will need to be replaced to provide FLISR functionality. These devices should be monitored remotely which means they should be installed with a Remote Terminal Unit (RTU) for supervision. Currently the N/O points are operated manually and they will have to be replaced so that they can be operated remotely so RTUs will be added to them in order to remotely operate them. Sectionalizers are also operated manually and it will be necessary to replace them so that they can be operated remotely. The auto-restoration process was applied for this case study.

5.2. Case Study 2: The Lebohang/Lebohang 2 22 kV Feeder

The second case study was the Lebohang/Lebohang 2 22 kV feeder which is fed from Lebohang Substation. This feeder was also chosen based on its poor performance and poor back-feeding capabilities. This feeder also features on the SAIDI and SAIFI Top 100 worst performing feeder list for Mpumalanga Operating Unit. The feeder is ranked number 35 in the Operating Unit, number 3 in the Ermelo Zone and number 1 in the Secunda Sector as a worst performing feeder. This feeder has experienced an excessive number of trips and long duration customer outages.

Table 5.3: Lebohang/Lebohang 2 22 kV feeder characteristics

Feeder	Customers	N/O Points	Reclosers	Line length	SAIDI	SAIFI
Lebohang/Lebohang 2 22kV	6117	1	2	11.91 km	33.5 hr	22.92

As shown on Table 5.3, this feeder has about 6117 customers, is only 11.79 km in length. It currently has a SAIDI of 33.5 hours against the target of 27 hours and a SAIFI of 22.92 interruptions against the target of 16 interruptions.

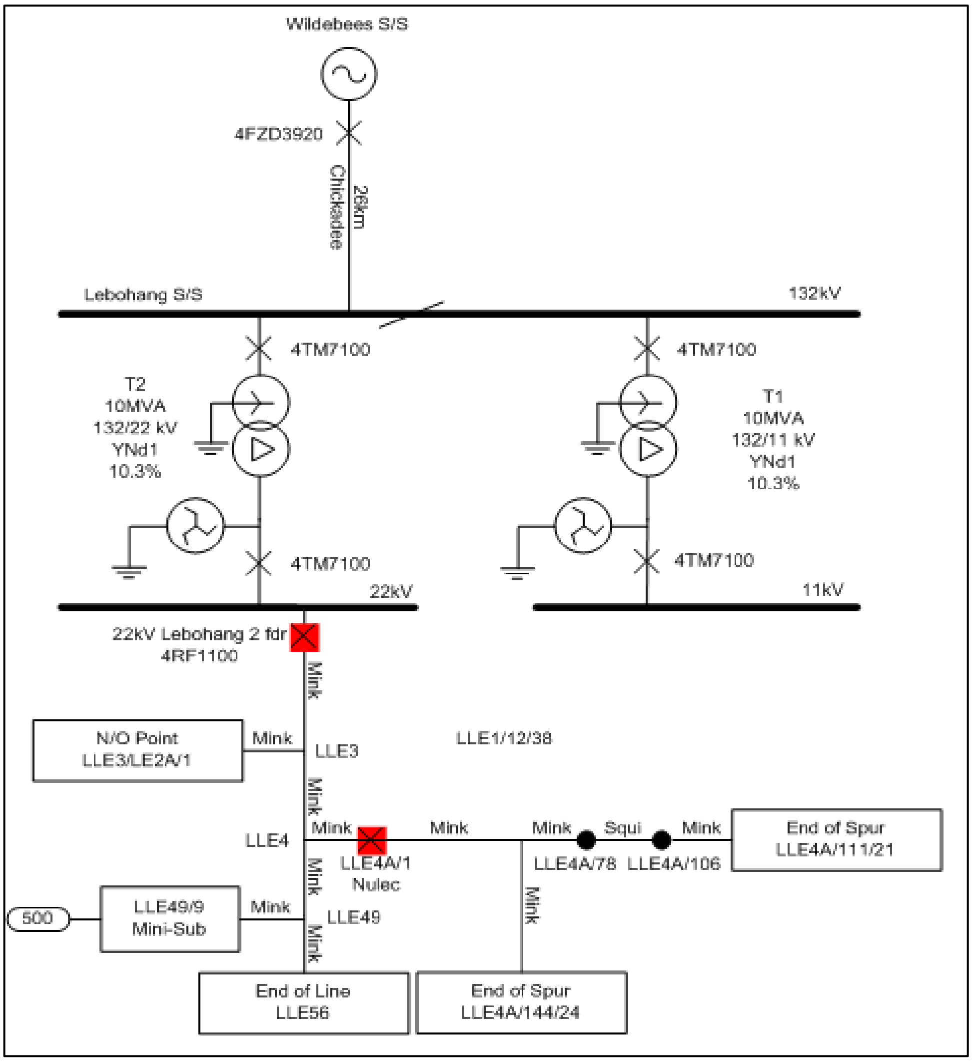

Figure 5.3: The Lebohang/Lebohang 2 22 kV OHL Feeder

Figure 5.3 shows a single line diagram of the Lebohang/Lebohang 2 22 kV OHL feeder. It shows points where there are equipment such as Nulec reclosers, N/O points and isolators. The Lebohang/Lebohang 2 22 kV feeder has one N/O point at 2LLE5/1 which is back-feeding from the Lebohang/Lebohang 1 22 kV feeder and is protected by one Nulec Recloser at 2LLE4A/1. Table 5.4 shows the distribution of faults per recloser and the impact of the fault in terms of customer interruption.

Table 5.4: Fault per Recloser - Lebohang/Lebohang 2 22 kV OHL Feeder May 2017

Lebohang/Lebohang 2 22 kV OHL Feeder				
Breaker	**No. of Faults**	**Fault Contribution (%)**	**Customer Interruption**	**Customer Interruption Contribution (%)**
Feeder breaker	7	37%	49522	35%
2LLE4A/1 22 kV Recloser	12	63%	90269	65%

Figure 5.4 shows that the Nulec Recloser at 2LLE4A/1 experiences the majority of the faults that affect many customers. The portion of the feeder downstream of the Nulec Recloser 2LLE4A/1 has a lot of customers and there is no back-feeding point on that portion.

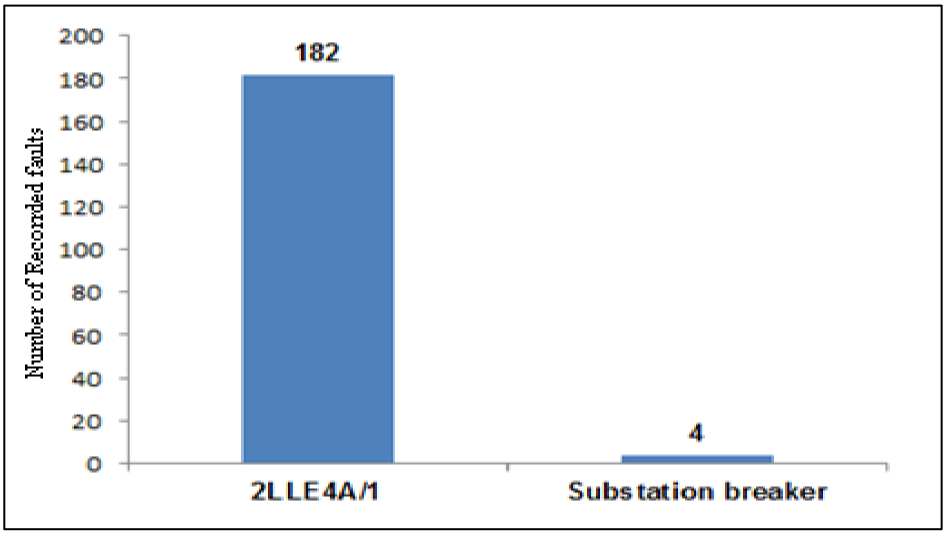

Figure 5.4: Lebohang/Lebohang 2 22 kV breaker faults.

The majority of trips are seen by the Nulec Recloser 2LLE4A/1 and only a few trips were encountered by the substation breaker.

5.2.1. Applying FLISR features on the Lebohang/Lebohang 2 22 kV OHL Feeder

The problem with the Lebohang/Lebohang 2 22 kV feeder is that it has limited back-feeding capabilities. So in order for FLISR to operate on this feeder, interconnectors from other supply sources (with N/O points) will have to be built to provide back-feeding capabilities. The existing N/O point at 2LLE5/1 will be replaced with a remotely controlled Nulec recloser for remote supply restoration. An additional recloser will be installed at 2LLE3 to improve supply restoration to the respective customers.

5.3. Case Study 3: Applying FLISR on an Underground Cable Feeder

The third case study was the Lebohang/Leslie Town 11 kV cable network. Remotely operated N/O point circuit breakers were simulated and will be installed. Figure 5.5 shows a reduced network diagram for Lebohang/Leslie Town 11 kV feeder.

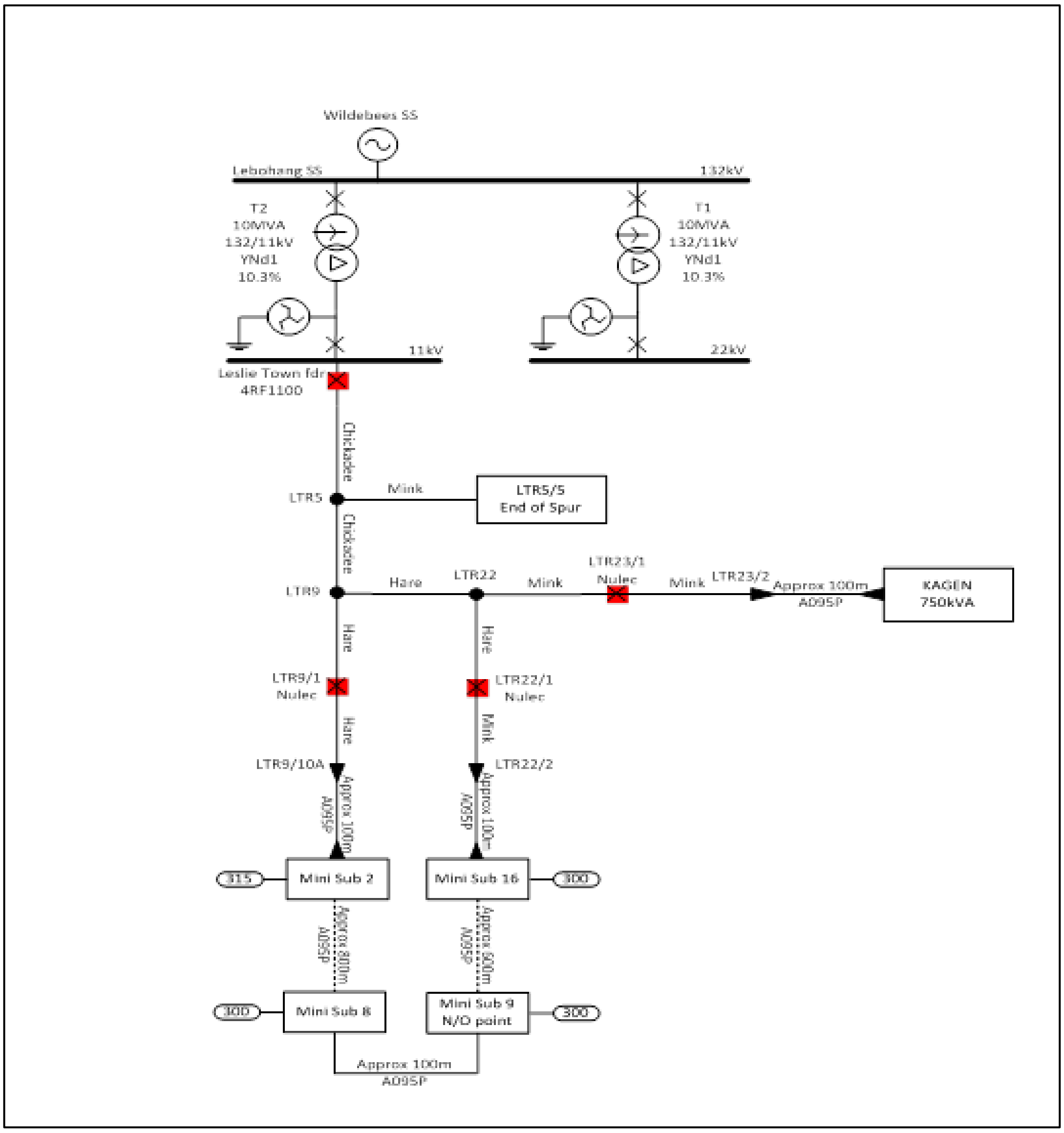

Figure 5.5: Lebohang/Leslie Town 11 kV cable network.

Table 5.5: The Lebohang/Leslie Town 11 kV Feeder characteristics

Feeder	Customers	Transformers	Line length	SAIDI	SAIFI
Lebohang/Leslie Town 11 kV cable	719	20	7.73 km	2.51 hr	3.41

The performance of this feeder was satisfactory as can be observed from the SAIDI and the SAIFI in Table 5.5. However, automated restoration is applied to see how it can improve the supply restoration of the feeder.

Table 5.6: Faults contribution per recloser.

Lebohang/Leslie Town 11 kV Cable Feeder				
Breaker	**No. of Faults**	**Fault Contribution (%)**	**Customer Interruption**	**Customer Interruption Contribution (%)**
LTR 11 kV Breaker	1	20%	687	28%
LTR22/1 11 kV Recloser (Mini-sub Problem)	1	20%	340	14%
LTR9/1 11 kV Recloser (Mini-sub Problem and cable theft)	2	40%	699	28.98%
Lebohang TRFR 1 132 kV Breaker (Wire touching the conductor)	1	20%	686	28.44%

Table 5.6 presents the fault contribution per recloser. It can be seen that for a fault contribution impact is high when LTR9/1 operates for a fault. This cable feeder has a number of mini-substations of which most are old and need to be replaced. The feeder begins with an OHL and has reclosers at LTR9/1 and LTR22/1. Interconnectors with remotely operated N/O points will be introduced to quickly restore other customers during fault conditions. LTR mini sub 9 is N/O.

6. Simulation Results

6.1. Load flow studies

DIgSILENT PowerFactory was used for the load flow simulations. In distribution networks the maximum allowable voltage variation is a major and often primary constraint in network planning and design. Assumptions for allowable voltage regulation limits have a major impact on both the capital and life cycle costs of distribution networks [23]. Traditional rural networks (networks in these case studies) comprise long (20-100 km) MV feeders, typically operating at 11, 22 or 33 kV (22 kV for these case studies), supplying individual or small groups of customers through small (16-200 kVA) distribution transformers. Most LV feeders are short (<100 m) relative to the MV feeders, and most of the voltage drop occurs in the MV network [23]. The limits and voltage drops refer to steady-state values and voltage variation occurs because of changes in load and active voltage control. It must be ensured that the expected voltages and voltage drops do not exceed acceptable limits. This is achieved by feeder load flow analysis, and comparison of the steady-state simulation results with utility standards for voltage limits and voltage drop limits. For this project, the voltage limits were based on Eskom distribution reliability standard DST_34-542 and NERSA limits as per NRS 048-2 which are maximum of 1.05 p.u. and minimum of 0.925 p.u. The following steps were followed during the load flow studies:

- **Step 1**: It is initially assumed that the voltage at all points along the feeder is the same as the voltage measured at the substation busbar. This information can be automatically received by the remote measurement systems installed at the substations.

- **Step 2**: Active and reactive components of the primary currents absorbed and/or injected in the system by the electrical elements are calculated.

- **Step 3**: The procedure to obtain the current in all network branches consists of two stages:
  - A search in the node set is performed adding the current values in the set of branches and
  - Currents from the final sections up to the substation are accumulated.

- **Step 4**: Voltage drops in primary conductors are determined.

- **Step 5**: From the substation bus it is possible to obtain the voltage drops accumulated at any other part of the primary network and consequently the voltage values at any point.

- **Step 6**: The difference between the new voltage values for all nodes and the previous values is checked. If this difference is small enough comparing to a previously defined threshold, the solution for the load flow calculation was found and the system is said to be convergent. Otherwise, steps 2 to 6 are repeated, using the calculated voltages to obtain the current values. The threshold of 1% was chosen, because it leads to accurate values for the voltages and currents without requiring too much processing time

At the end of the process, the active and reactive powers and the technical losses in the primary conductors were determined for all branches of the feeder. The load flow study is used to determine whether any equipment is overloaded and this will make the decision on whether a N/O point can be closed remotely.

6.2. Case study 1: Balfour Munic/Siyathemba 1 and 2 (1BMS and 2BMS) 22 kV OHL

The Balfour Munic/Siyathemba 1 and 2 22 kV feeders are fed from the Balfour Munic 88/22 kV Substation. Both feeders are constructed with Mink conductors.

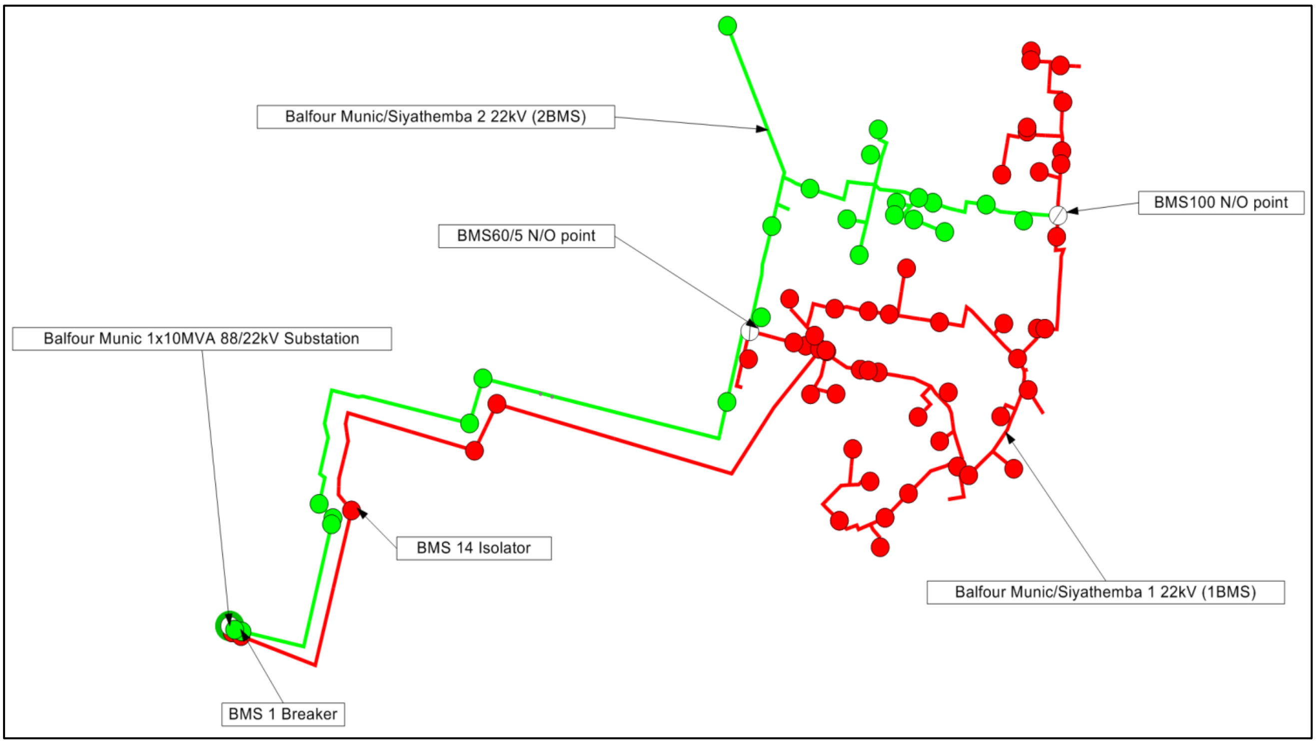

Figure 6.1: The Balfour Munic/Siyathemba 1 and 2 22 kV Feeder Geographic Layouts

Figure 6.1 presents a geographic layout of the Balfour Munic/Siyathemba 1 and 2 22 kV feeders which indicate the protection configuration by showing breakers and N/O point positions (represented by pole numbers). Both feeders have two options of back-feeding each other.

Table 6.1: Feeders parameters before back-feeding

Feeder	Peak Load(MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Balfour Munic/Siyathemba 1 22 kV (1BMS)	3.2	3.2	58.67	0.98	Mink
Balfour Munic/Siyathemba 2 22 kV (2BMS)	0.85	0.85	44.80	1.01	Mink

Table 6.1 presents the Balfour Munic/Siyathemba 1 & 2 22 kV feeder parameters. The parameters illustrate that both feeders are healthy as the loadings and voltages are within the limits. According to the Eskom Conductor Current Rating Distribution Standard DST-240-100176272 [13], the thermal loading of the conductor should not exceed 80% of the rated current of that conductor during normal conditions.

The voltage profiles in Figure 6.2 and Figure 6.3 show that the voltage is within the limits as per Eskom standard i.e. voltage must be between 0.925 p.u and 1.05 p.u.

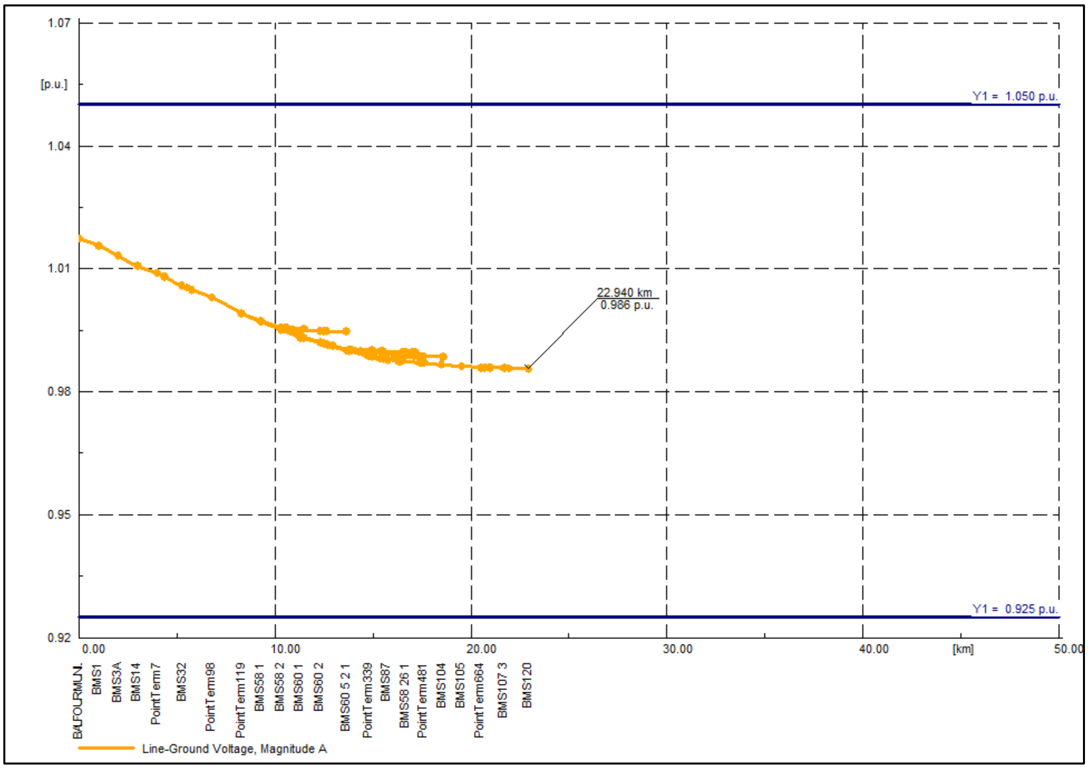

Figure 6.2: Balfour Munic/Siyathemba 1 22 kV Feeder Voltage Profile

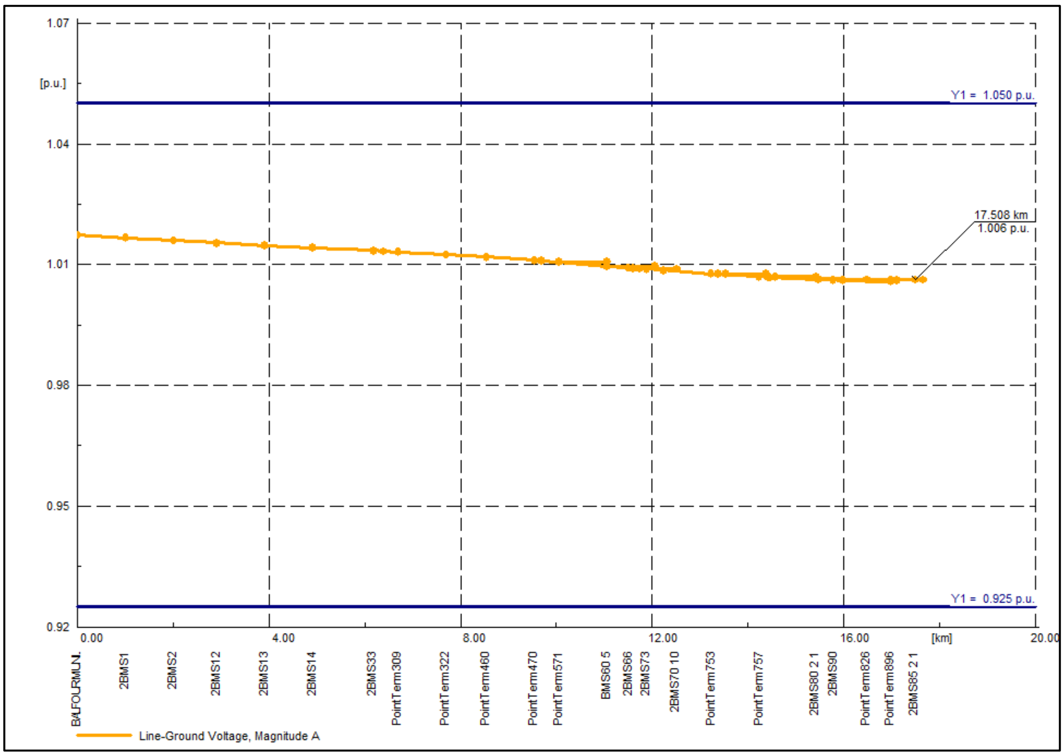

Figure 6.3: The Balfour Munic/Siyathemba 2 22 kV Feeder Voltage Profile

Automatic power restoration load flow studies were conducted to examine the possibility of back-feeding the Balfour Munic/Siyathemba 1 22 kV feeder with the Balfour Munic/Siyathemba 2 22 kV and vice versa. The studies calculated the amount of load that needs to be back-fed and checked whether the back-feeding interconnector is capable of back-feeding this load. The studies analysed the feasibility of the load transfers and the results are considered as constraints in the optimization procedure. Load transfers may not cause an overload on the conductors and transformers, nor reach the pickup threshold of the protective devices, nor exceed the limits of voltage range of the primary network. The checking of the constraints is performed by considering the voltage and thermal loading limits of back-feeding feeder if they are compatible with the period of the failure.

6.2.1. Back-Feeding Scenario 1: Losing the Balfour Munic/Siyathemba 2 22 kV (loosing 0.85 MVA)

The Balfour Munic/Siyathemba 1 & 2 22 kV feeders currently have peak loads of 3.2 MVA and 0.85 MVA, respectively. If the Balfour Munic/Siyathemba 2 22 kV feeder breaker opens, all Balfour Munic/Siyathemba 2 customers will lose supply. To back-feed these customers, the N/O point at BMS 100 will automatically close to back-feed the whole of the 0.85 MVA load through Balfour Munic/Siyathemba 1 22 kV. The Balfour Munic/Siyathemba 1 22 kV feeder will be able to carry 2BMS load without violating conductor thermal and voltage limits as shown in Table 6.2. The 22 kV MV feeders are standardised to be loaded up to 5 MVA as per the Eskom MV Reliability Standard.

Table 6.2: Parameters after closing BMS 100 to transfer load from 2BMS to 1BMS

Feeder	Peak Load(MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Balfour Munic/Siyathemba 1 22 kV	3.2	4.08	61.63	0.97	Mink
Balfour Munic/Siyathemba 2 22 kV	0.85	0	0	-	Mink

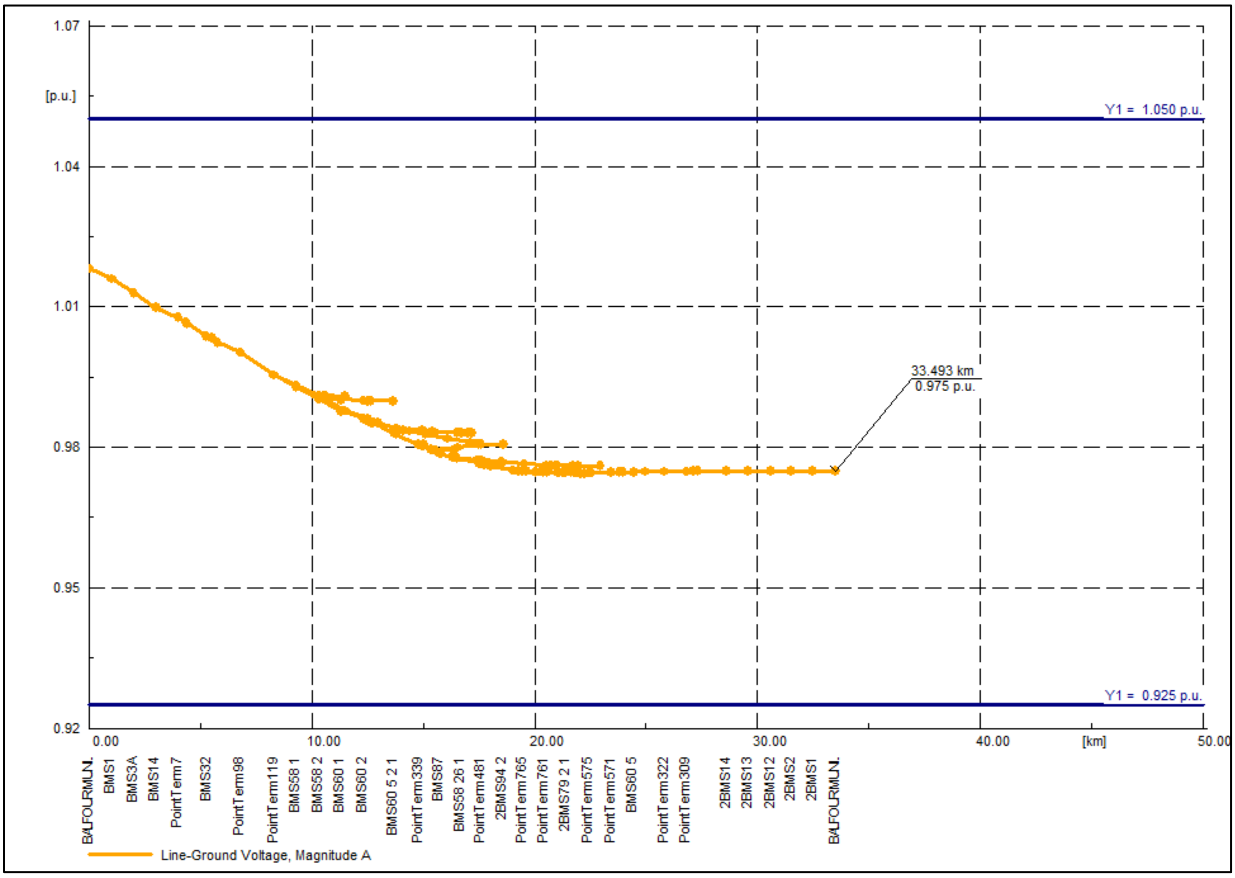

Figure 6.4: 1BMS voltage profile after back-feeding 2BMS load through BMS 100 N/O Point

6.2.2. Back-feeding Scenario 2: losing the Balfour Munic/Siyathemba 1 22 kV (losing 3.2 MVA)

If there is a fault on the Balfour Munic/Siyathemba 1 22 kV feeder affecting the entire feeder (losing the entire 3.2 MVA load), the remotely operated N/O point at BMS 60/5 will be closed to transfer the entire load from 1BMS to Balfour Munic/Siyathemba 2 22 kV without violating thermal and voltage limits as shown on Table 6.3.

Table 6.3: Closing N/O point at BMS 60/5

Feeder	Peak Load(MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Balfour Munic/Siyathemba 1 22 kV	3.2	0	0	-	Mink
Balfour Munic/Siyathemba 2 22 kV	0.85	4.09	58.61	0.96	Mink

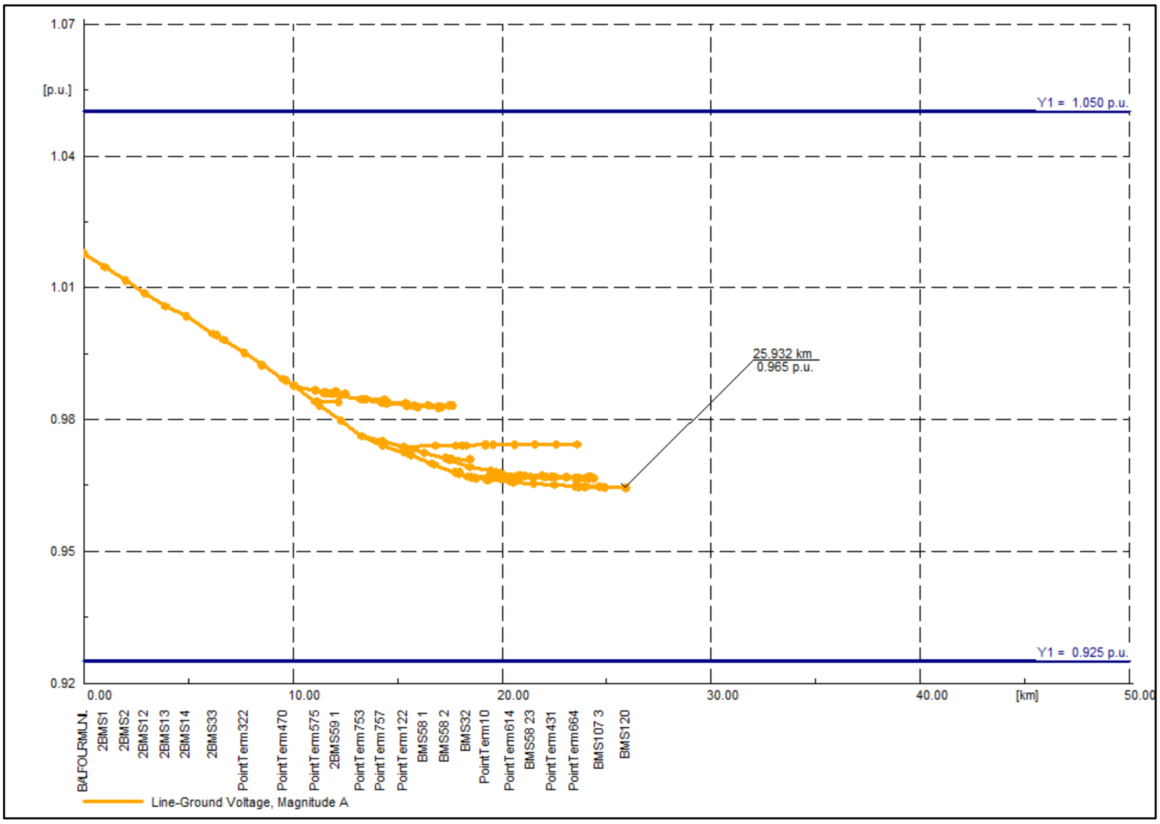

Figure 6.5: 2BMS after back-feeding 1BMS with BMS60/5 N/O point

- The peak load does not exceed the 5 MVA limit of the 22 kV network according to the Eskom reliability standard during back feeding. So back-feeding is possible.
- The voltages are within the NERSA limits which are 1.05 p.u. and 0.925 p.u.
- The thermal loading for a healthy network should be between 0% and 80% of the rated conductor capacity according to the Eskom Reliability Standard. Both back feeding scenarios are within these limits.
- The protection configuration of the network when back feeding is feasible. When there is a fault, the protection configuration will isolate the affected part of the network.

6.2.3. Protection Settings

Figure 6.6 is the protection coordination and configuration of the Balfour Muni/Siyathemba 1 22 kV feeder. The feeder breaker looking at the whole feeder, the first auto-recloser is looking at the BMS58/1 tee-off and the second auto-recloser is looking at BMS62.

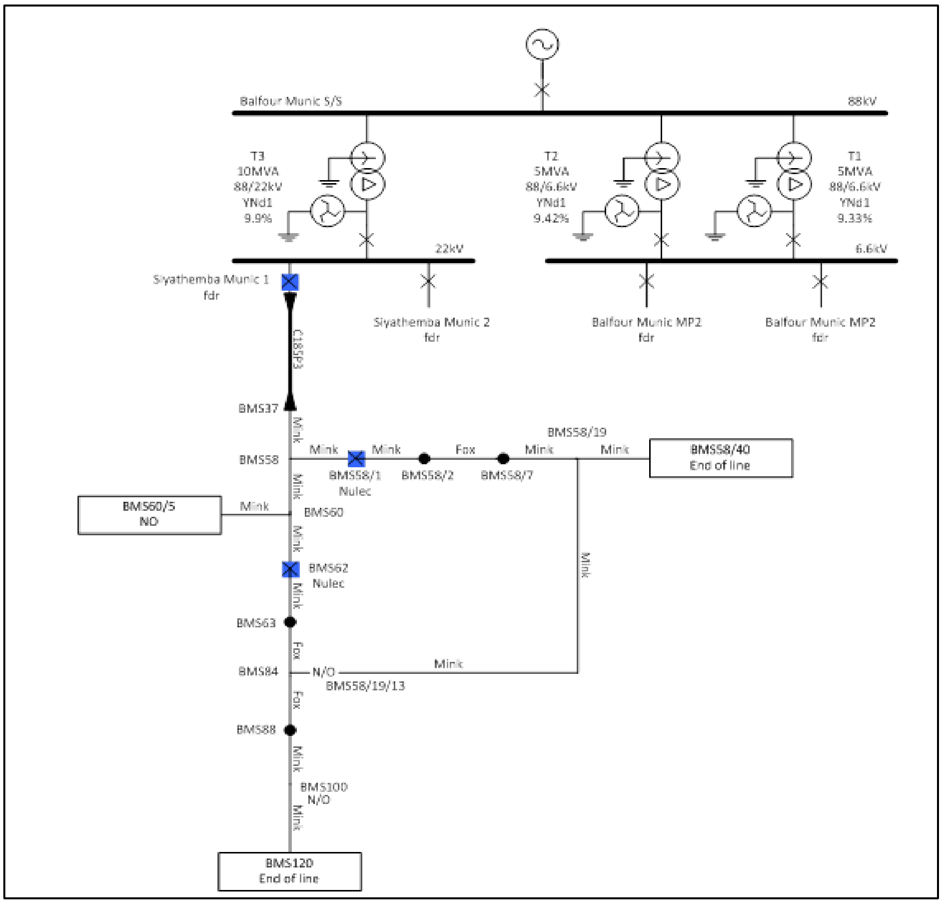

Figure 6.6: Balfour Munic/Siyathemba 1 22 kV reduced single line diagram

Table 6.4 is the three-phase, phase-phase and single-phase fault levels of Balfour Munic/Siyethamba 1 22 kV that were used to determine the protection setting for the breaker and auto-recloser.

Table 6.4: Fault levels for the Balfour Munic/Siyathemba 1 22 kV at Balfour Munic Substation.

Position	3phase [A]	phase-phase [A]	1phase [A]
Feeder breaker	2369	2052	306
BMS1	2366	2049	306
BMS37	2252	1950	301
BMS58	1932	1673	288
BMS58/1	1918	1661	288
BMS58/2	1904	1649	287
BMS58/7	1821	1577	283
BMS58/19	1672	1448	276
BMS58/19/13	1531	1326	270
BMS58/40	1454	1259	265
BMS60	1904	1649	287
BMS60/5	1837	1591	284
BMS62	1877	1625	286
BMS63	1864	1614	285
BMS84	1541	1335	270
BMS88	1487	1288	267
BMS100	1376	1192	261
BMS120	1221	1057	251

Breaker settings are as shown in Table 6.5:

Table 6.5: Feeder breaker settings

Breaker	Overcurrent	Earth fault	Sensitive earth fault
Feeder Breaker	326 A	40 A	5 A
BMS58/1	230 A	20 A	3 A
BMS62	230 A	20 A	3 A

During normal operation, both feeders are in service and each carry a portion of the load. The time and instantaneous overcurrent elements are coordinated with the downstream relays according to the system conditions. When the Balfour Munic/Siyathemba 1 22 kV OHL feeder goes out of service the entire load current is carried by the Balfour Munic/Siyathemba 2 22 kV OHL feeder and the time and instantaneous overcurrent settings have to be changed due to the change in system conditions to achieve proper coordination.

6.2.4. Simulations for case study 1

Transient stability studies of the power system are crucial in determining the system's ability to maintain synchronism when subjected to a severe transient disturbance. The disturbance can be a fault on the transmission line, loss of a large load or loss of generation. In these studies, a three-phase short circuit fault on the line was considered for a period of 5 seconds. After running the simulation with these fault conditions, results of the terminal voltage and current were monitored as clearly indicated on Appendix B.

6.2.4.1. Fault detection

Simulations were performed to create events and to study the behaviour of the system during the fault and power restoration. The first step was to simulate a three-phase short circuit fault in the system at t = 5 seconds with a fault resistance of 1 ohm. The fault was introduced in feeder 1 between pole BMS11 and pole BMS12. The next event was fault detection by tripping a protection device which was the recloser at BMS1 as seen on the Figure 6.7 below which affected all 2836 customers.

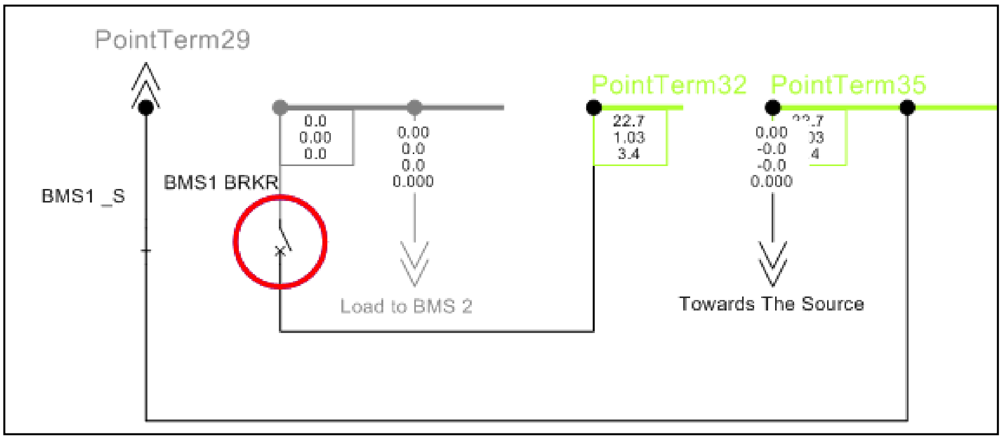

Figure 6.7: Fault detection.

6.2.4.2. Fault Isolation

The next event was fault isolation by opening an isolation switch at BMS14 as seen on the Figure 6.8 below. Figure 6.8 also shows the fault location.

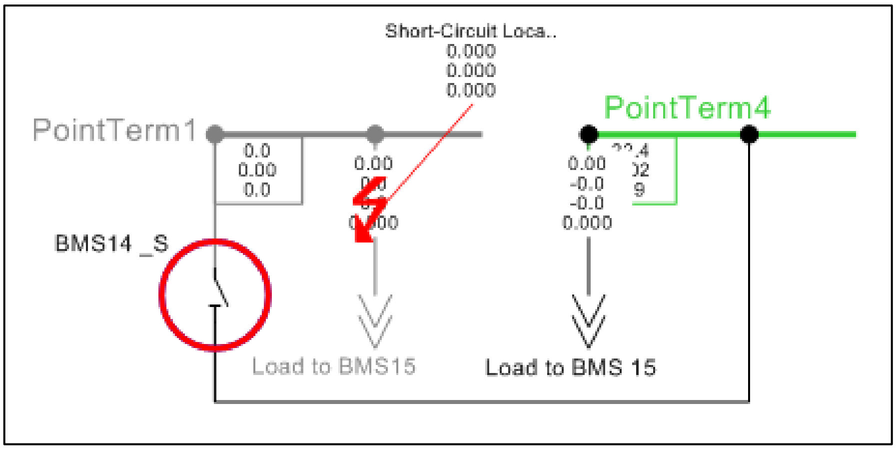

Figure 6.8: Fault Isolation.

6.2.4.3. Service Restoration

The last event is power restoration by closing the N/O point and restoring supply to healthy customers through the Balfour Munic/Siyathemba 2 22 kV feeder as seen on Figure 6.9. At 5.4 seconds the supply was restored back to healthy customers. The N/O point at BMS60/5 restored all 2836 customers since there are no customers at the isolation point.

Figure 6.9: Service restoration.

An automated N/O point will be represented by a Nulec recloser which costs as follows:

6.3. Case study 1 Costing

Scope:

- Install an automated N/O point at BMS 100
- Install an automated N/O point at BMS 60/5

The total cost for material and labour is **ZAR 204 713.67**

6.4. Case Study 2: Lebohang/Lebohang 2 22 kV OHL Feeder

The Lebohang/Lebohang 2 22 kV OHL feeder is fed from the Lebohang 132/22 kV substation via a single 10 MVA transformer. This feeder is currently loaded at 3.7 MVA and uses the Mink conductor. This feeder has 6117 customers which are residential loads and commercial loads.

The Lebohang/ Lebohang 2 22 kV feeder is one of the top 100 poor performing feeders in the Mpumalanga Operating Unit. Protection coordination and recloser positioning of this feeder is not good since it has one recloser at 2LLE4A/1 that is looking at most of the customers. According to the Eskom Reliability Standard, a recloser should look at a maximum of 1000 customers. Tripping of this recloser affects most of these customers which contributes to the poor performance of this feeder and this feeder does not have a back-feeding alternative. The existing N/O point at 2LLE5/1 from the Lebohang/Lebohang 1 22 kV feeder is not enough to restore supply to most of the customers when there is a fault.

The solution to resolve the performance of this feeder is to provide a back-feeding alternative interconnector with a remotely controlled N/O point, install an additional auto-recloser and automate the existing N/O point.

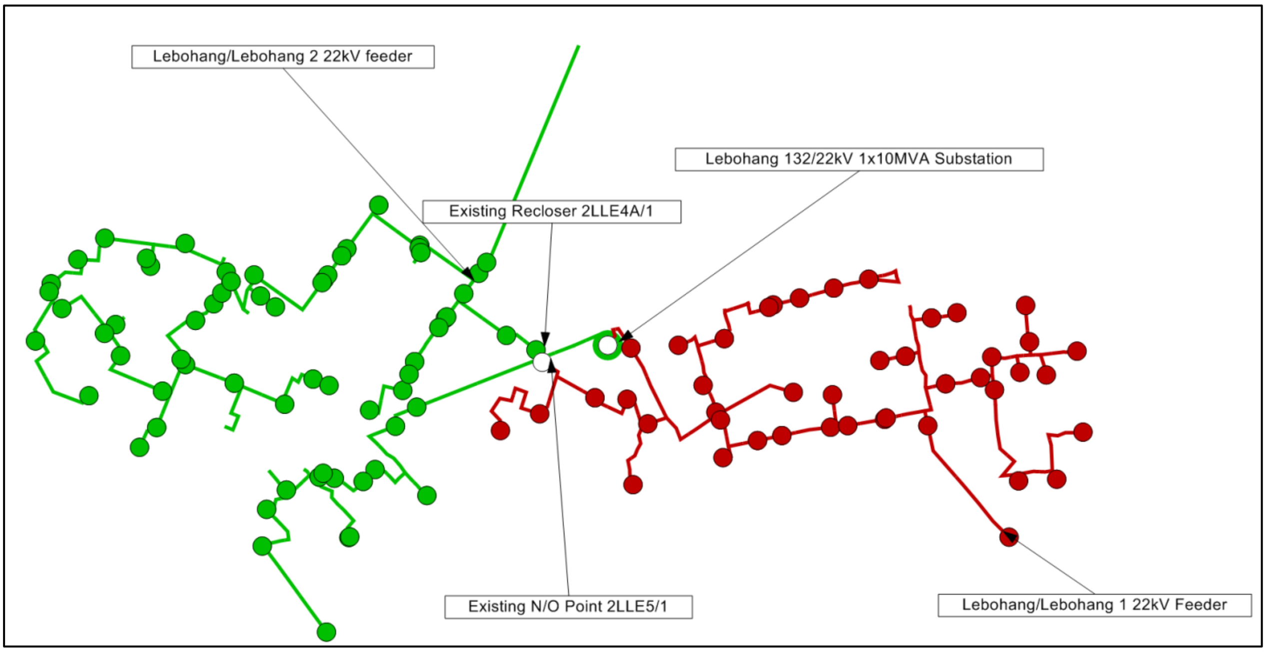

Figure 6.10: Lebohang/Lebohang 1 22 kV and Lebohang/Lebohang 2 22 kV feeders geographic layouts showing an existing N/O point and the existing auto-recloser

Figure 6.10 presents the geographical layout of the Lebohang/Lebohang 1 & 2 22 kV feeders and positions of the existing auto-recloser and N/O. Both feeders are currently used for back-feeding each other using the existing 2LLE5/1 N/O Point.

Table 6.6 presents the Lebohang/Lebohang 1, 2 22 kV and the Lebohang/Eendrag 22 kV feeder parameters under normal operating conditions. The parameters illustrate that all mentioned feeders are healthy as the thermal loadings and voltage limits are within the reliability limits.

The voltage profiles on Figure 6.11, Figure 6.12 and Figure 6.13 show that the voltage is within the limits as per Eskom standard i.e. voltage must be between 0.925 p.u and 1.05 p.u.

Table 6.6: Lebohang/Lebohang 1 22 kV, Lebohang/Lebohang 2 22 kV and Lebohang/Eendrag 22 kV feeder parameters

Feeder	Peak Load(MVA)	Losses (kW)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Lebohang 1 22 kV	3.6	12.62	43.9	1.02	Mink
Lebohang/ Lebohang 2 22 kV	3.7	12.9	45	1.00	Mink
Lebohang/Eendrag 22 kV	0.5	1.18	6.13	1.03	Mink

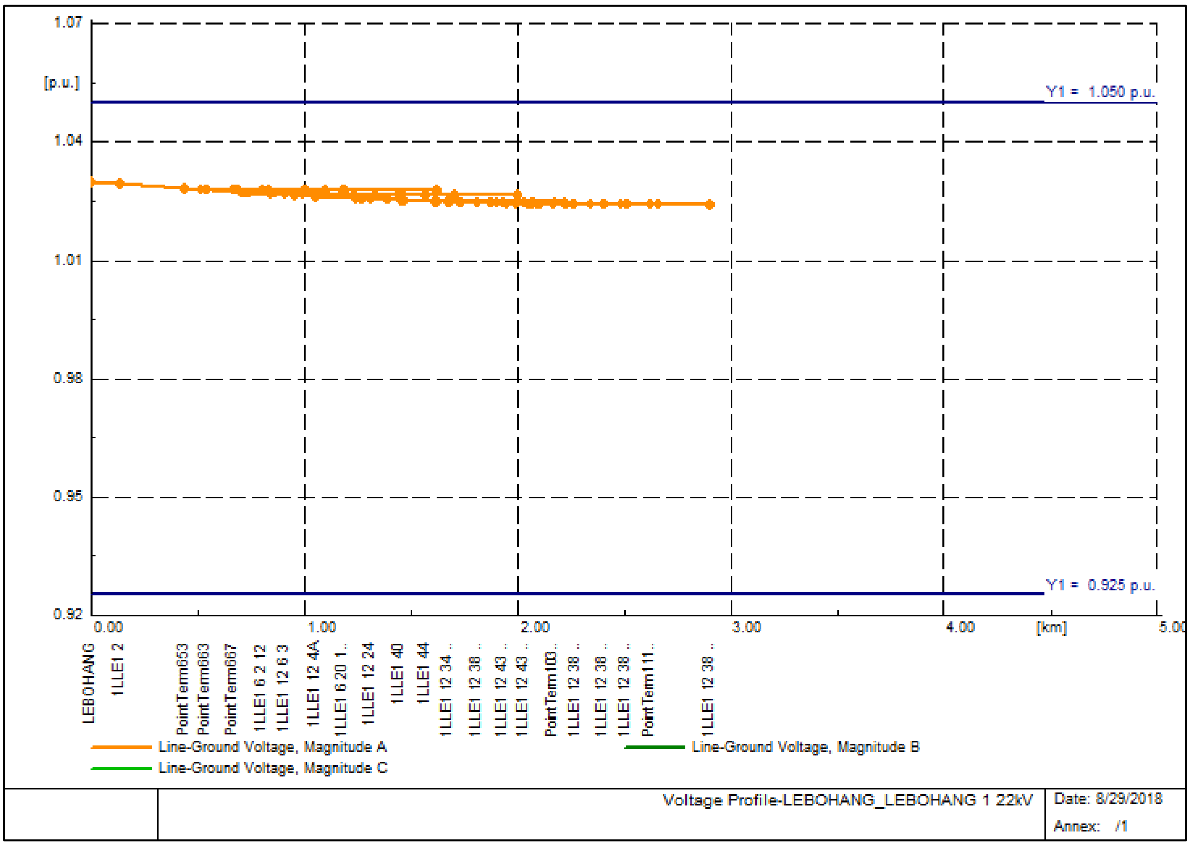

Figure 6.11: Lebohang/Lebohang 1 22 kV feeder voltage profile

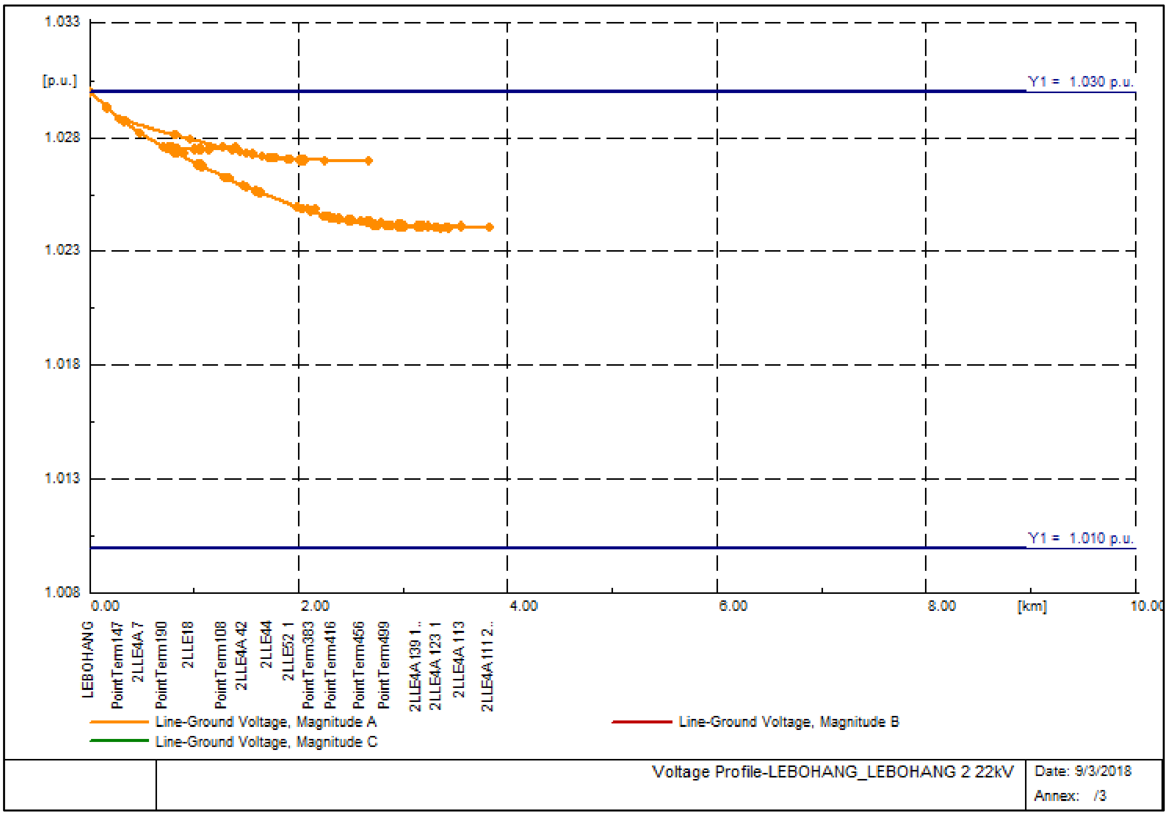

Figure 6.12: Lebohang/Lebohang 2 22 kV Voltage Profile before interconnector

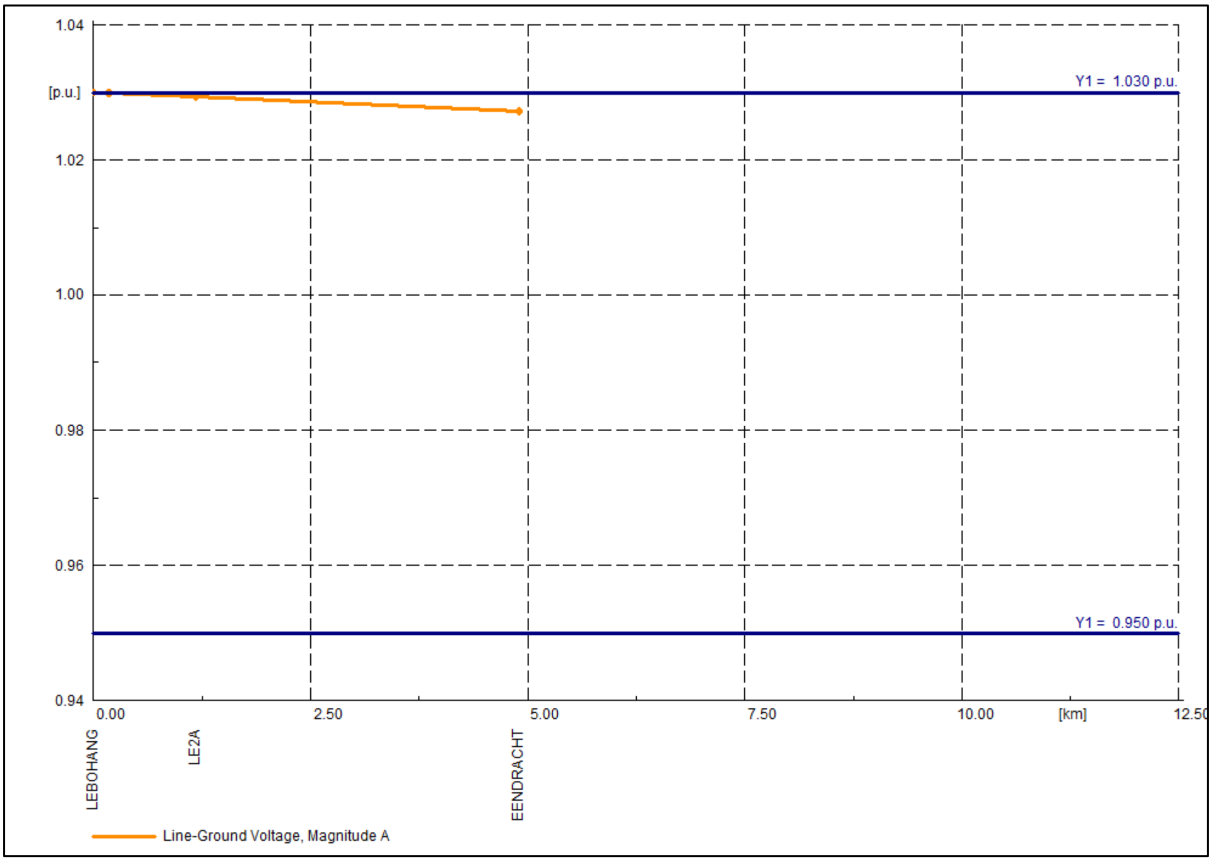

Figure 6.13: Lebohang/Eendrag 22 kV Voltage Profile before installing the interconnector

Figure 6.14 presents the Lebohang/Lebohang 2 22 kV feeder load forecast projection over the period of 21 years. The forecast shows that the Lebohang/Lebohang 2 22 kV feeder will exceed 5 MVA as from year 2022.

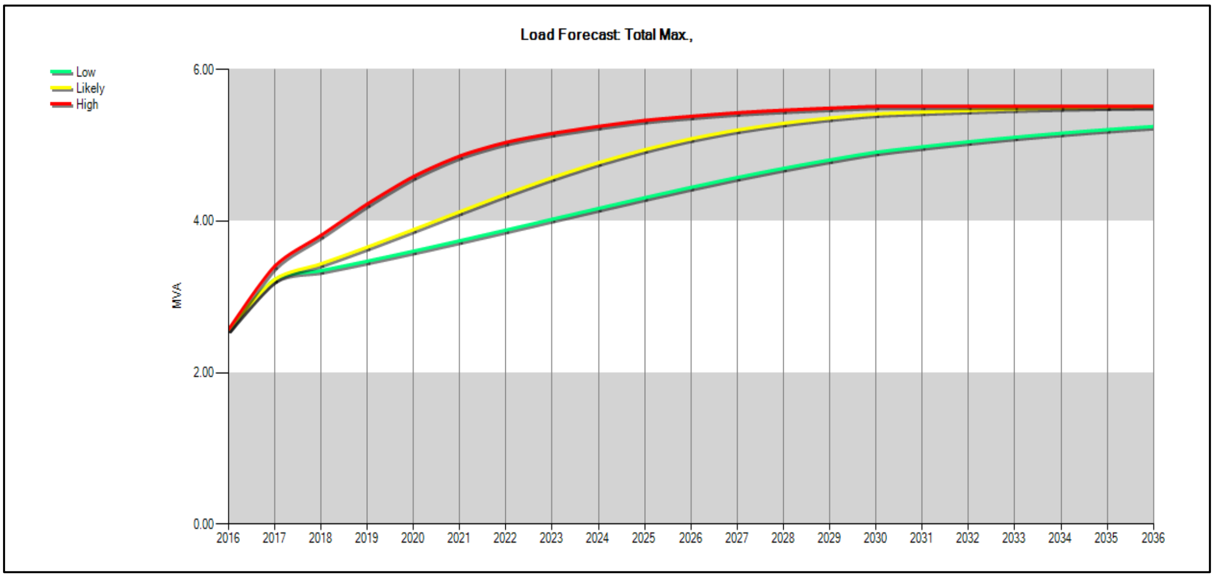

Figure 6.14: Lebohang/Lebohang 2 22 kV Load Forecast

The Lebohang/Lebohang 2 22 kV is mainly supplying two load profiles that are residential and commercial. Figures 6.15 and 6.16 present the Lebohang/Lebohang 2 22 kV residential and commercial load profiles during weekdays, respectively.

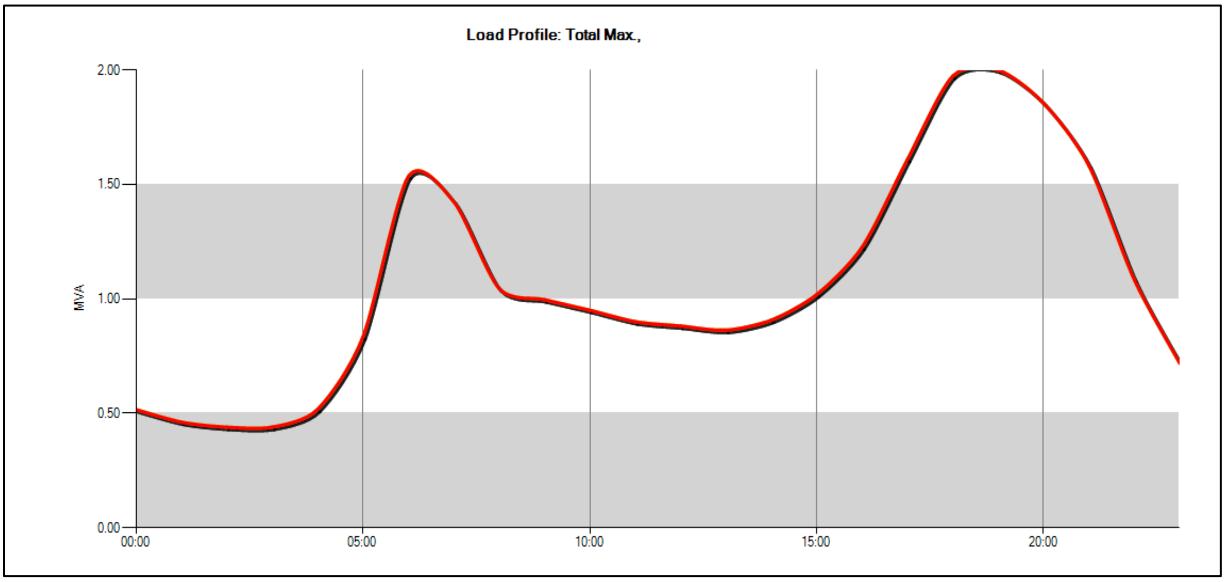

Figure 6.15: Lebohang/Lebohang 2 22 kV Load Profile for the township load vs hours

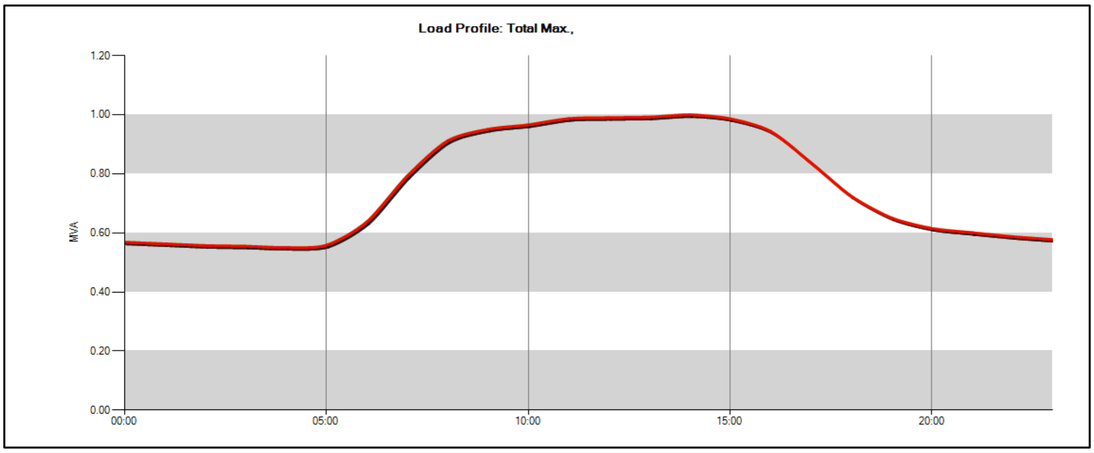

Figure 6.16: Lebohang/Lebohang 2 22 kV load profile for commercial load

Figure 6.17 presents the integration of the above load profiles. Normally, in winter during weekdays the Lebohang/Lebohang 2 22 kV feeder load peaks in the morning up to 2.2 MVA and afternoon up to 2.8 MVA. The studies were done using 3.7 MVA which was the highest recorded peak load that occurred in the afternoon.

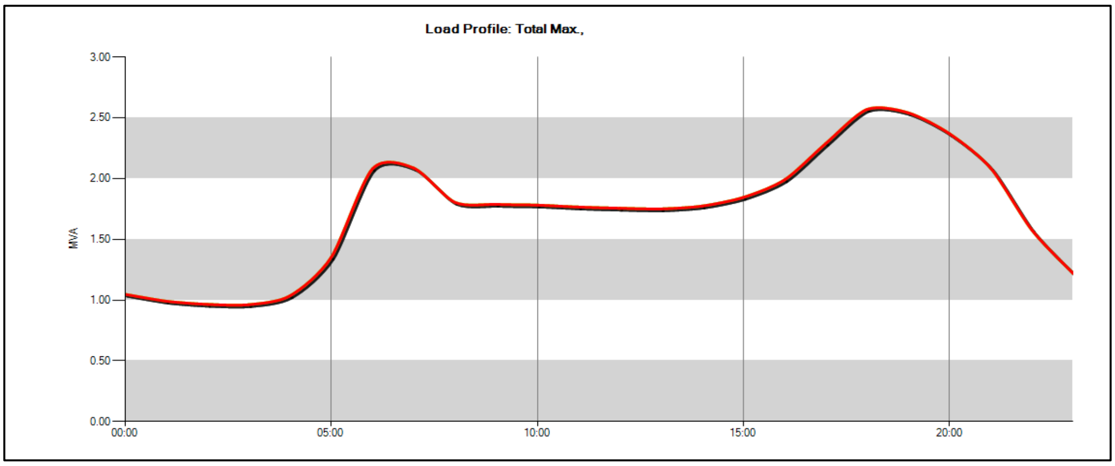

Figure 6.17: Lebohang/Lebohang 2 22 kV total load profile for both township and commercial loads

When the N/O Point at 2LLE5/1 is closed to back-feed the Lebohang Lebohang 2 22 kV feeder with the Lebohang Lebohang 1 22 kV feeder, the Lebohang/Lebohang 1 22 kV experiences backbone conductor thermal loading of 101.21% as it is exceeding 80% that a conductor should be loaded at which poses a threat to electrical equipment. Therefore it is necessary to provide a back-feeding alternative that will not violate these limits. This feeder needed more back-feeding capabilities in order for auto-restoration to be applied without violating any feeder parameter limits, see Table 6.7.

Table 6.7: Feeder parameters after closing the existing 2LLE5/1 N/O Point

Feeder	Peak Load(MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Lebohang 1 22kV	3.6	7.3	101.21	1.02	Mink
Lebohang/ Lebohang 2 22kV	3.7	0	0	-	Mink

6.4.1. Interconnector option 1

The scope of work for option 1 is as follows:

- Construct +/-0.7km Mink conductor interconnector from pole number 2LLE56 to 2LLE4/16/25.
- Create an automated N/O point by installing a circuit breaker between 2LLE56 and 2LLE4/16/25 for back-feeding purpose.
- Install an additional auto-recloser at pole 2LLE4A/61/1 to reduce the customer base seen by auto-recloser 2LLE4A/1.

Figure 6.18 and 6.19 present the geographical scope of work and voltage profile after implementing interconnector option 1.

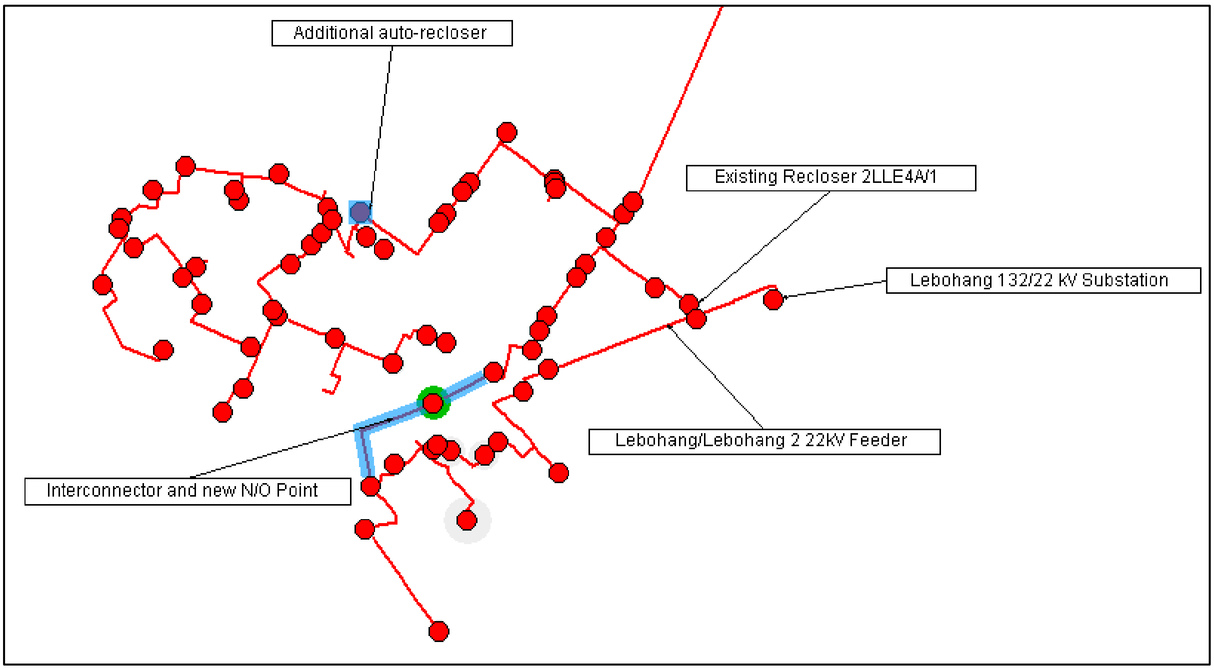

Figure 6.18: Option 1 Geographical scope of work.

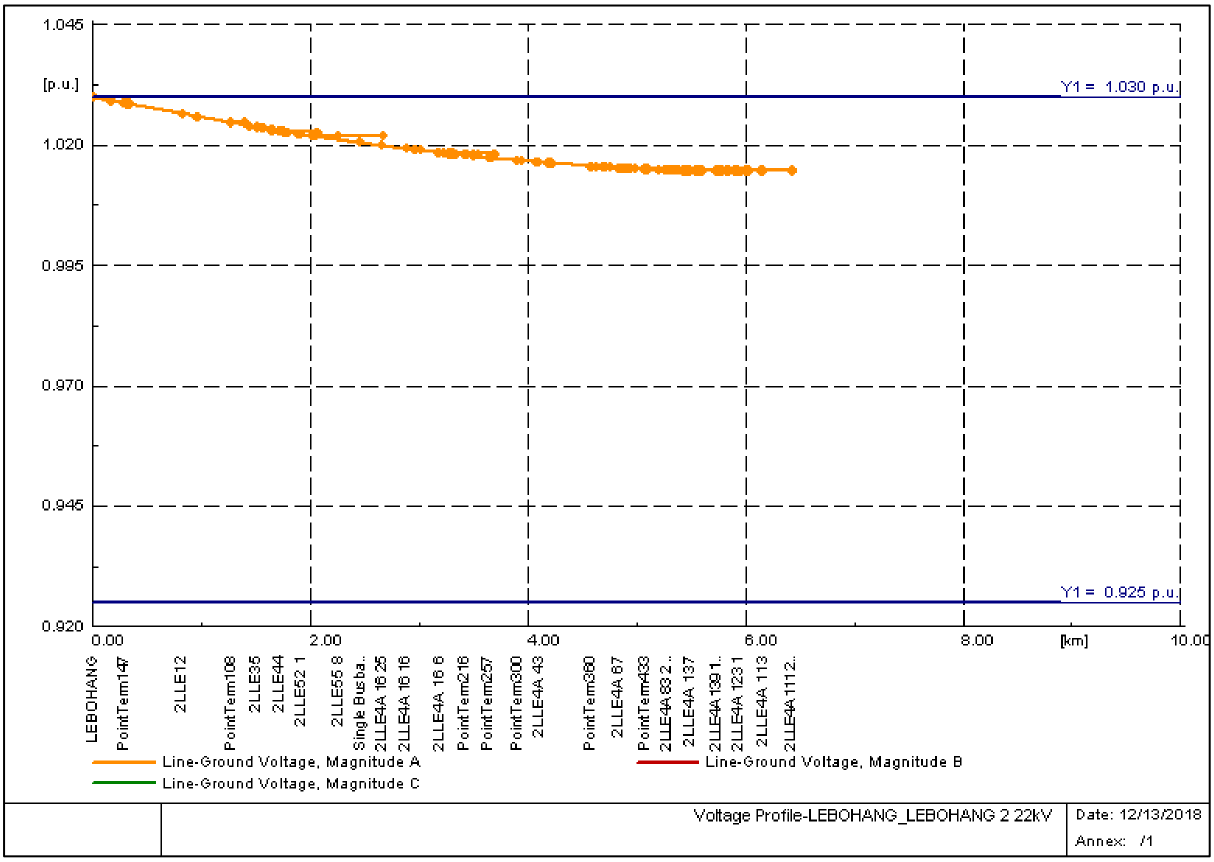

Figure 6.19: Voltage Profile of Lebohang/Lebohang 2 22 kV after the interconnector is installed

Table 6.8 presents the Lebohang/Lebohang 2 22 kV feeder parameters, after implementing interconnector option 1 scope of work.

Table 6.8: Feeder parameters after implementing option 1

Feeder	Peak Load (MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Lebohang 2 22kV	3.7	3.7	45	1.01	Mink

6.4.2. Interconnector option 2

The scope of work for the second option is as follows:

- Build a 5 km Mink interconnector from the Lebohang/Eendrag 22 kV closest pole number from the backbone to 2LLE4A/139/10
- Install automated N/O point on the interconnector.
- Install an additional auto-recloser at pole 2LLE4A/61/1 to reduce the customer base seen by auto-recloser 2LLE4A/1.

Figure 6.20 presents the geographical scope of work, Figure 6.21 presents the Lebohang/Lebohang 2 22 kV voltage profile and Figure 6.22 the Lebohang/Eendrag 22 kV voltage profile, after implementing interconnector option 2.

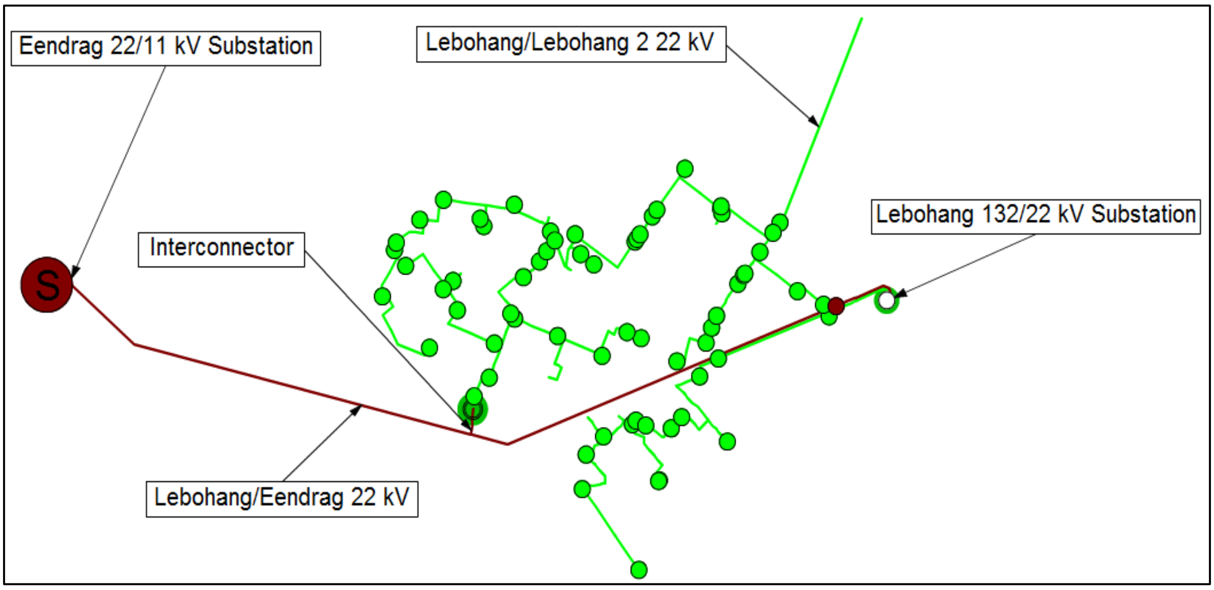

Figure 6.20: Lebohang/Lebohang 2 22 kV OHL feeder interconnected with Lebohang/Eendrag 22 kV OHL feeder.

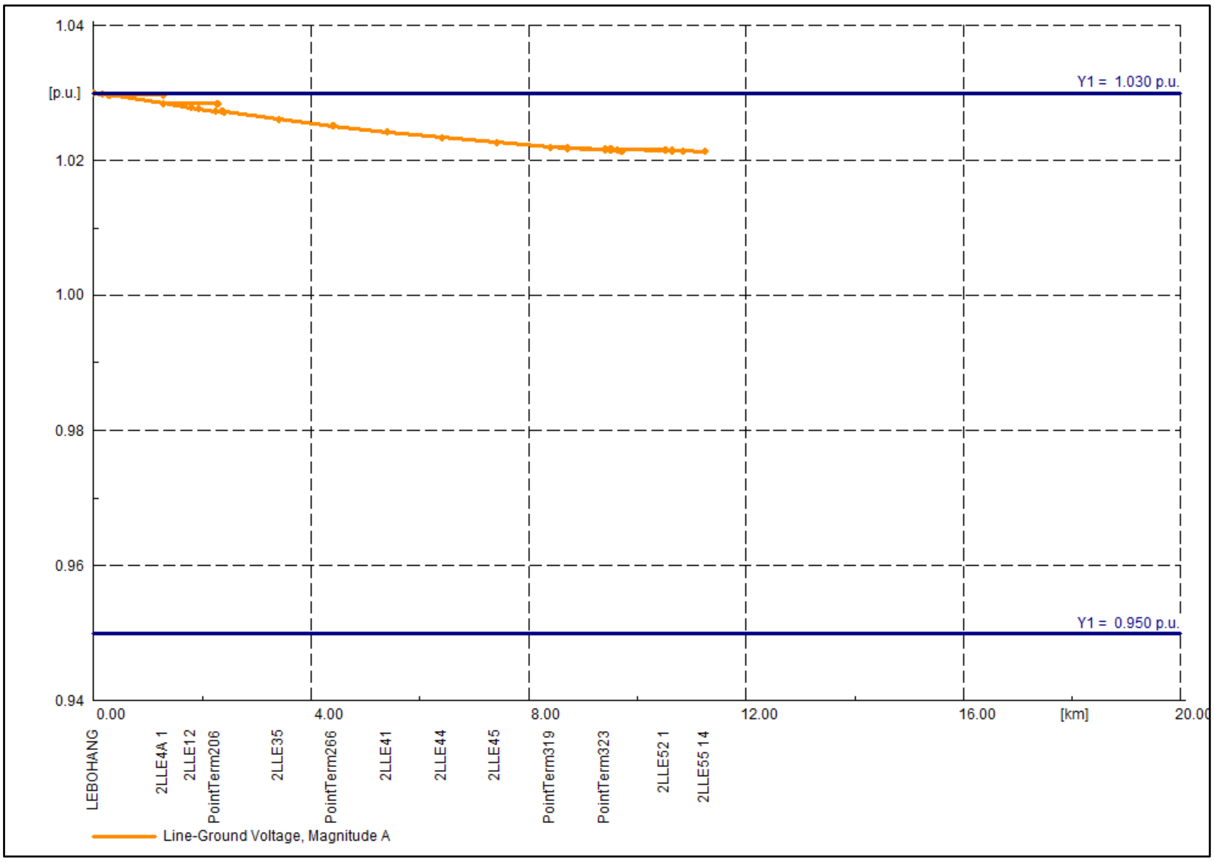

Figure 6.21: Lebohang/Lebohang 2 22 kV feeder voltage profile after interconnector is installed

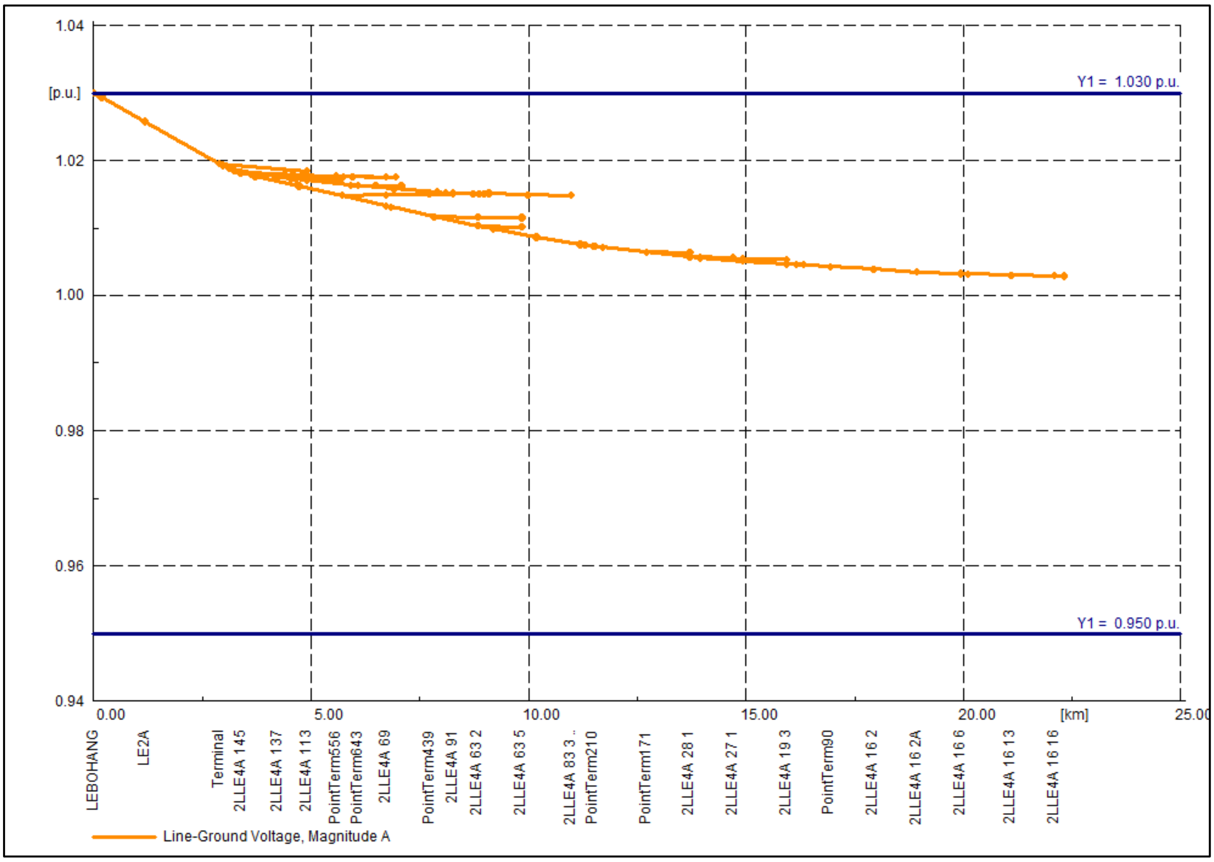

Figure 6.22: Lebohang/Eendrag 22 kV feeder voltage profile after interconnector is installed

The Lebohang/Eendrag 22 kV feeder is highly recommended as a solution to back-feed Lebohang Lebohang 2 22 kV because it has 4.5 MVA capacity to back-feed and it is built using a Mink conductor that has an 80% of its 7.5 MVA carrying capacity. Table 6.9 shows the parameters of both feeders after closing the proposed N/O point with the Lebohang/Eendrag 22 kV taking load from Lebohang/Lebohang 2 22 kV feeder.

Table 6.9: Parameters after implimenting option 2

Feeder	Peak Load (MVA)	Total Apparent Power (MVA)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Lebohang 2 22 kV	3.7	1.05	31.28	1.01	Mink
Lebohang/ Eendrag 22 kV	0.5	3.12	38.13	1.02	Mink

6.5. Case study 2 Costing

Scope:

- Build a 5 km Mink conductor interconnector from the Lebohang/Eendrag 22 kV feeder to 2LLE4A/139/10

- Install an automated N/O point at the interconnector for back-feeding.
- Install an additional auto-recloser at pole 2LLE4A/61/1 to reduce the customer based seen by auto-recloser 2LLE4A/1.

The total cost for material and labour is **ZAR 225 915.45**

Table 6.10 Case Study 2 Life Cycle Cost Option Evaluation

Project Evaluation Model v 14-01

Project inputs		Project ID	
Network Investment Category	Strengthening/Reliability - Mandatory	Project Name	**Case Study 2**
Decision criteria	Economic LCC	Remotely controlled N/O point.	
Project start year	2019	☑ Show incremental costs	
Final year of evaluation	2044		
Year of commercial operation	2020	Print	
Customer Interruption Costing method	SAIDI		

Project summary results (Incremental Net Present Costs in 2014 base year)

	Alternative 1	Alternative 2
NPC Acquisition	R 391 544	R 155 186
NPC Losses	R 190 515	R 134 948
NPC O&M Scheduled (exc Energy)	R 134 440	R 116 630
NPC O&M Unscheduled	R 92 137	R 145 609
NP Disposal Cost / Value	R 0	R 0
Life-Cycle Cost to Eskom	**R 808 637**	**R 552 373**
NP Customer Interruption cost	R 0	R 0
Life-Cycle Cost to Eskom & Customers	**R 808 637**	**R 552 373**

☑ Alternative 1:
☑ Alternative 2:
☐ Alternative 3:
☐ Alternative 4:

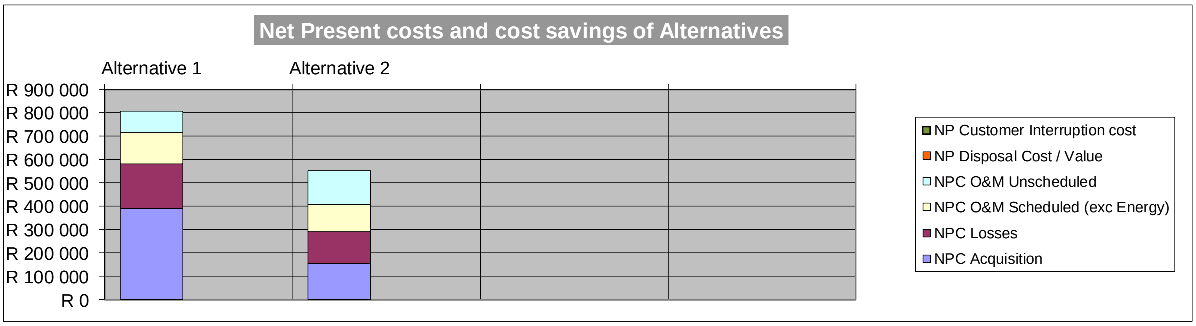

Table 6.10 present the evaluation of option 1 and 2. Option 2 has the least life cycle cost. The life cycle cost is influenced by material and labour cost, maintenance cost and losses cost. Option 2 is the most feasible option.

6.6. Case Study 3: Cable feeder: Lebohang/Leslie Town 11 kV underground cable.

The Lebohang/Leslie Town 11 kV feeder is fed from the Lebohang 88/11 kV Substation. This feeder is constructed with both overhead line and cable. The backbone is made of Chickadee conductor, Hare conductors and A095P cable. The Lebohang substation consists of a single 10 MVA (88/11 kV) transformer.

Figure 6.23 shows the geographical layout of the Lebohang/Leslie Town 11 kV feeder which also indicates the existing positions of auto-reclosers and N/O point.

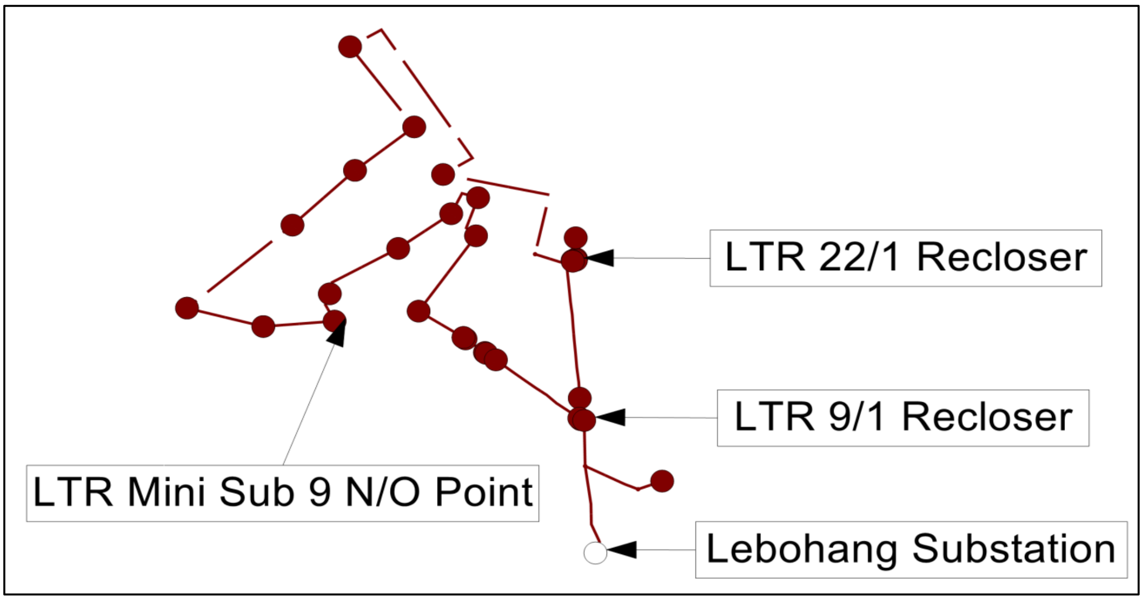

Figure 6.23: Geographic layout of Lebohang/Leslie Town 11 kV cable feeder

Table 6.11 shows the Lebohang/Leslie 11 kV feeder parameters. The parameters illustrate that the feeder is healthy as the thermal loadings and voltage limits are within the Eskom Reliability limits.

Table 6.11: Feeder parameters before automating the N/O point

Feeder	Peak Load(MVA)	Losses (KW)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Leslie Town 11 kV	1.6	5.75	19.98	1.023	Chickadee, Hare and Cable A095P

Figure 6.24 shows the voltage profile of the Lebohang/Leslie Town 11 kV feeder.

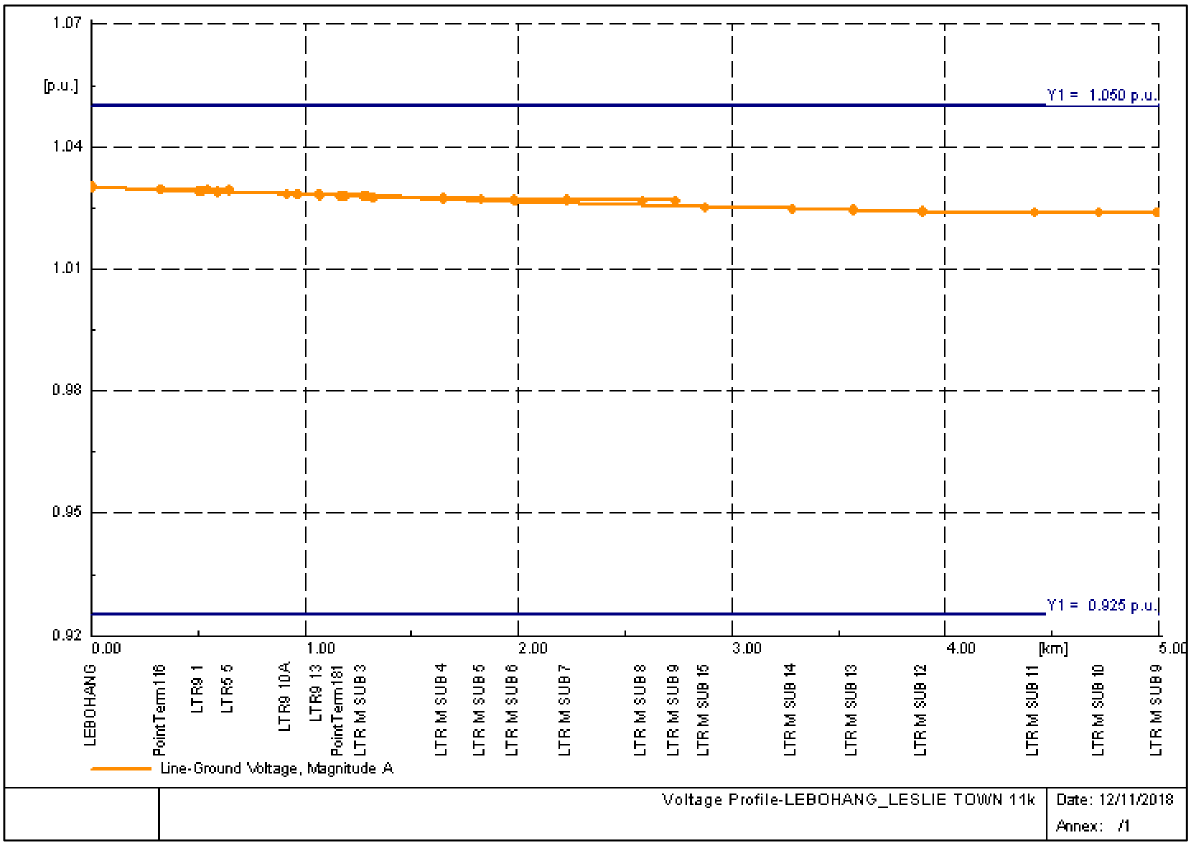

Figure 6.24: Lebohang/Leslie Town 11 kV cable feeder voltage profile.

Figure 6.25 shows the Lebohang/Leslie Town 11 kV feeder load forecast projection over the period of twenty one years. The forecast shows that this feeder will not exceed 3 MVA which is the maximum loading for 11 kV feeder as per the Eskom Reliability Standard.

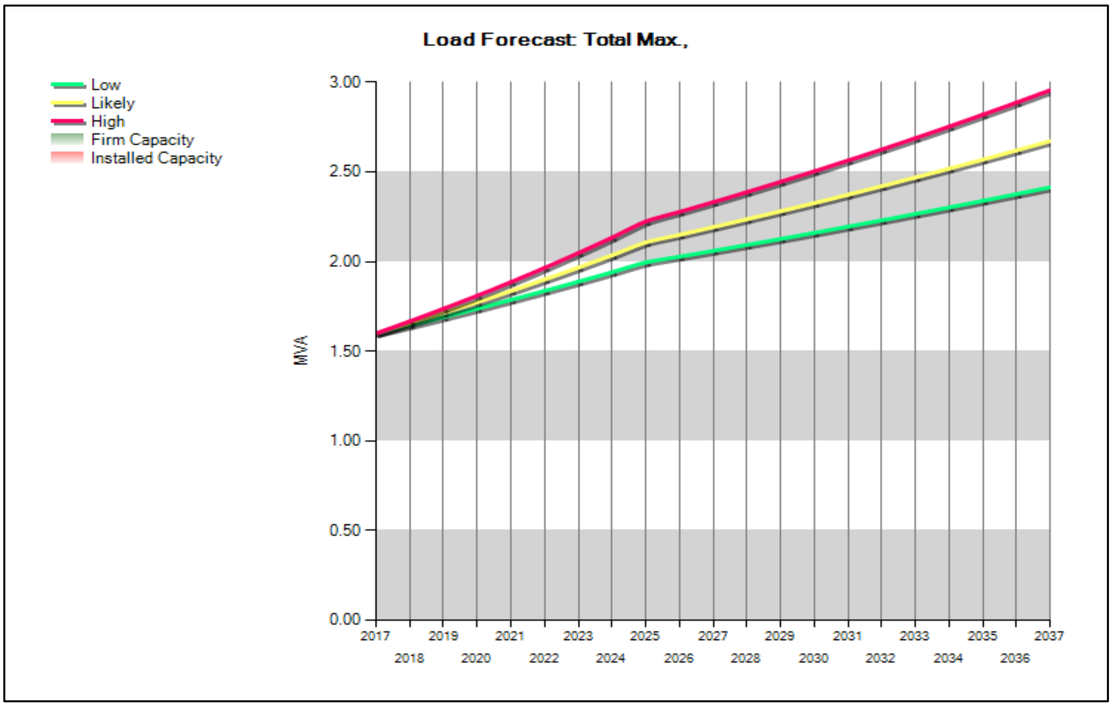

Figure 6.25: Lebohang/Leslie Town 11 kV Cable Feeder Load forecast

Lebohang/Leslie Town 11 kV feeder is supplying urban residential load types. Figure 6.26 shows the Lebohang/Leslie Town 11 kV feeder load profile in summer during weekdays. The Lebohang/Leslie Town 11 kV feeder load peaks in the morning up to 1.25 MVA and afternoon up to 1.53 MVA. The studies were done using 1.6 MVA which was the highest recorded peak load that occurred in the afternoon.

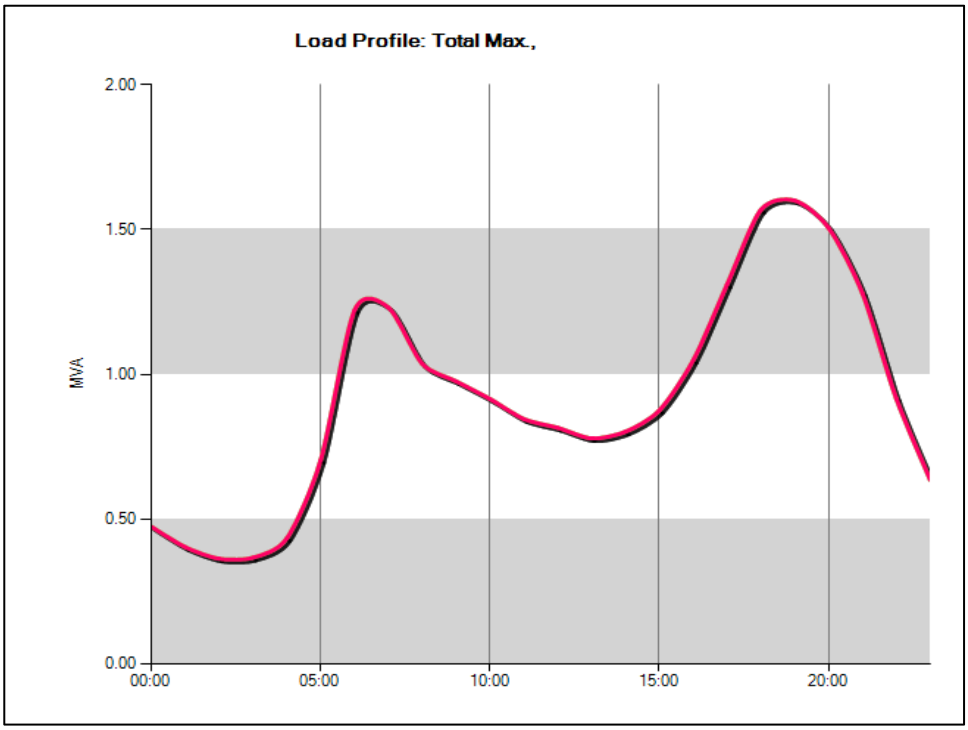

Figure 6.26: Lebohang/Leslie Town 11kV Cable Feeder Load Profile

6.6.1. Fault Scenario 1

Introducing a fault at LTR mini sub 1, the breaker at LTR 9/1 will open and automatically close the N/O point at LTR mini sub 9 in order to back-feed affected customers. In this case the automated N/O point will be able to back-feed customers without violating thermal and voltage limits. This can be seen from the Table 6.12 and Figure 6.27 below.

Table 6.12: Feeder parameters when introducing a fault at LTR mini sub 1

Feeder	Peak Load(MVA)	Losses (KW)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Leslie Town 11kV Cable	1.6	20.20	41.66	1.00	Chickadee, Hare and Cable A095P

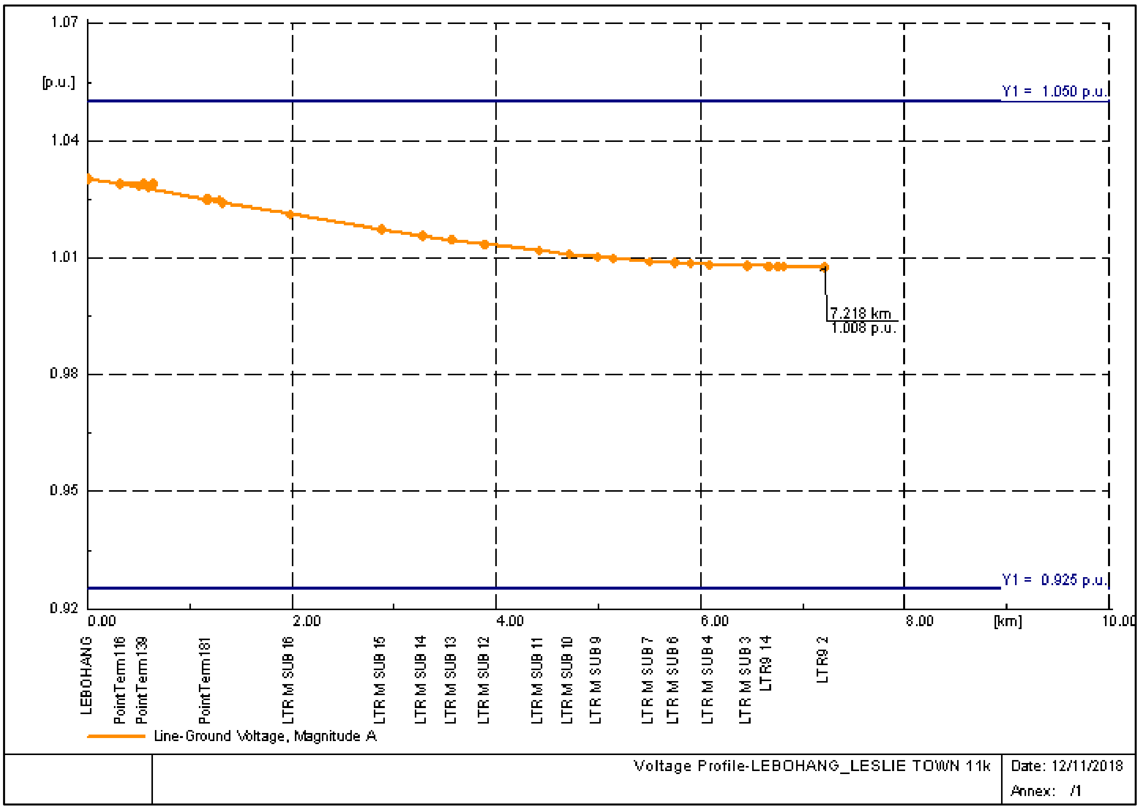

Figure 6.27: Voltage Profile after auto-restoration during a fault at LTR Mini sub 1

6.6.2. Fault Scenario 2

Introducing a fault at LTR Mini sub 16, automatically opens a normally closed breaker LTR 22/1 and automatically closes a N/O point at LTR mini Sub 9 to back-feed affected customers. The following results show no exceedance of thermal limits and no exceedance of minimum voltage limits of the feeder on Table 6.13 and Figure 6.28.

Table 6.13: Feeder parameters when auto-restoring after a fault at LTR Mini sub 16

Feeder	Peak Load(MVA)	Losses (KW)	Thermal loading (%)	Minimum Voltage (p.u.)	Backbone Conductor
Lebohang/ Leslie Town 11kV Cable	1.6	8.47	38.44	1.01	Chickadee, Hare and Cable A095P

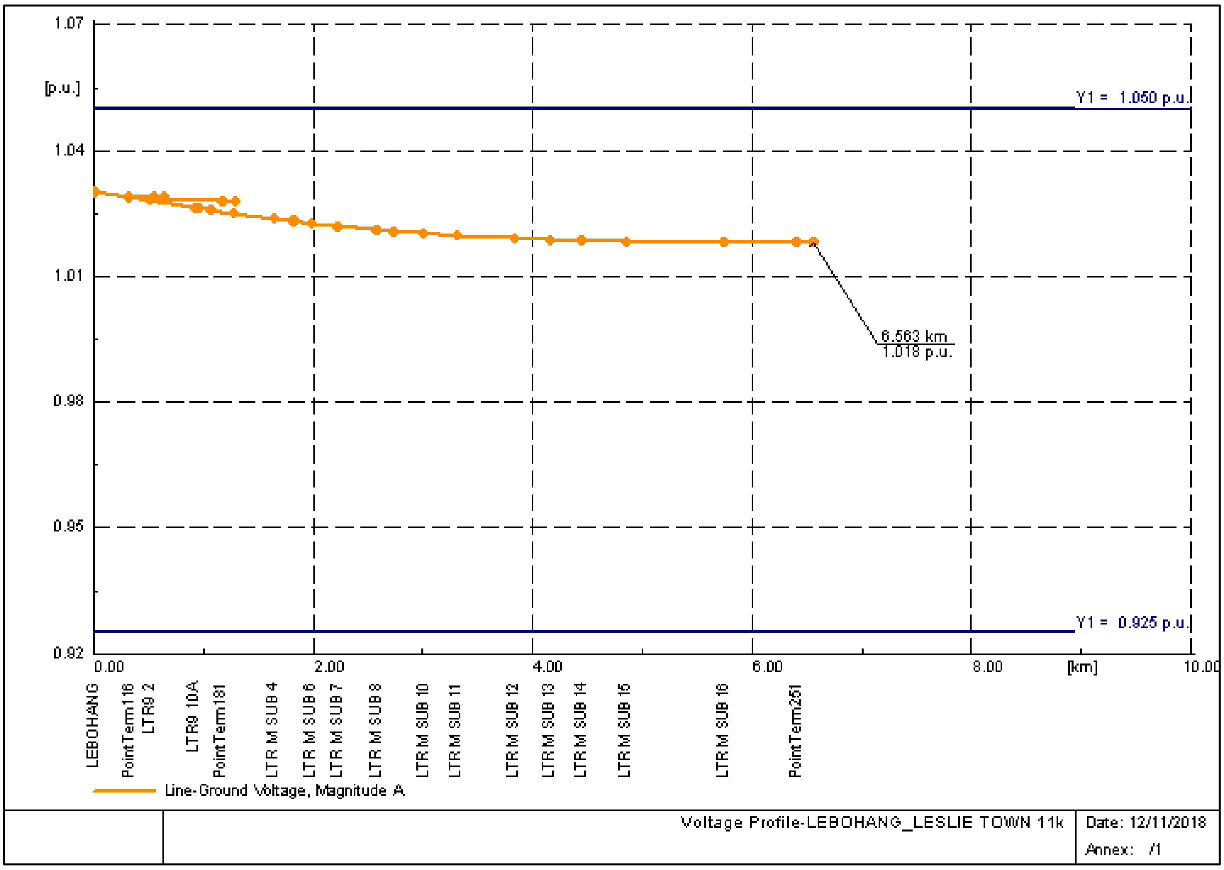

Figure 6.28: Voltage Profile after auto-restoration for a fault at LTR mini sub 16

6.7. Case study 3 Costing

Scope:

- Install an RTU at a N/O point LTR mini sub 9 to make it remotely controlled.

The total cost for material and labour is **ZAR 43 205.52**

7. Conclusion and suggestions for future research

In this dissertation a tool for the implementation and evaluation of the FLISR system for MV distribution networks has been described.

Studies on MV networks were performed to show the performance of a remotely closed N/O point. The first case study was done on a well configured network. The simulation proposed the implementation of a remotely closing N/O point and the results were healthy for all conditions. The second case study was done on a feeder that has limited back-feeding capabilities. Two options for back-feeding were considered. The first option was to install an interconnector from the same feeder and create a remotely closed N/O point. The second option was to build an interconnector from an adjacent feeder which has enough capacity to back-feed the entire feeder. The second option was recommended because the feeder had enough capacity to back-feed the entire feeder without violating voltage and conductor thermal limits. The last case study was done on an underground cable network. On this case, a remotely operated N/O was proposed and simulated to improve the reliability of the network and the results were good for all conditions. The cost of implementing automatic restoration is reasonable.

Auto restoration lessens the time customers are without supply and reduces the number of customers affected during the fault by remotely closing the N/O point. Reducing duration in which customers are affected and number of customers affected reduces SAIDI and SAIFI indices. This improves the performance of the feeders in this research and the model will be used to improve the rest of the badly performing feeders. The proposed automated supply restoration algorithm will in future be of great value for FLISR. With the proposed methodology Eskom will be able to monitor back-feeding functionalities thereby reducing the time customers are without supply.

The proposed approach is being implemented on an MV network that is far from the customer network centre. It takes many hours to drive to the N/O point and customers experience outages of a long duration, so automating the N/O point will minimize this outage time. Effective long-term strategic planning for maintenance will be essential for these networks as they are being introduced to new rapidly evolving technologies.

7.1. Future Work

This dissertation only considers the proposed FLISR approach for MV distribution networks without penetration of distributed generators (DGs). New distribution network topologies with integration of DGs may lead to certain difficulties on the proposed FLISR approach, such as bi-directional power flows, contribution of DG short-circuit currents, mis-coordination of protective relays and reclosers, over/under tripping of overcurrent relays, etc. In currently operational policies, DG units are automatically disconnected when any fault occurs in a distribution network. Therefore, the proposed FLISR approach should be expanded to be adaptable to high penetration of various DG types into the distribution network in future.

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A. Appendix A: General data

Table A.1: Examples of network reliability improvement strategies and interventions

Network reliability improvement strategy	Capital interventions	O&M interventions
Reduce the number of faults	• Address constrained networks (e.g. overloaded networks) • Apply more robust substation and/or line designs • Refurbish substations/lines that are in poor condition	• Increase the frequency of line and substation inspections to identify early signs of equipment failure • More proactively planned maintenance
Limit the impact of outages	• Reduce the number of customers per feeder by adding more feeders or splitting existing feeders • Add additional lines and/or substations for redundancy • Implement fuses at transformers • Add reclosers to isolate upstream networks from faults • Use backfeeding capability (where it exists)	• Optimal sectionalising of the network to temporarily restore supply to as many customers as possible
Limit the duration of outages	• Install substation RTUs and fault path indicators (FPIs) • Distribution automation	• Reduce dispatch time • Reduce travelling time • Reduce time to sectionalise the network and locate the fault • Improve repair time through better access, availability of the correct spares and tools etc.

Table A.2: Conductor thermal rating [26]

	ACSR Single Layer				
	Percentage		9.83%	49%	80%
	Probability		1.20E-06	6.00E-06	9.78E-06
Conducting Area mm²	Single	Temp	Rate A	Rate B	Rate C
20.98	SQUIRREL	50	104	143	179
20.98	SQUIRREL	60	122	165	200
20.98	SQUIRREL	70	138	183	221
20.98	SQUIRREL	80	150	198	238
42.79	FOX	50	148	203	255
42.79	FOX	60	173	234	287
42.79	FOX	70	196	258	314
42.79	FOX	80	213	279	340
63.13	MINK	50	206	285	369
63.13	MINK	60	241	325	411
63.13	MINK	70	270	361	450
63.13	MINK	80	294	391	489
104.98	HARE	50	280	392	534
104.98	HARE	60	335	448	597
104.98	HARE	70	376	496	647
104.98	HARE	80	410	538	697
10.58	MAGPIE	50	33	40	
10.58	MAGPIE	60	47	52	
10.58	MAGPIE	70	58	62	
10.58	MAGPIE	80	67	70	

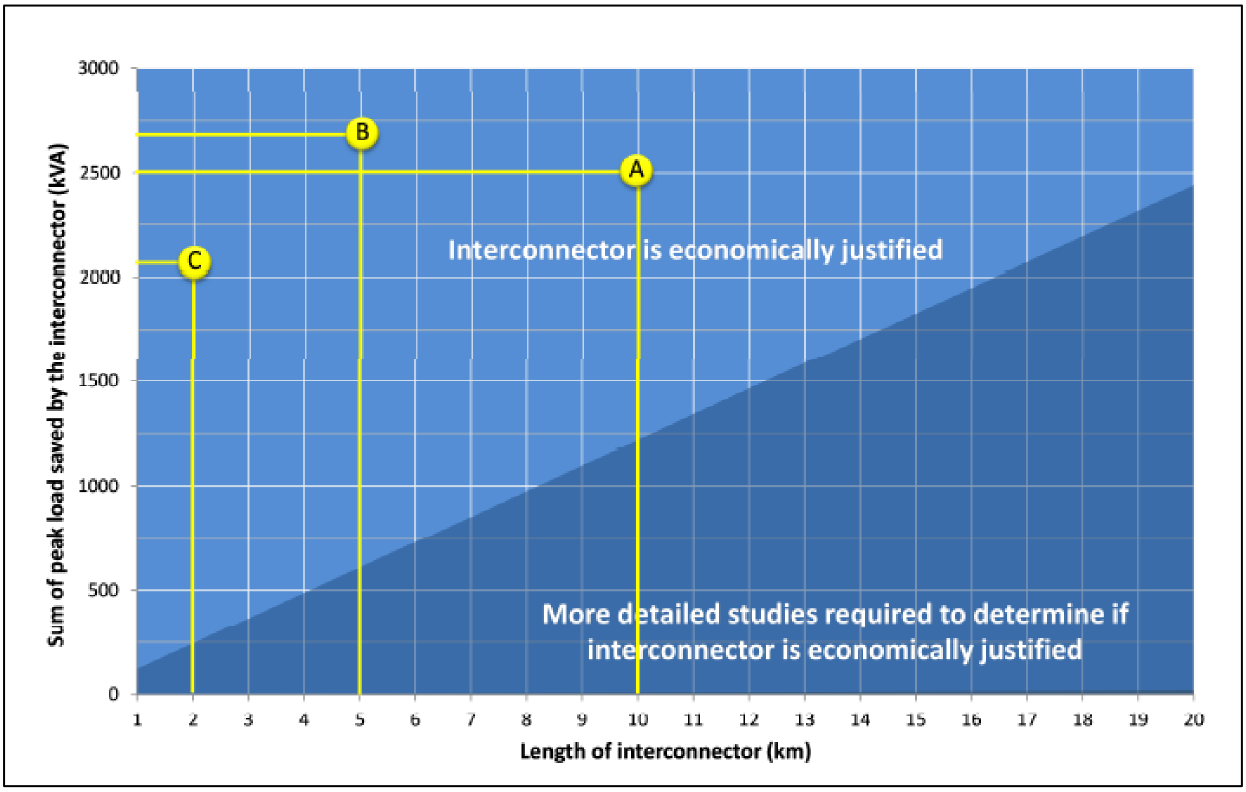


Figure A.1: Determining which interconnectors are economically justified

B. Appendix B: Modelling and simulation results

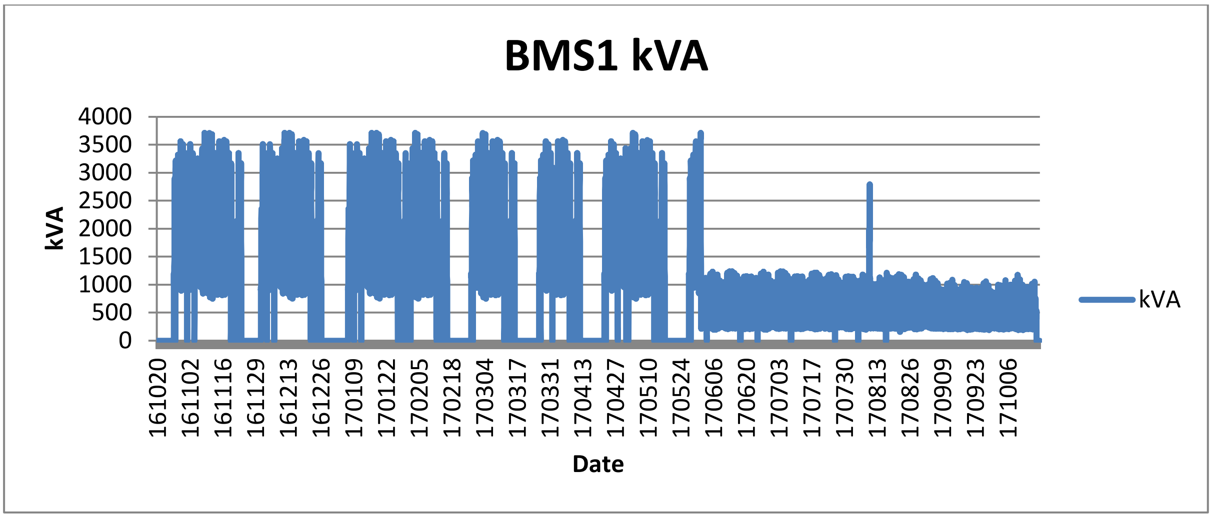


Figure B.1: BMS1 peak load

The following codes and results were done during the programming in PowerFactory using Python for Case Study 1: Balfour Munic/Siyathemba 1 and 2 22kV feeders

Injecting a short circuit fault in Balfour Munic/Siyathemba 1 22kV line

```python
import powerfactory
app = powerfactory.GetApplication()
app.ClearOutputWindow()

app.EchoOff()

SC = app.GetFromStudyCase("ComShc")
SC.Execute()

SC.iopt mde = 1   #using IEC60909 method
SC.iopt shc = "3psc"      #applying a three phase short circuit
SC.iopt_allbus = 0       #user selection

line = app.GetCalcRelevantObjects("Balfour Munic/Siyathemba 1 22kV.ElmLne")[0]
#selecting Siyathemba line
SC.shcobj = line

Res = app.GetFromStudyCase("MyResults.ElmRes")
Res.Clear()   #clears the result file

Res.AddVariable(SC,"ppro")   #setting the position of the fault
Res.AddVariable(line,"m:Ikss:bus1")  #displaying current
Res.AddVariable(line,"m:Ikss:bus2")
Res.AddVariable(line,"m:Z:bus1")
Res.AddVariable(line,"m:Z:bus2")
Res.AddVariable(line,"m:Ikss:busshc")  # displaying short circuit current
Res.InitialiseWriting()

for i in range(11):  # for different fault positions
  SC.ppro = i*10
  SC.Execute()
  Res.Write()

Res.FinishWriting()

output = app.GetFromStudyCase("*.ComRes")
output.pResult = Res
output.iopt exp = 6   #representing csv from the MyResult drop down
output.f name = r"E:\ShortResults.csv"
output.Execute()

app.EchoOn()
```

Figure B.2: Short circuit fault script using python in PowerFactory

Table B.1: Detailed results for short circuit vs feeder distance

Index	Ik/Terminal i in kA"	Ik/Terminal j in kA"	Z, Magnitude/Term	Z, Magnitude/Termi	Short-Circuit C
0	1.205104	1.205104	0	6.408003	0
1	0.768469	0.768469	21.782744	28.126072	10
2	0.49919	0.49919	52.044618	58.35849	20
3	0.31136	0.31136	101.346816	107.609146	30
4	0.167398	0.167398	209.376557	215.475387	40
5	0.054657	0.054657	680.644254	685.003796	50
6	0.080342	0.080342	477.703372	471.800574	60
7	0.184435	0.184435	210.117601	203.76726	70
8	0.297366	0.297366	129.016832	122.6242	80
9	0.424426	0.424426	87.526527	81.125806	90
10	0.576336	0.576336	60.552302	54.15149	100

```python
import powerfactory
app = powerfactory.GetApplication()
app.ClearOutputWindow()


SC = app.GetFromStudyCase("ComShc")
Res = app.GetFromStudyCase("MyResults.ElmRes")
lines = app.GetCalcRelevantObjects("Balfour Munic/Siyathemba1.ElmLne")
line = lines[0]

oGraph = app.GetGraphicsBoard()
oViPage = oGraph.GetPage("SHC_Sweep",1)
oVi = oViPage.GetVI("SHC_Swp","VisXyplot",1)

oVi.ResFile = [Res]
oVi.pyObj = [line]
oVi.yvar = ["m:Ikss:busshc"]
oVi.iObjx = 1
oVi.pxObj = [SC]
oVi.xvar = ["ppro"]

oVi.auto_y = 1
oVi.auto_x = 1
oViPage.DoAutoScaleY()
oViPage.DoAutoScaleX()
```

Figure B.3: A script to show a graphic representation of the result

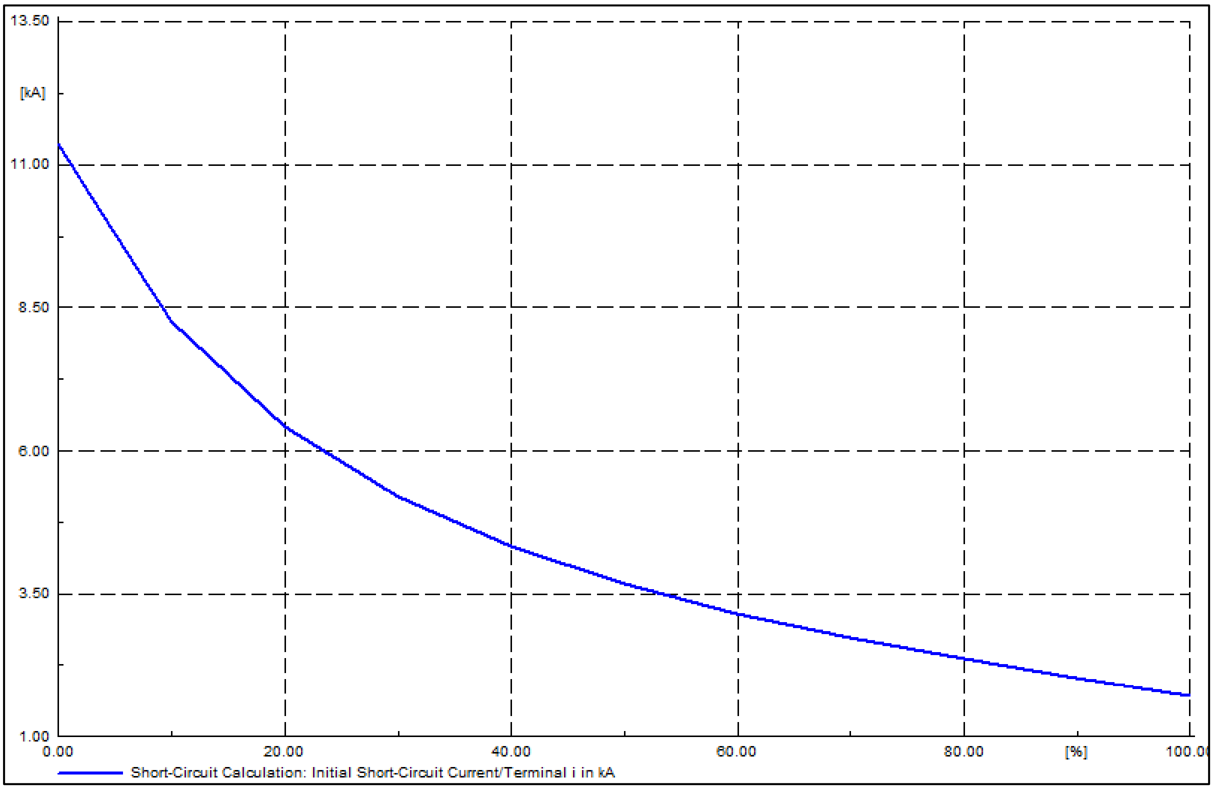
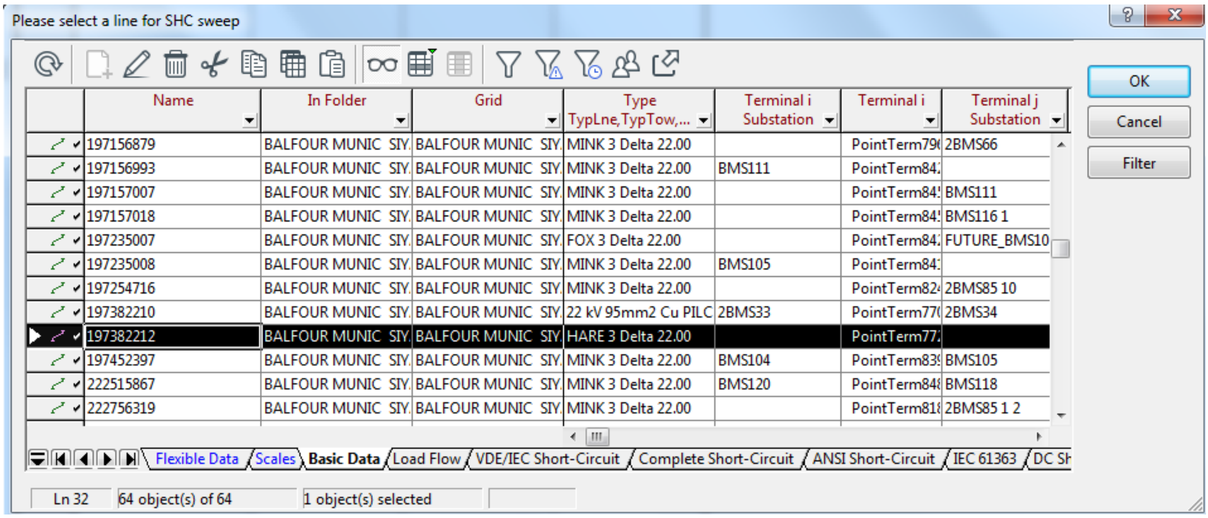


Figure B.4: Fault current vs fault distance BMS1

Table B.2: Selection of line to introduce fault to (BMS2)



Name	In Folder	Grid	Type TypLne,TypTow,...	Terminal i Substation	Terminal i	Terminal j Substation
197156879	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00		PointTerm79(	2BMS66
197156993	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00	BMS111	PointTerm84	
197157007	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00		PointTerm84!	BMS111
197157018	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00		PointTerm84!	BMS116 1
197235007	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	FOX 3 Delta 22.00		PointTerm84	FUTURE_BMS10
197235008	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00	BMS105	PointTerm84	
197254716	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00		PointTerm82	2BMS85 10
197382210	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	22 kV 95mm2 Cu PILC	2BMS33	PointTerm77(	2BMS34
197382212	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	HARE 3 Delta 22.00		PointTerm77	
197452397	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00	BMS104	PointTerm83!	BMS105
222515867	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00	BMS120	PointTerm84!	BMS118
222756319	BALFOUR MUNIC SIY	BALFOUR MUNIC SIY	MINK 3 Delta 22.00		PointTerm81!	2BMS85 1 2

```
Position: 0%    Ishc=10.71kA
Position: 10%    Ishc=10.40kA
Position: 20%    Ishc=10.11kA
Position: 30%   Ishc=9.83kA
Position: 40%   Ishc=9.57kA
Position: 50%   Ishc=9.32kA
Position: 60%   Ishc=9.09kA
Position: 70%   Ishc=8.86kA
Position: 80%   Ishc=8.65kA
Position: 90%   Ishc=8.45kA
Position: 100%   Ishc=8.25kA
```

Figure B.5: Short circuit vs distance for Balfour Munic/Siyathemba 2

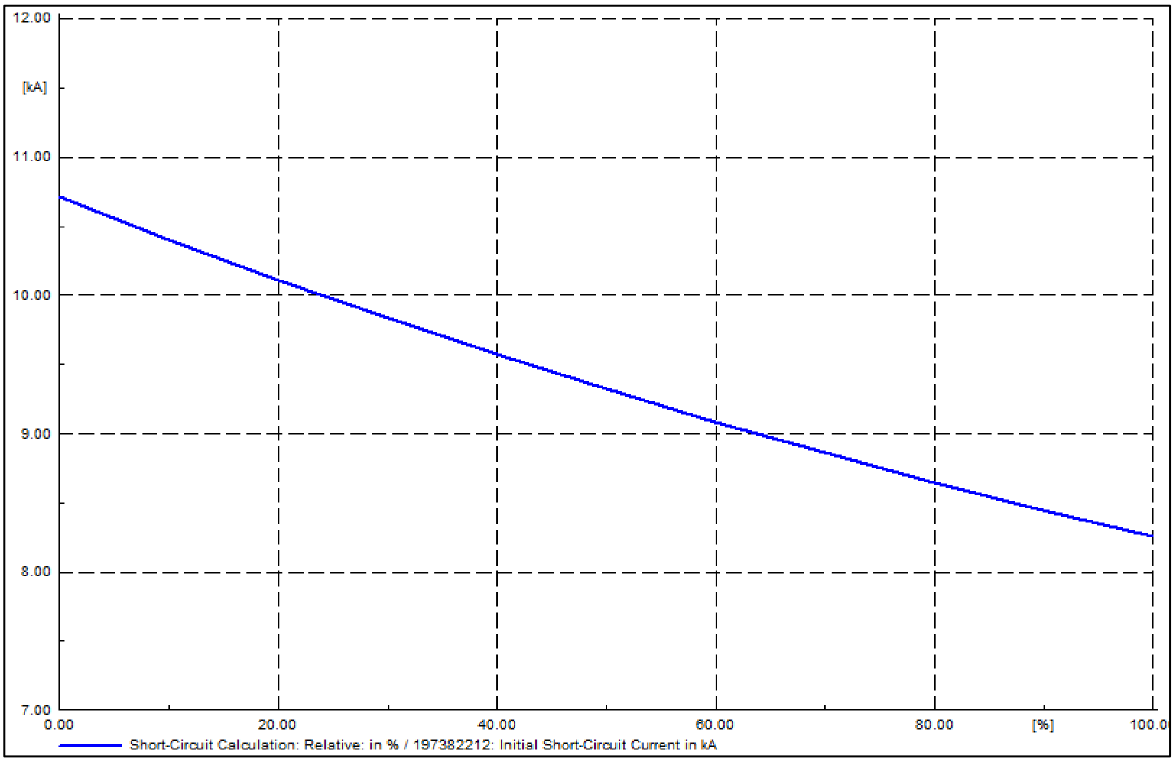


Figure B.6: BMS2 distance and fault current

B.1. Dynamic Simulations for Case Study 1

To examine the level of reliability improvement and customer satisfaction enhancement, a reliability assessment study is applied for the proposed automated distribution networks. The results presented in this dissertation emphasize that the proposed automated networks have a higher reliability compared to non-automated networks. After performing studies, remotely controlled N/O points will be implemented on three actual MV networks i.e. two OHL networks and one cable network. This research aims to show how automated service restoration can reduce switching and restoration time from hours to minutes. The load point reliability and system reliability indices for the chosen distribution networks were determined. Network reliability assessment was used to calculate the expected interruption frequencies and duration (SAIFI and SAIDI). Faults were introduced into the simulation to determine the performance of FLISR in the network. The reliability assessment study for the proposed automated distribution networks was performed to ensure improvement in reliability indices and achieve higher customer satisfaction. The results showed that the proposed automated distribution network has a higher reliability level compared to a conventional one, i.e. non-automated network. This is observed through the reduction in the reliability indices such as the SAIDI.

The constraints considered are the maximum loading of system, the protection settings and the allowable voltage drop in the primary network. The allowable voltage drop is difficult to meet, but a percentage of overloading of the network elements for back feeding is acceptable in a temporary situation, assuming that the fault can be fixed in a couple of hours. The voltage dropped from 22 kV to 6 kV and went back to 22 kV after power has been restored by closing the N/O point as can be seen on Figure B7.

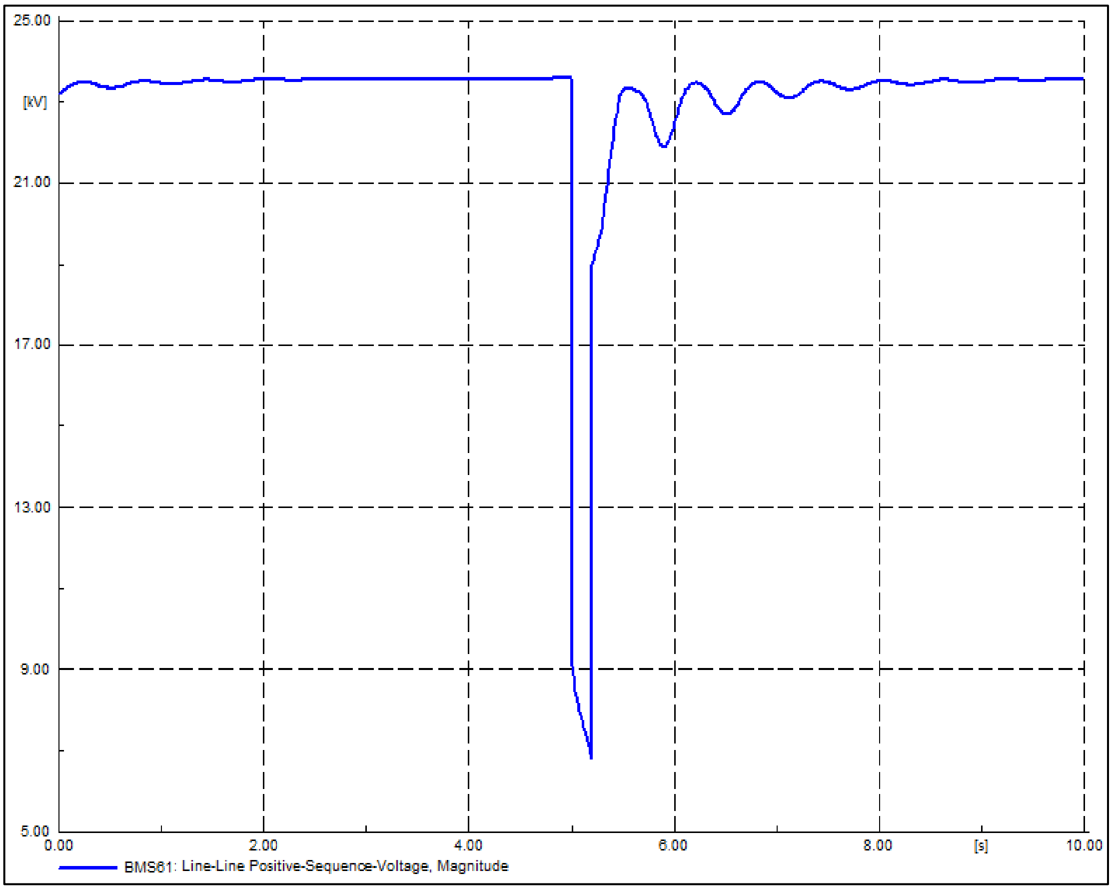


Figure B.7: Voltage drop during a fault and restoration.

Figure B7 shows the fault current seen by the recloser BMS1 during the fault. During the fault, the current increased from the rated current of 0.23 kA to 1.8 kA. After 0.2 seconds the recloser opened.

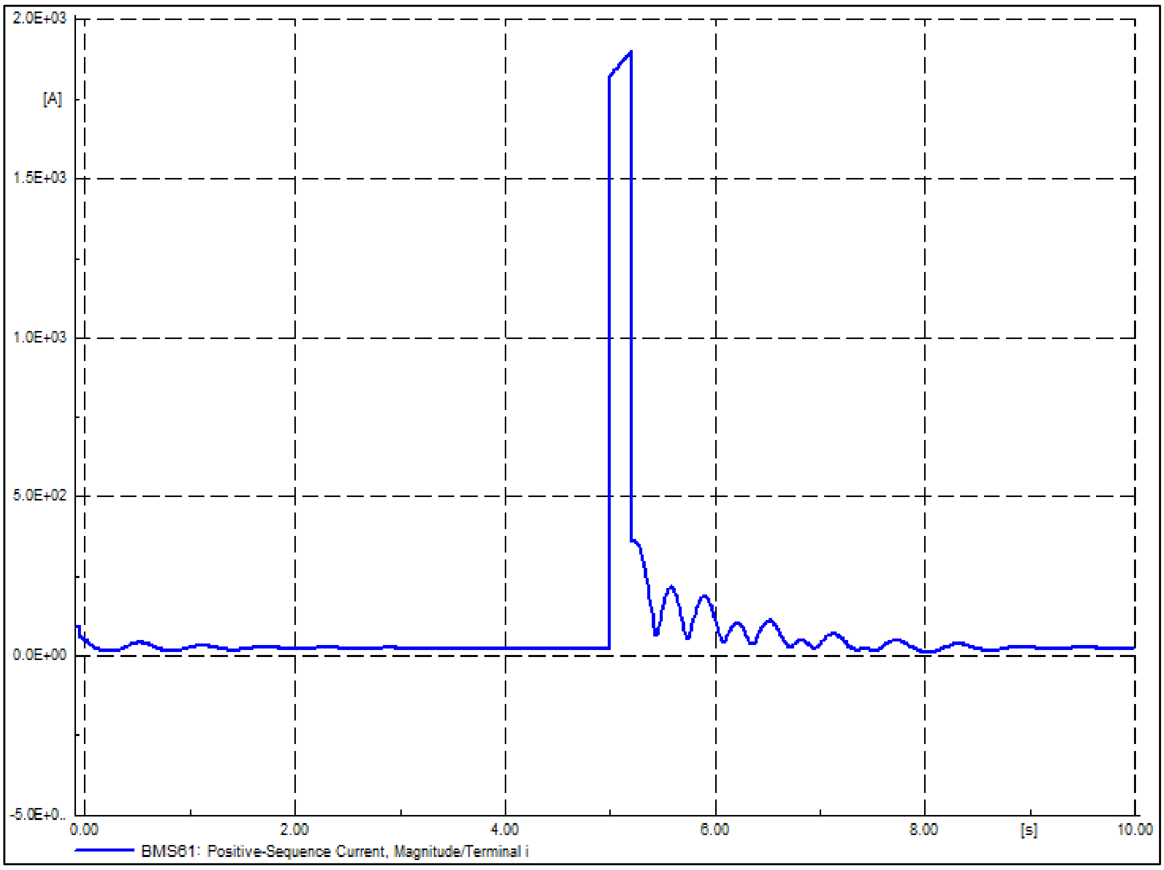


Figure B.8: Current Rise during fault and after restoration

The reliability level of the distribution system depends mainly on the overall time of the FLISR procedure after fault occurrence. The FLISR studies were conducted using Python programming in PowerFactory. The fault was introduced at 5 seconds and quickly restorable customers were restored at 5.4 seconds by means of FLISR. Figure B7 and Figure B8 present voltage and current before, during and after the fault. Both voltage and current stabilise after 2.6 seconds. This proves that SAIDI and SAIFI will improve significantly as the supply will be restored back to customers in 0.4 seconds according to the studies.

Table B.3: 2BMS line and TRFR loading

Line 197051133 is loaded at 1.47 %	Line 197452397 is loaded at 7.73 %	Transformer 2BMS53 _T is loaded at 117.22 %
Line 197051135 is loaded at 1.47 %	Line 222515867 is loaded at 1.47 %	Transformer 2BMS59 1 _T is loaded at 116.79 %
Line 197051138 is loaded at 1.47 %	Line 222756319 is loaded at 4.64 %	Transformer 2BMS66 _T is loaded at 116.78 %
Line 197051140 is loaded at 10.67 %	Line 222756325 is loaded at 29.78 %	Transformer 2BMS70 10 _T is loaded at 120.09 %
Line 197051149 is loaded at 1.47 %	Line 222756329 is loaded at 25.64 %	Transformer 2BMS73 _T is loaded at 116.78 %
Line 197051155 is loaded at 1.47 %	Line 222756333 is loaded at 6.52 %	Transformer 2BMS79 2 1 _T is loaded at 116.78 %
Line 197051158 is loaded at 1.47 %	Line 222756339 is loaded at 10.67 %	Transformer 2BMS79 5 _T is loaded at 116.78 %
Line 197051161 is loaded at 1.47 %	Line 222756343 is loaded at 4.42 %	Transformer 2BMS80 2 1 _T is loaded at 116.78 %
Line 197051164 is loaded at 1.47 %	Line 223015963 is loaded at 1.04 %	Transformer 2BMS80 4 _T is loaded at 116.78 %
Line 197155173 is loaded at 39.43 %	Line 223023329 is loaded at 1.04 %	Transformer 2BMS85 1 2 _T is loaded at 116.65 %
Line 197155174 is loaded at 37.96 %	Line 344678233 is loaded at 29.96 %	Transformer 2BMS85 10 _T is loaded at 116.78 %
Line 197155178 is loaded at 2.94 %	Line 344678236 is loaded at 30.13 %	Transformer 2BMS85 13 _T is loaded at 116.78 %
Line 197155179 is loaded at 2.94 %	Line 344678239 is loaded at 36.44 %	Transformer 2BMS85 2 1 _T is loaded at 116.78 %
Line 197155180 is loaded at 21.51 %	Line 344678240 is loaded at 30.16 %	Transformer 2BMS86 _T is loaded at 116.70 %
Line 197155181 is loaded at 9.05 %	Line 344678251 is loaded at 30.22 %	Transformer 2BMS90 _T is loaded at 116.70 %
Line 197155183 is loaded at 9.20 %	Line 344678252 is loaded at 40.90 %	Transformer 2BMS94 2 _T is loaded at 116.65 %
Line 197155184 is loaded at 2.95 %	Line 344739878 is loaded at 37.59 %	Transformer BMS103 2 _T is loaded at 116.78 %
Line 197155270 is loaded at 30.24 %	Line 344768907 is loaded at 30.13 %	Transformer BMS104 _T is loaded at 116.78 %
Line 197156812 is loaded at 10.67 %	Line 344768936 is loaded at 30.22 %	Transformer BMS105 _T is loaded at 117.18 %
Line 197156867 is loaded at 36.12 %	Line 344768972 is loaded at 30.13 %	Transformer BMS107 3 _T is loaded at 117.04 %
Line 197156879 is loaded at 37.96 %	Line 344774631 is loaded at 30.21 %	Transformer BMS111 _T is loaded at 116.78 %
Line 197156993 is loaded at 5.89 %	Line 344774645 is loaded at 30.21 %	Transformer BMS116 1 _T is loaded at 116.78 %
Line 197157007 is loaded at 4.42 %	Line 344774760 is loaded at 33.18 %	Transformer BMS118 _T is loaded at 116.78 %
Line 197157018 is loaded at 1.47 %	Line 344830348 is loaded at 36.12 %	Transformer BMS120 _T is loaded at 116.78 %
Line 197235007 is loaded at 2.07 %	Line 344830355 is loaded at 10.67 %	
Line 197235008 is loaded at 7.36 %	Line 344830362 is loaded at 4.42 %	
Line 197254716 is loaded at 2.95 %	Line 344919430 is loaded at 30.13 %	
Line 197382210 is loaded at 36.51 %		
Line 197382212 is loaded at 30.22 %		

Table B.4: BMS 1 line and Transformer loading

Line 197051124 is loaded at 22.76 %	Line 197235008 is loaded at 4.84 %	Line 222882390 is loaded at 1.94 %
Line 197051130 is loaded at 26.21 %	Line 197254011 is loaded at 3.87 %	Line 222897905 is loaded at 22.45 %
Line 197051140 is loaded at 7.03 %	Line 197260102 is loaded at 21.79 %	Line 222926603 is loaded at 20.82 %
Line 197051143 is loaded at 2.90 %	Line 197382204 is loaded at 39.37 %	Line 344678243 is loaded at 39.41 %
Line 197051181 is loaded at 15.97 %	Line 197382206 is loaded at 32.58 %	Line 344678244 is loaded at 32.61 %
Line 197155163 is loaded at 8.23 %	Line 197382208 is loaded at 32.59 %	Line 344678247 is loaded at 39.42 %
Line 197155164 is loaded at 7.26 %	Line 197382432 is loaded at 44.54 %	Line 344678248 is loaded at 32.62 %
Line 197155165 is loaded at 1.94 %	Line 197401925 is loaded at 39.37 %	Line 344678254 is loaded at 22.76 %
Line 197155167 is loaded at 2.90 %	Line 197430993 is loaded at 39.39 %	Line 344774612 is loaded at 39.38 %
Line 197155169 is loaded at 2.91 %	Line 197452397 is loaded at 5.09 %	Line 344774614 is loaded at 32.59 %
Line 197155170 is loaded at 1.94 %	Line 222409443 is loaded at 23.48 %	Line 344774725 is loaded at 32.58 %
Line 197155183 is loaded at 6.06 %	Line 222702479 is loaded at 1.36 %	Line 344830341 is loaded at 3.39 %
Line 197155184 is loaded at 1.94 %	Line 222702485 is loaded at 23.81 %	Line 344830355 is loaded at 7.03 %
Line 197155267 is loaded at 20.82 %	Line 222756279 is loaded at 2.72 %	Transformer BMS103 2 _T is loaded at 76.85 %
Line 197156147 is loaded at 7.03 %	Line 222756293 is loaded at 2.72 %	Transformer BMS104 _T is loaded at 76.85 %
Line 197156924 is loaded at 24.84 %	Line 222756299 is loaded at 20.58 %	Transformer BMS105 _T is loaded at 77.17 %
Line 197156936 is loaded at 22.12 %	Line 222756303 is loaded at 18.04 %	Transformer BMS107 3 _T is loaded at 76.96 %
Line 197156947 is loaded at 15.32 %	Line 222756305 is loaded at 2.72 %	Transformer BMS111 _T is loaded at 76.85 %
Line 197156959 is loaded at 15.32 %	Line 222756313 is loaded at 19.40 %	Transformer BMS116 1 _T is loaded at 76.85 %
Line 197156971 is loaded at 7.99 %	Line 222756315 is loaded at 12.60 %	Transformer BMS118 _T is loaded at 76.85 %
Line 197156993 is loaded at 3.88 %	Line 222765253 is loaded at 2.72 %	Transformer BMS120 _T is loaded at 76.85 %
Line 197157007 is loaded at 2.91 %	Line 222765259 is loaded at 4.08 %	Transformer BMS58 11 5 _T is loaded at 76.70 %
Line 197157526 is loaded at 21.79 %	Line 222765261 is loaded at 6.80 %	Transformer BMS58 13 1 _T is loaded at 76.78 %
Line 197157550 is loaded at 3.39 %	Line 222765267 is loaded at 21.09 %	Transformer BMS58 16 1 _T is loaded at 76.85 %
Line 197157558 is loaded at 3.39 %	Line 222765271 is loaded at 2.72 %	Transformer BMS58 19 1 _T is loaded at 76.85 %
Line 197157572 is loaded at 2.42 %	Line 222765277 is loaded at 10.17 %	Transformer BMS58 19 13 3 _T is loaded at 76.85 %
Line 197235007 is loaded at 1.36 %	Line 222834309 is loaded at 24.84 %	Transformer BMS58 19 5 2 _T is loaded at 76.85 %

```
import powerfactory
app = powerfactory.GetApplication()
app.ClearOutputWindow()


SC = app.GetFromStudyCase("ComShc")
Res = app.GetFromStudyCase("MyResults.ElmRes")
lines = app.GetCalcRelevantObjects("Balfour Munic/Siyathemba1.ElmLne")
line = lines[0]

oGraph = app.GetGraphicsBoard()
oViPage = oGraph.GetPage("SHC_Sweep",1)
oVi = oViPage.GetVI("SHC_Swp","VisXyplot",1)

oVi.ResFile = [Res]
oVi.pyObj = [line]
oVi.yvar = ["m:Ikss:busshc"]
oVi.iObjx = 1
oVi.pxObj = [SC]
oVi.xvar = ["ppro"]

oVi.auto_y = 1
oVi.auto_x = 1
oViPage.DoAutoScaleY()
oViPage.DoAutoScaleX()
```

Figure B.9: Distance vs fault current script

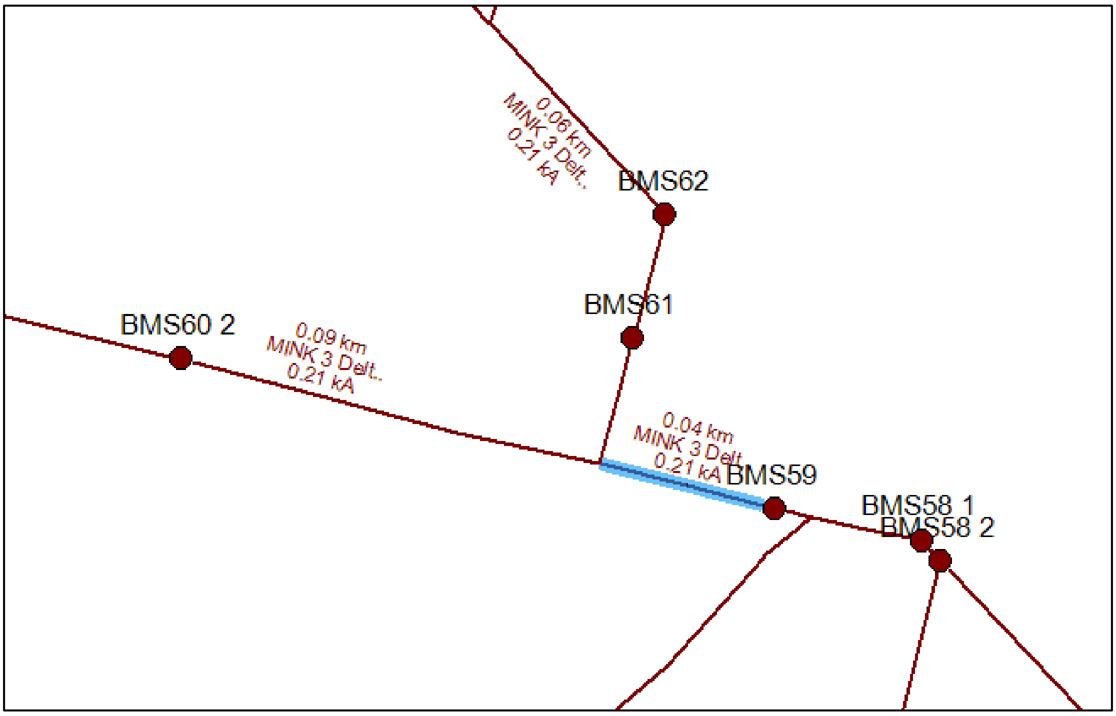


Figure B.10: Balfour Mumic/Siyathemba 1 22kV location of the fault

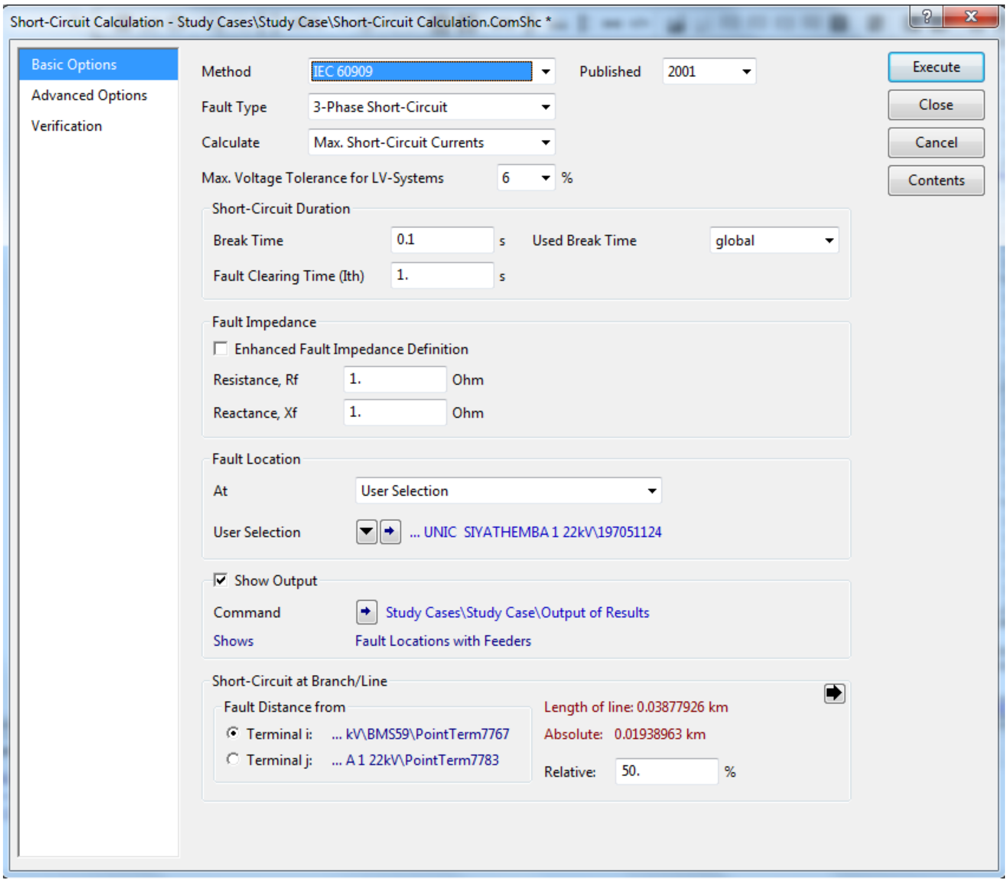


Figure B.11: Short circuit fault calculation

Automatically closing of BMS N/O point using python script on PowerFactory

```
import powerfactory
app = powerfactory.GetApplication()
app.ClearOutputWindow()

app.EchoOff()

def toggle_switch(switch_name):
#Changes N/O point switch (recloser) state from off to on and vice versa.
    switches = app.GetCalcRelevantObjects('*.ElmCoup')
    switch = [sw for sw in switches if str(switch_name) in sw.loc_name][0]
    current_state = switch.on_off
    if current_state == 0:
        switch.SetAttribute('on_off', 1)
    else:
        switch.SetAttribute('on_off', 0)
toggle_switch('Balfour Munic/Siyathemba 1 22kV')

app.EchoOn()
```

Figure B.12: Automatically closing of BMS N/O point using python script on PowerFactory

Ensuring that the back-feeding line is not overloaded before closing the N/O point

```
import powerfactory
app = powerfactory.GetApplication()
app.ClearOutputWindow()

app.EchoOff()

def toggle_switch(switch_name):
#Changes N/O point switch (recloser) state from off to on and vice versa.
    switches = app.GetCalcRelevantObjects('*.ElmCoup')
    switch = [sw for sw in switches if str(switch_name) in sw.loc_name][0]
    current_state = switch.on_off
    if current_state == 0:
        switch.SetAttribute('on_off', 1)
    else:
        switch.SetAttribute('on_off', 0)

lines = app.GetCalcRelevantObjects("*.ElmLne")
  for line in lines:
      if line.GetAttribute("c:loading")<103: #checking if the backfeeding line is not overloaded
        app.PrintPlain("Line %s is loaded at %.2f %%" %(line.loc_name,line.GetAttribute("c:loading")))
        toggle_switch('Balfour Munic/Siyathemba 1 22kV')

app.EchoOn()
```

Figure B.13: A script to ensure that the back-feeding line is not overloaded before closing the N/O point

Getting transformers and line loadings

```
def loading(app):
  lines = app.GetCalcRelevantObjects("*.ElmLne")
  trfs = app.GetCalcRelevantObjects("*.ElmTr2")
  for line in lines:
      if line.GetAttribute("c:loading")>70:
        app.PrintPlain("Line %s is loaded at %.2f %%" %(line.loc_name,line.GetAttribute("c:loading")))
  for trf in trfs:
      if trf.GetAttribute("c:loading")>50:
        app.PrintPlain("Transformer %s is loaded at %.2f %%" %(trf.loc_name,trf.GetAttribute("c:loading")))
```

Figure B.14: Getting transformers and line loadings

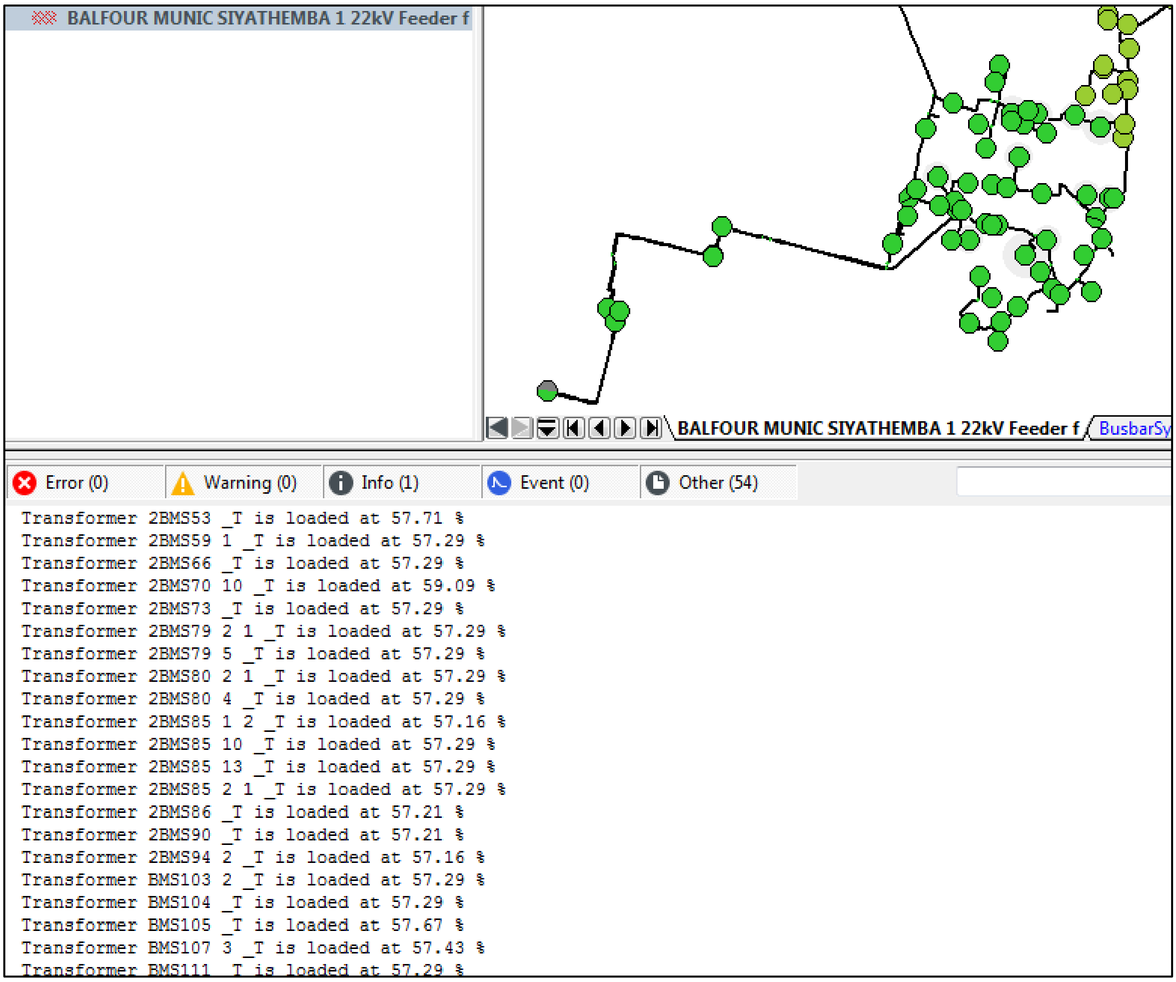


Figure B.15: Transformer Loading of Balfour Munic/Siyathemba 2 22kV feeder

Table B.5: 2BMS load flow

Load 2BMS53 P= 0.02 kW
Load 2BMS59 1 P= 0.03 kW
Load 2BMS66 P= 0.03 kW
Load 2BMS70 10 P= 0.01 kW
Load 2BMS73 P= 0.03 kW
Load 2BMS79 2 1 P= 0.03 kW
Load 2BMS79 5 P= 0.03 kW
Load 2BMS80 2 1 P= 0.03 kW
Load 2BMS80 4 P= 0.03 kW
Load 2BMS85 1 2 P= 0.11 kW
Load 2BMS85 10 P= 0.03 kW
Load 2BMS85 13 P= 0.03 kW
Load 2BMS85 2 1 P= 0.03 kW
Load 2BMS86 P= 0.07 kW
Load 2BMS90 P= 0.07 kW
Load 2BMS94 2 P= 0.11 kW
Load 24 19 2 P= 0.03 kW
Load A2 24 20 P= 0.03 kW
Load A2 24 21 P= 0.01 kW
Load 24 22 3 P= 0.02 kW
Load A2 24 26 P= 0.03 kW
Load 24 31 1 P= 0.03 kW
Load A2 24 33 P= 0.03 kW
Load JMA_L1 P= 0.03 kW
Load AUX2 P= 0.02 kW

B.2. Dynamic Simulations for Case Study 2

Simulations were performed to create events and studying the behaviour of the system during fault and power restoration. The first step was to simulate a three-phase short circuit fault in the system. The next event was a fault detection and fault clearing by tripping a protection device. The last event is power restoration by closing the N/O point and restoring supply to healthy customers within the three minutes threshold through the interconnector. The objective is to restore supply to the maximum number of customers within 3 minutes thereby improving the reliability indices which are SAIDI and SAIFI.

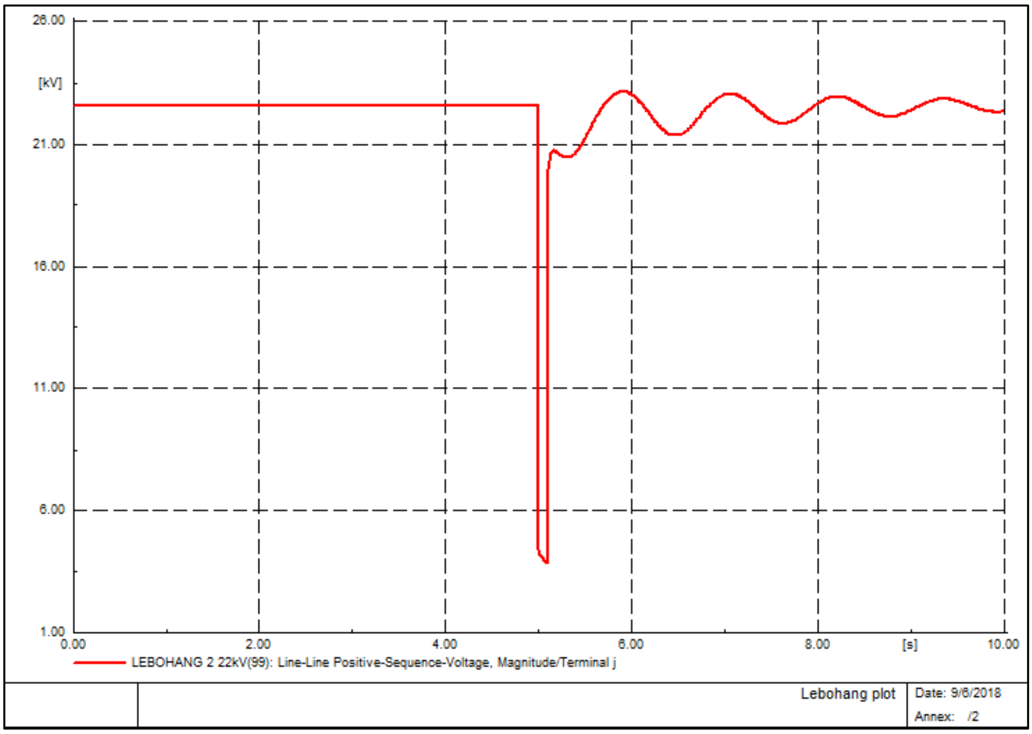


Figure B.16: Voltage drop during the fault and after auto-restoration

The constraints considered are the maximum loading of system, the protection settings and the allowable voltage drop in the primary network. The allowable voltage drop is difficult to meet, but a percentage of overloading of the network elements for back feeding is acceptable in a temporary situation, assuming that the fault can be fixed in a couple of hours. The voltage dropped from 22 kV to 4 kV and went back to 22 kV after power had been restored by closing the N/O point as can be seen on Figure B16. Figure B17 shows the current rise during the fault

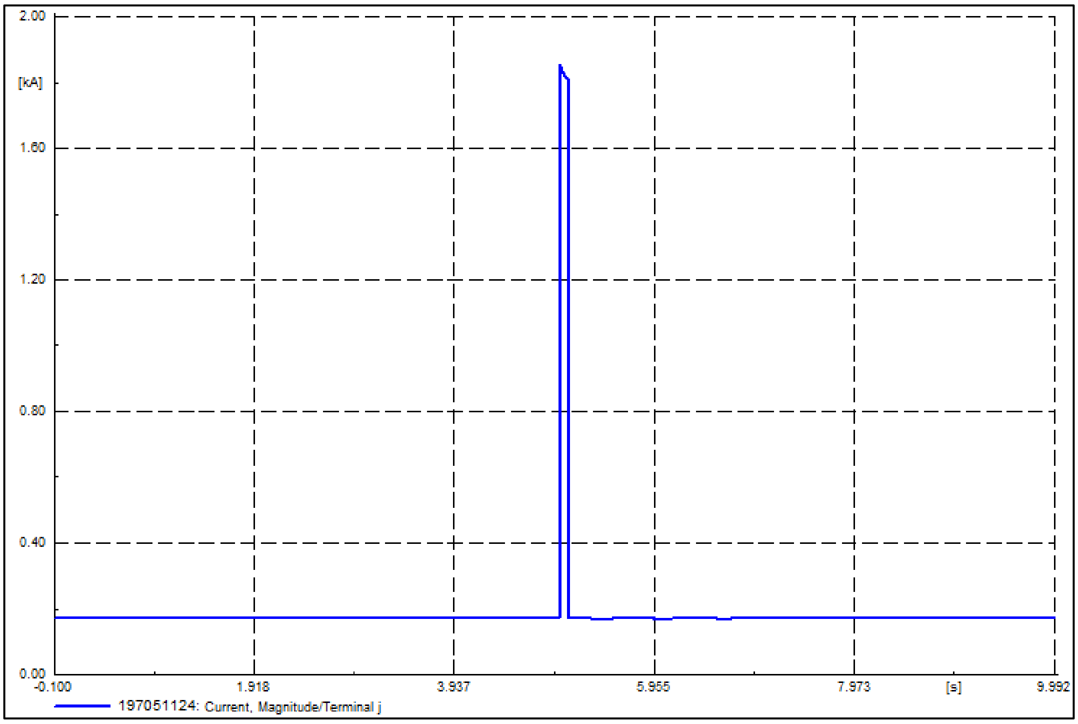


Figure B.17: Current rise during the fault and after auto-restoration