IMPROVING RELIABILITY ON DISTRIBUTION SYSTEMS BY NETWORK RECONFIGURATION AND OPTIMAL DEVICE PLACEMENT

By

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IN FULFILMENT OF THE DEGREE OF

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DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication) are listed below.

Publication 1:
R. Bhugwandeen and A. Saha, "Component Failure Analysis for Reliability Modelling," in *Proceedings of the 26th South African Universities Power Engineering Conference*, Johannesburg, South Africa, 24-26 January 2018, pp. 393-398, SAUPEC2018-RCM-12.

Publication 2:
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Publication 3:
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Publication 4:
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Abstract

A distribution system without reliable networks impacts production; hinders economy and affects day to day activities of its customers who demand uninterrupted supply of high quality. All power utilities try to minimize costs but simultaneously strive to provide reliable supply and achieve customer satisfaction. This research has focused on predicting and thereafter improving the South African distribution network reliability. Predictive reliability modelling ensures that utilities are better informed to make decisions which will improve supply to customers. An algorithm based on Binary Particle Swarm Optimization (BPSO) was implemented to optimize distribution network configuration as well as supplemental device placement on the system. The effects on reliability, network performance and system efficiency were considered. The methodology was applied to three distribution networks in KwaZulu-Natal, each with diverse topology, environmental exposure and causes of failure. The radial operation of distribution networks as well as the practical equipment limitations was considered when determining the optimal configuration. The failure rates and repair duration calculated unique to each network was used to model the performance of each component type. Historical performance data of the networks was used as a comparison to the key performance indicators obtained from DigSILENT PowerFactory simulations to ensure accuracy and evaluate any improvement on the system. The results of a case study display improvements in System Average Interruption Duration Index (SAIDI) of up to 20% and improvements in System Average Interruption Frequency Index (SAIFI) of up to 24% after reconfiguration. The reconfiguration also reduced the system losses in some cases. Network reconfiguration provides improved reliable supply without the need for capital investment and expenditure by the utility. The BPSO algorithm is further used to optimally place and locate switches and reclosers on the networks to achieve maximum improvement in reliability for minimal cost. The results show that the discounted future benefit of adding additional protection devices to a network is approximately R27 million over a twenty-five-year period. The maximum SAIDI improvement from adding reclosers to a network was 21%, proving that additional device placement is a cost-effective means to improve system reliability.

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List of Abbreviations

ACSR	-	Aluminium conductor steel-reinforced
BPSO	-	Binary Particle Swarm Optimization
CDF	-	Customer Damage Function
DFB	-	Discounted Future Benefit
DPL	-	DigSILENT Programming Language
ENS	-	Energy Not Supplied
FMEA	-	Failure Modes and Effects Analysis
HV	-	High Voltage
KPI	-	Key Performance Indicator
KZN OU	-	KwaZulu-Natal Operating Unit
LPU	-	Large Power User
LV	-	Low Voltage
MV	-	Medium Voltage
NOP	-	Normally Open Point
NEPS	-	Network and Equipment Performance System
NERSA	-	National Energy Regulator of South Africa
OHL	-	Overhead Line
PPU	-	Prepaid Power User
PSO	-	Particle Swarm Optimization
SAIDI	-	System Average Interruption Duration Index
SAIFI	-	System Average Interruption Frequency Index
SPU	-	Small Power User
SQI	-	Service Quality Incentive

1 Introduction

1.1 Background

South Africa and a few surrounding African countries are powered by the state owned utility Eskom. Eskom remains as the integrated monopoly in South Africa and owns the generating plants as well as transmission and distribution networks in the country. Approximately 95% of the energy used in South Africa and approximately 45% of the energy used in Africa is generated by Eskom. They supply residential, agricultural, industrial and commercial customers as well as redistributors. Due to constrains on the power system, lack of capital and increased demand for energy there is increased focus on improving and reinforcing the core business of electricity supply and trading [1].

The power system is one of the most complex systems often making planning, maintenance and operation difficult. It is designed to continuously supply electricity, with only the occasional or ideally no interruptions. The number of interruptions which occur together with the quality of power supplied determines the reliability of the system. A continuous supply of power ensures that utilities are profitable and that end consumers are satisfied [2]. Hence, it is essential for utilities to prioritize a sustainable and reliable power system.

Reliability of the power system can be further divided into system adequacy and system security. Adequacy evaluates the available facilities within the power system and if they are able to satisfy the load demand of customers. The facilities evaluated include the ability to generate enough energy and having sufficient networks in the transmission and distribution space to transfer energy to the end customer. It is a static evaluation which considers the connectivity of the system and does not consider disturbances. System security considers the ability of the power system to respond to the dynamic disturbances within the system. Disturbances related to system security include the loss of major transmission and generation facilities as well as localized effects. Improving the overall system reliability is possible considering either aspect separately; however; the improvement would be more significant considering both aspects [3].

Distribution systems are often overlooked as they require less capital in comparison to generation and transmission systems. Loss of generation and transmission are deemed more critical as they may impact the entire power system. Previously any outages on the distribution system were also assumed to have only a localized effect. However; having sufficient generating capacity and means to transmit power becomes useless when the end user cannot be supplied due to a failure on the distribution system. The faults on the distribution network make the largest impact on failure events and customer interruptions, contributing the most to customer outages [4]. Residential customers are unable to use basic facilities for lighting and cooking while industrial and commercial operations are brought to a halt which can result in severe financial losses regardless of the duration. Similarly, the costs incurred by the utility from major power outages on distribution networks can exceed millions of Rands.

Electricity is viewed as a social right in modern times as opposed to being a luxury. While paying increasing amounts for electricity due to tariff hikes, the customer must also deal with issues on a daily basis ranging from poor supply voltages to outages lasting for extended periods. The occurrence of several interruptions may cause damage and even failure of equipment and appliances. There is an increasing dependency on electricity but existing networks have countless issues such as aging equipment, unpredictable weather, theft and overload. Due to these issues the South African network reliability is in fact deteriorating each year [5].

1.2 Research problem

In recent times there has been an effort to move towards more efficient and reliable functioning of electric distribution utilities along with a constant need to improve network performance and reliability. The intent of the National Energy Regulator of South Africa (NERSA) is to keep the utility competitive in the industry and thus requires them to deliver the best service to consumers at the most reasonable cost. In addition to prescribing the minimum quality of supply standards, NERSA drives the improvement of reliability and measures the utility performance each year. To regulate the continuity of supply, Service Quality Incentives (SQIs) are used to financially reward or penalize the utility based on performance, which is in line with international practice [6]. Thus short-term activities and the implementation of solutions to improve reliability are extremely important.

Strategic planning is required to reduce the frequency and duration of outages and improve system restoration periods. As the primary aim of the power system is to meet the demands of customers, the power system equipment needs to function continuously for the period which it is required. Economic constraints and network reliability often restrict each other and usually require some compromise. Selecting projects which minimize costs but yield the maximum benefit to both the utility and customer requires in-depth analysis of the trade-off to support the decision making process.

1.3 Research motivation

Reliability evaluation is an effective means to assess network performance where the results offer great insight to problematic areas and specific networks and component types can be flagged. It is also a means for the utility to review their power system performance in comparison to other countries. Predictive reliability modelling can be further used to test possible solutions theoretically and gauge their benefit before they are physically implemented [7]. This research aims to provide options to the utility which are practical and economically feasible as well as sustainable for the foreseeable future.

DigSILENT PowerFactory software is required to model the distribution networks and perform simulations as it is regularly used by the South African power utility for analysis. Reliability evaluation and optimization algorithms can be applied to both simplified and complex network models. The limitations when using complex models is the longer simulation time to produce results, while simplified models may not provide a true assessment of reliability [8]. A method which can be applied to real distribution networks needs to be developed, thus requiring a complex model to be evaluated which includes all power system components. A suitable optimization method should be considered in this research as exhaustive enumeration would be time consuming. The optimization algorithm should be suitable to evaluate large search spaces and find the optimal solution efficiently, while still being simple enough to implement on diverse networks [9].

One of the major hurdles when evaluating the reliability of a power system is access to accurate component failure data [10]. The state of system equipment varies from network to network and has a large impact on the power interruptions. The operational stance and environmental conditions in which the network exists make it difficult to predict the system reliability. In some cases the environment and lack of maintenance leaves components more prone to ageing and thus failure. Usually, blanket failure rates are available, but their actual effectiveness when used on specific networks is unknown. The readily available access to information related to failure events and network outages make this an appropriate field to conduct research. It also allows a quantitative approach to be taken as opposed to relying on experience to make decisions.

Reliability has financial as well as technical aspects which need to be considered. A power system interruption has an economic impact dependent on the type of customers being supplied. Each customer group has distinct characteristics and power consumption patterns, hence the economic worth of customers vary. Customers also desire lower electricity tariffs but improvement in the reliability of their supply resulting in a trade-off to their requirements, which may differ for various customer types [11]. In order to establish cost effective customer service and accurate cost to benefit assessments, customer damage functions need to be calculated for a specific network. Access to the allocation of customer types per network and their usage patterns make this research possible. The research aims to use objective and credible input data to achieve comprehensive and sound results.

Reliability studies output many different reliability indices which are often dependent on each other. The indices provide insight to the components of the system, the protection available and its co-ordination, the network topology as well as the operating and maintenance strategy. Suitable indices which support the objective of the study need to be chosen [3]. Basic power system reliability indices of

System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are monitored and used in this research work as they are customer-centered. They are also international Key Performance Indicators (KPIs) which allow the South African power utility to be benchmarked against other utilities. The interruption costs are also considered in this research which utilized the Energy Not Supplied (ENS) and system expected outage cost to gauge the financial implications on the utility.

Switches and reclosers are protection devices which can isolate the faulted section of the system while maintaining supply to the rest of the network. Switches can be installed at any location on the network while multiple reclosers require co-ordination in order to function effectively. Reclosers can also clear transient faults and restore power to the network. Reclosers can be placed strategically to define boundaries between different authorities and separate large numbers of customers on networks. Reclosers can also be installed for the isolation and clearance of faults which will enhance network performance [12]. This research aims to quantify the benefit of installing more switches and reclosers on the network to boost performance.

The safe and reliable transfer of power within the distribution space is the main focus of this research. Improving the distribution system reliability improves the overall power system reliability and improves availability of supply to the consumer. A reduction in the frequency and duration of outages leads to improved customer satisfaction. It also results in a reduction of associated operation and maintenance costs to the utility related to outage management. With the enhanced system security, there is also a greater reserve margin available to be used during contingency events and the reduction in losses leads to overall savings for the power utility. The need for utilities to provide economical and reliable power supply to customers is increasing, thus improving reliability in a cost-effective manner is important.

This research work aims to consider and answer the following questions:

1. What are the common causes of customer interruptions?
2. How reliable are distribution system components?
3. What is the reliability of a rural South African distribution network?
4. How can the reliability on a distribution network be improved?
5. What is the economic worth of customers being supplied?
6. How will reconfiguring the distribution network impact reliability?
7. What are the effects of reconfiguration on thermal loading and voltage?
8. How will reconfiguring the distribution network impact system losses?
9. How will the number of switches and reclosers and their placement affect network reliability?
10. Is it a cost-effective solution for the utility to place additional protection devices on distribution networks?
11. Is the return on investment from device installation lucrative?

1.4 Hypothesis

Based on the need to improve the reliability, availability and maintainability of existing South African distribution networks in a quick and financially feasible way

1. Reconfiguration of existing distribution networks is easily implementable, incurs no costs and is an effective solution to improve reliability and network performance.
2. Strategically placed additional protection devices such as switches and reclosers can further enhance performance and reliability of distribution systems in a cost-effective manner.

1.5 Objectives

This research work focuses on Medium Voltage (11 – 33 kV) South African rural networks; chosen for their complexity; which distribute power to different consumers. The increase in load and lack of new infrastructure forces an investigation to the current network capabilities and performance to ensure the socio-economic development of the country. Initially, background research needs to be conducted into various reliability improvement methods and algorithms to determine the various advantages and disadvantages. Thereafter a methodology will be proposed and developed to be tested on real distribution networks. The research work aims to assess networks and proposes strategic solutions which will optimize existing networks by improving reliability and power delivery efficiency. Evaluation and discussion of the results will allow the quality and performance of the proposed solutions to be measured.

The main aims of this research include the following:

1. Model real existing distribution networks fully using DigSILENT PowerFactory software
2. Evaluate historical fault data to ascertain the causes of interruption and to determine different component type failure rates and repair durations specific to a distribution network
3. Perform predictive reliability modelling using suitable simulation software to establish reliability indices for various networks and compare simulation results to historical reliability records to ensure their likeness
4. Investigate the concept of network reconfiguration using a suitable optimization algorithm on real distribution networks and determine the effects on reliability indices and network efficiency
5. Study the influence that different customer types have on the customer interruption costs due to outages and calculate a customer damage function specific to each distribution network
6. Investigate the effectiveness of placing additional devices on the network using a suitable optimization algorithm to further improve reliability indices and estimate the financial benefit to the utility if any

7. To provide suitable recommendations to the power utility for distribution network reliability improvement solutions which are feasible, economical and lasting
8. To provide a process and develop a tool which is effective on diverse rural distribution networks and can be used in other parts of the world to support network planning

1.6 Limitations of research

The following was not considered as part of this research:

1. Only distribution networks were considered in this study and reliability of upstream equipment such as generators and transmission substations and lines were excluded from this study
2. Only networks in the KwaZulu-Natal province were considered in this research
3. The implementation of the methodology and optimization algorithm on any hardware environment was excluded from this study
4. The construction space, terrain and tele-control functionality at the planned locations of reclosers are assumed to be suitable
5. Physical implementation of the given solutions on the field has not been included as part of this study
6. All data, costs and standards used are deemed to be correct at the time of study

1.7 Research goals

The impacts of faults and resultant outages on distribution networks will be studied by means of simulations. The goal of this research work includes improving on previous reliability evaluations to gain the most accurate reliability model and resultant reliability indices. Furthermore; the purpose is to evaluate the impact of network reconfiguration on reliability indices and network efficiency using an algorithm to produce only feasible options taking into consideration the network constraints. In addition a modified algorithm will be implemented to place protection devices in the optimal positions to achieve results which improve reliability, minimize costs and consider protection co-ordination.

1.8 Structure

This research work consists of various sections which are organized as follows:

Chapter 1 provides an introduction to the power system, the problem statement and objectives of the research. A brief overview of the dissertation and research scope are also discussed.

Chapter 2 presents a review of literature which explores research previously conducted around reliability improvement on distribution systems including simulation methods and optimization algorithms. The subsequent approach to this research and impact is discussed.

Chapter 3 describes the relevant theory behind the concept of reliability and evaluation of the relevant indices. Key aspects which influence reliability including faults and outages are also discussed. The general theory and application behind the Binary Particle Swarm Optimization (BPSO) algorithm is discussed, with the objective being to perform network reconfiguration to optimize reliability indices and establish the effect on network efficiency. The algorithm modification to optimize the placement of switches and reclosers to further improve system reliability is then proposed.

Chapter 4 evaluates three test networks where fault analysis using historical data is completed to determine failure rates and repair durations of components. Thereafter Monte Carlo reliability simulations are performed using DigSILENT PowerFactory and the network performance is gauged. The effects of network reconfiguration on the SAIDI and SAIFI are assessed. During reconfiguration the radial nature of the network is maintained, and the voltage and thermal limits are evaluated to ensure they still comply with legal requirements. As a secondary objective the effects of network reconfiguration on the system losses are also assessed.

In Chapter 5 BPSO is also utilized to optimize the number of additional devices and their placement on the three reconfigured test networks, as an economically feasible solution to improve reliability. The protection devices considered in this research include switches and reclosers. Customer damage functions specific to each network are calculated considering the different customer types being supplied. The objective function aims to reduce the outage costs of the network using switches or reclosers in the most cost effective manner.

Chapter 6 provides the conclusions and recommendations which can be made from this research and the scope for future research is also investigated.

2 Literature review

This chapter provides a review of the previous approaches taken to improve reliability with key contributions and limitations used as a basis for this current research. Thereafter, the practice of network reconfiguration and placement of additional devices are motivated as techniques to maximize reliability on South African networks.

2.1 The power system

The South African power system comprises of generation and power delivery systems including transmission and distribution. Transmission systems transfer power over long distances at higher end voltages while distribution systems are operated in the ranges of 11 kV to 33 kV [13]. The Medium Voltage (MV) or distribution networks supply commercial, industrial and residential loads and thus have a direct effect on the end customer as displayed in Figure 2-1.

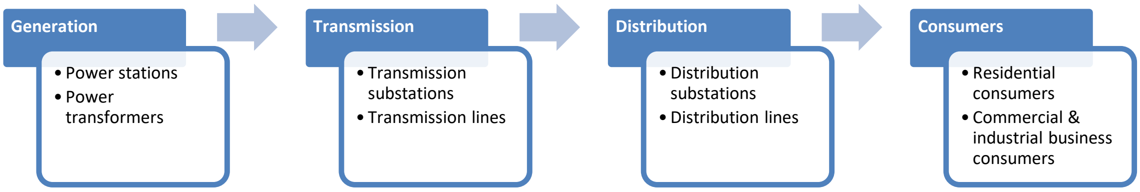

Figure 2-1: The power system

2.1.1 Power system reliability

Power system reliability is defined as the probability that a system or component will effectively perform its intended functions for a given period of time under the conditions it was designed to operate. This ensures the continuity of electric service to customers, where the generation resources are sufficient and the transmission and distribution networks are able to transport power [13]. Normal operating conditions may be disrupted by unscheduled events such as faults and scheduled events including construction and maintenance operations. Consumer outages and equipment failure are thus central to distribution system reliability. Measured reliability parameters are a key indicator of the utility performance and are monitored by NERSA. They also provide a comparative measure to the performance of other power utilities in Africa and around the world.

2.2 Reliability challenges on distribution networks

Distribution networks in South Africa are now more problematic than ever due to the growing demand for electricity. The addition of load on existing systems results in weaker networks with poor reliability due to inadequate planning and capacity shortages. The resultant networks are large and complex in nature due to the long distances to supply diversely located customers in both rural and more developed areas. The use of overhead lines is preferred due to their reduced cost compared to cable network; however; they are more prone to failure. Due to their exposure to increased environmental conditions such as adverse weather conditions, contact with fauna and flora as well the occurrence of structure and conductor failures they usually have high SAIDI and SAIFI values. Due to the radial nature of many of these networks, it results in customers being without electricity for extended periods of time due to planned and unplanned outages [14].

Power system equipment is required to perform a continuous function which it was designed for except when planned work is conducted. However, faults may occur at any location and time and result in unplanned interruptions. Interruptions may be caused due to technical complications such as faults on the networks which occur due to failure of components such as insulators, structures and conductors. They may also occur due to external factors such as adverse weather conditions which damage infrastructure or human intervention such as theft and vandalism. Other factors which cause component failure are aging, design, manufacture and lack of maintenance [15]. Certain fault types may occur more often than others and have a longer duration. The duration of the fault depends on the location, the availability of staff and spare equipment as well as the ease with which the equipment may be replaced. These faults may result in damaged equipment and customers being disconnected for any period of time which has an adverse effect on system security [16].

The quality of the power supply as well as the reliability of the power system affects the economic growth of the country. The power utility is also affected by a loss of income during the outages as well as a negative impact on its brand image and measured key performance indicators. All power utilities try to minimize costs but simultaneously strive for customer satisfaction. Thus, it is vital to plan, design, operate and maintain reliable distribution networks where severity of interruptions is minimized, the frequency and duration of interruptions are reduced and the customer has continuous supply as far as possible [17].

2.3 Reliability improvement

Evaluating reliability allows the utility to effectively plan and improve the network performance where possible. By decreasing the duration and frequency of interruptions on distribution networks the quality of supply to customers will improve. All utilities strive to comply with international standards which govern reliability; hence various means of improvement are constantly being explored in different parts of the world [18]. The focus of this research is improving reliability of rural distribution feeders specifically in South Africa which consist of long radial lines and multiple types of equipment.

Conventional ways of improving reliability such as upgrading existing equipment or implementing redundancy on the distribution system usually requires large capital investment [19]. Redundant networks allow customers to be transferred to and supplied from adjacent networks while repairs or routine maintenance is being conducted. It allows flexibility in operating the networks; reduces loss in revenue and improves the key performance indicators of the electrical utility. While redundancy on the distribution networks will allow customers to have continuous supply, infrastructure is expensive and maintaining additional networks is both time-consuming and costly to the power utility.

Ranking and prioritizing maintenance operations on networks using the Reliability Centered Maintenance method aims to improve reliability. It is a cost-effective method which is concentrated around good operational practices of the utility. For maximum benefit it could possibly be used in conjunction with other reliability improvement methods as opposed to being implemented as a stand-alone solution [20]. Distribution automation and other smart grid technology are also used extensively to minimize the impact of failures and improve the system reliability. While they are effective and have numerous other benefits such as theft identification and real-time load management they require a large capital investment by the utility [21]. Distributed Generation (DG) has the ability to supply certain loads in the event of outages and grid failure. However, only specific customers able to be supplied by the DG, experience the improvement in reliability. DG is also expensive and a lengthy process to implement and their possible failure results in additional interruptions to the customers [22].

Network reconfiguration was first introduced in 1975 to minimize losses on the network [23]. Network reconfiguration changes the operating conditions of the feeder, where the losses and service restoration time is possibly altered. The changes to the number of customers affected by faults, possible options to restore power as well as the time required to restore power allow for reliability improvement. The reconfiguration can be implemented at no cost to the utility making it a favorable solution [8].

Placing protective and control devices on a network improves the safety as well as the quality of supply. When permanent faults occur the devices can isolate the faulted section of network and also allow the partial restoration of power in some cases. The capital costs of adding additional devices such as switches, fuses and reclosers can be justified if they are strategically placed to improve the system reliability [24]. This solution has potential long-term benefits but can be swiftly and easily implemented by the power utility.

2.3.1 Optimization methods for network reconfiguration

Network reconfiguration involves obtaining a new network topology by opening and closing existing switches on the network. The new topology needs to be technically feasible and should optimize the objective function. The change in topology may be used to improve reliability, reduce system losses, and improve voltages among other factors. There have been many different approaches to determine the optimal configuration of MV networks. An assortment of these methods was considered to determine which would be most effective on large rural MV networks.

A brute-force-algorithm where a closed-switch is opened and an existing open switch is closed to keep the feeder radial was developed in [25] and tested on the Baran and Wu 33-bus test system. The objective was to minimize losses by measuring currents and losses to gain the optimal configuration; however; it did not consider operational limits of the feeder. Other branch-exchange algorithms have been presented in [26], [27] and [28] with the primary aim also being to minimize power losses on the system but no consideration to the effects on the reliability indices. Similarly, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) have been used to also improve system losses in [29]. While minimizing losses would have great financial benefit to the power utility, the reconfiguration could have an adverse effect on the system reliability and should also be considered.

An economic analysis was conducted in [30] where the power supply interruption damage costs and cost of power losses was minimized as far as possible. The network reconfiguration based on the branch exchange method was tested on a small distribution network where monetary savings were achieved. In [31] another heuristic approach based on graph theory has been taken which aims to minimize the customer interruption cost as well as cost of losses on the IEEE 33-bus and 119-bus systems. The codification developed ensures radial structure of the feeder and that voltage and current violations do not occur. The node-power difference is calculated across all existing open tie lines and the tie line with the maximum difference value is considered. The tie line is closed, and a neighboring tie line is opened to form the new configuration. The original SAIDI of 59.61 is reduced to 42.29 h/Ca when minimizing customer interruption costs on the 33-bus system. These approaches are effective on the small test systems which were tested; however; on real complex distribution systems, the computational time would be lengthy and success not guaranteed.

In [32] an Enhanced Genetic Algorithm (EGA) is used to improve reliability and loss parameters which can also be utilized on both radial and meshed systems. A single loop formation was used to improve the accuracy and speed of convergence of the GA algorithm whereby an open switch is closed to create a loop in the crossover process and for the mutation process branches in the corresponding tree are closed. The radial IEEE 33-bus, 69-bus and 136-bus systems were tested utilizing MATLAB which showed the EGA had an improved computational time in comparison to GA. The objective function consisted of weighted functions of ENS and losses but did not consider operational limits of the test systems. The SAIDI reduced from 1.247 to 1.047 h/Ca and the ENS from 3.846 to 3.302 MWh/a for the 33-bus system. GA is also used in [33] where a combination of factors is optimized including losses, ENS, SAIFI and the feeder voltage by transformation to a single objective function. The IEEE 33-bus and 69-bus systems were used as test networks and it was ensured that all technical requirements were met. The results present reconfiguration options to minimize and maximize individual indices as well as optimize different combinations of the various indices. There is a conflict between the improvement of reliability and power quality indices but evaluating different options allows the solution to be chosen based on need. In [34] the 33-bus and 83-bus systems are used with a non-dominated sorting genetic algorithm-II (NSGA-II) to optimize active power losses and SAIFI of the network. Networks with distributed generation, microgrids and radial topology were considered. The networks with microgrids have an improved SAIDI due to the continuous supply to some customers even after a fault event. To generate the initial population the branch exchange method is used and each chromosome symbolizes a configuration which may be non-valid or valid. The population is diversified and the search space is expanded to find good solutions with fewer generations.

The Simulated Annealing (SA) algorithm which is derived from the heating and cooling effects on metals uses a variable for temperature to find the optimal solution. In [35] SA was used to minimize the customer interruption costs on a Roy Billiton Test System (RBTS). The operational constraints and radial nature of the network are considered as solution constraints. MATLAB was used to perform simulations to determine the optimal network configuration where an annual saving of $2320 can be achieved. The method is effective however it would be beneficial to monitor the effects of reconfiguration on other network parameters. An annealed local search was developed in [18] where tie-switch shift using the parent-child theory is utilized to improve reliability ensuring a radial network configuration. This algorithm was developed to avoid the obstacles of GA and SA algorithm being computationally intensive and not always generating feasible solutions. SAIDI, SAIFI and the momentary average interruption frequency index (MAIFI) were the measured variables with the algorithm being tested on various distribution networks. The operational limits of the feeders were also considered. The improvement on SAIDI when utilizing the annealed local search and predictive reliability modelling is approximately 15% on urban networks but showed little benefit for rural networks with a 1% improvement.

The objective in [36] is to determine the optimal switch status to simultaneously minimize power losses and maximize reliability on the IEEE 33-bus and 123-bus systems. Load flows are used to evaluate the power losses and minimal cut sets used to determine reliability on the system. The average unreliability of the system and real power losses are used as factors in the objective function of the Binary Particle Swarm Optimization (BPSO) algorithm which is used to resolve the optimal network configuration. The 33-bus system unreliability was improved to 0.001113 from 0.001815 when maximizing the reliability. In [8] BPSO was also used and tested on the modified IEEE 13-bus distribution system to optimize less common reliability indices including the loss of load expectation (LOLE) and loss of energy expectation (LOEE) also known as Energy Not Supplied. A radial configuration was ensured and the historical performance was also considered during the reconfiguration. Normalized load curves are used to represent the network load as it varies throughout the day. The Monte Carlo simulations are performed using Risk_A software to maximize the power supplied to the loads. The actual reliability indices and subsequent improvement is not explicitly stated in this work, hence the effectiveness of this methodology cannot be gauged. BPSO was also used in [37] to maximize reliability by reconfiguration of the network while ensuring a feasible solution. However, the reliability indices before and after the implementation of the algorithm were not specified.

2.3.2 Optimization methods for device placement

Introducing additional protective devices to distribution systems minimizes customer outages and hence improves reliability. Switches can be used to isolate faulted areas of the network, restore power to the remaining customers if possible and aid during fault finding. They are inexpensive, manually operated devices and co-ordination on the network is simpler. Reclosers are devices used to sense over-current, earth-fault and sensitive earth-fault conditions in the network. After occurrence of a fault the recloser trips and thereafter closes automatically subject to the settings. Reclosers clear transient faults, isolate faulted sections of the network and provide tele-control and data capturing functionality among other benefits. However, reclosers placed in a series configuration require co-ordination to ensure all protection operates efficiently [12]. Installing multiple protective devices over a large MV network will improve reliability but large capital costs would be incurred. Therefore planning the number of additional device installations and selecting their optimal location is important. There have also been many different approaches to optimize the placement of devices on distribution networks.

In [38] a cost analysis was used to determine the optimal placement of reclosers on a real network which experiences frequent tripping. The devices were limited to placement on the main line and near tee-offs on the network, with the different option combinations being selected manually. The investment costs and financial losses of customers using an estimated Value of Lost Load (VoLL) were evaluated where the network topology, customer type and the loads on each section of the network were taken into consideration. The generalized objective function was calculated mathematically for each option to minimize the cost. While this method is effective to reduce the feeder risk it is impossible to determine if the recloser placements are at the optimal position or if it is possible to further improve the network performance at the same cost.

The Ant Colony System (ACS) is derived from the behavior of ants and their use of indirect communication. In [39] ACS is used to optimize the placement of existing switches in the network to reduce the customer interruption costs. While the results are proven to be beneficial, the cost to relocate switches is not included in the objective function. In [40] Ant Colony Optimization (ACO) is used to determine the location and number of switches, reclosers and fuses to be added to distribution networks. The objective is to minimize SAIDI and SAIFI on the network while also minimizing the total cost. Average repair time and failure rates were utilized and technical limitations of the networks were also considered. MATLAB was used to implement and test the algorithm on real distribution systems. The decrease in SAIDI and SAIFI was recorded at 52.74% and 52.03% respectively after adding thirty-six additional devices. While this is a significant improvement in reliability, it does not seem feasible for such a large amount of capital to be invested on protective devices on a single network. The algorithm can be easily implemented but due to the large search space the convergence time when using this algorithm is uncertain.

The Tabu search algorithm randomly places a device and evaluates the results, which are thereafter stored in memory. This allows the algorithm to recognize repeated solutions and create an effective search space where all areas of the network are explored. Tabu search is considered in [41] to locate protective devices on the main and secondary branches of the network and minimize the number of customers affected by faults. The Tabu search algorithm is also used in [24] to place switches, fuses and recloser devices on a real network. Mixed Integer Non-Linear Programming (MINLP) was used to model the problem and average failure rates and repair durations were utilized for the network. System constraints were also taken into consideration when simultaneously trying to optimize the investment costs and interruption costs. Placement of devices was limited to the main line, beginning of long lateral branches and before large or sensitive customer loads. The maximum number of reclosers was also limited to four. Due to the algorithm being metaheuristic, finding the global optimum solution is not always guaranteed. It is also a difficult algorithm to code due to the number of parameters required.

SA has been used for various optimization problems with complex and multi-objective functions. It was used to optimally place and size capacitors on distribution systems in [42] and [43] using minimization methodology. While the optimization function for capacitor placement is different to the switch allocation problem, the approach used would be comparable. In [44] SA was used to optimally place sectionalizing switches on different radial RBTS. Customer damage functions and equipment failure rates and repair durations are taken from known literature. The objective function is to minimize the investment, maintenance and outage costs of the system with the optimal number of switch installations. The placement of switches was limited to the main line and beginning and ends of main branches. While the algorithm search space is large and considers multiple options, the output is reliant on the assumption values and input parameters. The total annual minimum switching device costs were reduced with the addition of fourteen switches.

Genetic Algorithm (GA) is an evolutionary technique which is also used for device placement on networks. Genetic Algorithms are based on genetics and natural selection of a given population made up of many individuals. The fitness of individuals is evaluated to determine the optimal solution. In [45] GA is used for switch placement on a real radial network. Technical constraints were taken into consideration when optimizing the investment costs and expected outage costs. The switches are placed along the main branches of the distribution system and the SAIDI is reduced from 26.261 to 19.421 h/Ca in the favoured case, which is substantial improvement. The SAIFI of the network is not influenced by the additional switch placements as the frequency of system failure events is not altered. In [46] a GA is tested on the RBTS 2-bus system for additional sectionalizing switches. Reliability parameters are calculated mathematically using the shortest route method. The Average Service Availability Index (ASAI) is minimized as far as possible while ensuring the total power cost to the utility is minimal. Genetic algorithms work well to solve multi-objective problems as they can process results in parallel; however; in detailed models the optimal solution may not necessarily be determined.

Particle Swarm Optimization (PSO) is inspired by a flock of birds or school of fish and their social behavior was first established by Eberhart and Kennedy [47]. The algorithm allows each particle to investigate the search space around their position to determine the best destination. In [48] both GA and PSO are tested for the optimal switch placement problem on the IEEE 13-bus system. The MATLAB toolbox is used for the algorithm comparison. The ENS and SAIDI of the network are minimized with the objective being to maximize the profit of the utility. Both algorithms produce similar results however GA was found to be more dominant. Similarly in [49] The PSO and GA methods were compared on the IEEE 8-bus and 12-bus systems inclusive of distributed generation. The algorithm to optimally place switches was implemented using MATLAB. The results for both cases showed that fewer switches were required to output similar reliability results when using the PSO algorithm. Both papers have considered only the placement of switches and no other protective devices. In [50] a three-state PSO approach was taken to determine the placement of switches and reclosers. The algorithm is tested on the RTBS BUS 4 and IEEE 123-bus system where the expected outage cost and total cost to the utility is minimized. The devices are placed along the main line of the distribution systems only. The switch placement results are also compared to those previously determined using the SA algorithm and the PSO method utilized fewer switches to minimize the total cost on the same system. The PSO is a simple algorithm which works well in large search spaces; however; it is dependent on the algorithm parameters initially chosen.

2.4 Optimization algorithm

The approaches reviewed utilize different methods, objective functions and consider various constraints of distribution networks. While no optimization algorithm is superior the most suitable one needs to be chosen taking into account all aspects of the problem. An optimization method is required that will be effective for both the reconfiguration of networks as well as the placement of additional devices. All possible combinations need to be tested to determine the optimal network solutions; however; complete enumeration would be time consuming. Thus the evolutionary optimization algorithm of PSO was chosen as it is suitable for large search spaces. It also uses global optimization points as opposed to stopping at local maxima and minima [50]. It is a simple and effective algorithm which has fewer parameters in comparison to other techniques.

Basic test networks were utilized in many cases such as [31], [32], [36], [46] and even further simplified network models were used in [8], [38] and [44]. While this ensures the algorithm will converge faster, the potential locations to place devices are limited. It also does not prove the algorithm is suitable for real-world application. Hence real distribution networks will be used to test the optimization algorithms as in [18], [24], [38], [40] and [45]. This allows specific South African networks to be optimized where the given solution can in fact be implemented for improvement of the distribution system reliability.

Most of the reviewed work considers the placement of devices on the backbone of the network and at large tee-off points in [24], [44], [45] and [50]. However, on rural distribution networks the power consumption is not always uniformly distributed along the length of the feeder. Thus, limiting devices to certain positions may not result in the maximum benefit to the system. All existing lines on the network should rather be considered as a potential location for a device to be added. While this increases the search space and computation time of the algorithm it ensures that the optimal network solution can be determined.

Previous studies have used typical average component failure data to determine network reliability as in [24], [40] and [44] from known literature. Conducting reliability studies using average component failure rates and repair durations will output reliability indices relative to average network performance. None of the reviewed papers have attempted to develop failure rates and repair duration's specific to their utility or area. In this work the outage characteristics of each distribution network were considered and found to be dissimilar. Determining component failure rates and repair durations unique to each feeder using historical data would be required for accurate predictive reliability modelling and is implemented in this research.

The placement of fuses was also considered in [24] and [40]. Fuses are effective, and the equipment and installation costs are relatively inexpensive; however; they cannot be installed upstream of a recloser or on a feeder backbone. The fuse is unable to differentiate between permanent and temporary faults on the network and due to the many faults of a transient nature on rural distribution networks they are blown unnecessarily. Thus, customers may experience outages without cause and operation costs are increased due to operators needing to replace the fuse. Newer fuse technology which is able to differentiate fault types is more expensive and requires sophisticated installation. Hence, the placement of additional fuses on the network was not considered in this study. Only the placement of switches was considered in [44], [45], [48], [49] and similarly only the placement of reclosers in [38] and [51]. Both device types have both proven to be effective for reliability improvement in previous work. Since the same algorithm can be easily adjusted and utilized for placement of reclosers and switches both devices are considered in this research. The influence that reclosers and switches have on the objective function due to the difference in capital costs can also be monitored.

Many of the reviewed approaches take into account constraints and limitations of the network. Important technical constraints include the minimum voltage on the networks and the maximum thermal loading on the conductor and were factored into the studies by [18], [33] and [35] among others. It is also important that the radial nature of the distribution network is maintained as a constraint in this research work, similar to [8], [31] and [35]. The technical limitations of the network will be considered in this study as maintaining legal requirements are paramount for safety. In [24], the issue of recloser co-ordination was recognized and included as a constraint in the algorithm. It was also briefly touched on in [38] but most of the other literature does not consider a number or positions of reclosers which will not grade as a restriction. In this work a limitation to the number of reclosers which can be added to a single network will be factored into the optimization algorithm. Taking the co-ordination into consideration ensures that the additional reclosers added to the network are practical and offer effective protection.

The unreliability and ASAI were used in the objective functions of [36] and [46] respectively when considering reliability, but are less commonly used reliability measures. SAIDI, SAIFI and ENS as in [31] and [45] or a combination of the indices as in [18], [40] and [48] are more frequently used in objective functions. Measuring these reliability indices is dependent on the failure rates and restoration times for interruptions which affect the network. For this study to improve reliability, the SAIDI, SAIFI and ENS of the system are monitored and form part of the objective function. SAIDI considers the number of customers which are affected by outages while SAIFI considers the number of events which a single customer experiences. ENS considers the type of customer and calculates the cost of interruptions.

The cost of protection devices is critical to the objective function and is described in [24], [40], [44] and [50]. The reduction in outage duration and outage costs needs to be weighed up against the cost of installing additional protection devices on the network. The loads on a network consist of combinations of residential, commercial and industrial type customers which influence the customer damage function (CDF) and thus the outage costs. Accurate CDFs are essential to finding an economically feasible solution as the total customer costs in an area are dependent on the outage duration [52]. The CDF can be determined using customer surveys as in [53], [54] and [55] however; in some cases this may lead to inaccuracies as it depends on the consumers surveyed being objective. It also requires a large amount of data to be handled which is a time consuming and demanding exercise. The CDF is calculated in [24],

[44] and [50] using known literature as they are usually non-linear functions. Similarly, in this study by using the known existing customer types, the CDF will be calculated per network using available data. Other objectives often improved by network reconfiguration are system losses and load balancing [26] and system losses only as in [25], [27] and [28]. Likewise, in this study the system losses are included as a part of the weighted objective function. The configuration options to minimize losses are explored as well as the effects on system losses when the network is reconfigured to maximize reliability.

Previous studies have mostly been implemented using MATLAB as in [40], [48] and [49] or other similar software [8]. Modelling a real network using such software is difficult as it requires each component to be added from first principles. DigSILENT PowerFactory is a simulation package which allows networks to be modelled easily using predefined components with adjustable parameters. The software performs both load flow and reliability assessments. Load flow simulation can be used at various iterations to determine loading, voltage, radial nature and hence network feasibility. The reliability assessment requires an input of probabilistic data including the frequency and durations of failures which occur on the network [56]. The networks make use of Failure Modes and Effects analysis (FMEA) and the reliability evaluation is completed using Monte Carlo simulation methods similar to the assessment documented in [8] and [57]. This method simulates real power system performance which includes random events and is suitable for large systems. Analytical methods used in [18] are also effective but difficult when analyzing a complex system hence they were not considered. Furthermore, PowerFactory is capable of running algorithms coded using DigSILENT Programming Language (DPL) which saves the time-consuming process of linking to other software packages. Thus PowerFactory is the preferred tool to implement PSO for network reconfiguration and device optimization.

2.5 Conclusion

This review of previous studies has provided information and details of the various approaches to optimize reliability. The different benefits and limitations of the literature have been carefully considered. The evaluation of various methods and objectives has thus provided the opportunity to review, implement and where possible improve the optimization techniques previously used. The methodology proposed for network reconfiguration and additional device placement on South African distribution networks is detailed in Chapter 3.

3 Methodology

This chapter provides an overview and detailed analysis of the faults which occur in the KwaZulu-Natal area. This includes the fault types, fault classification and process to restore supply after a fault occurs. The simulation model and required probabilistic data inputs are discussed as well as the output reliability indices of interest to this study. The traditional method to obtain failure rates and repair duration of components is touched on. The methodology to determine failure rates and repair duration per component type; specific to a network; is also proposed. The proposed methodology of network reconfiguration using the BPSO algorithm is detailed in this chapter. The mathematical formulation and adapted BPSO algorithm to place additional switches and reclosers on the network are also discussed.

3.1 Faults and reliability

The Distribution system supplies customers throughout South Africa including major customers such as municipalities, industrial loads as well as rural households. The Distribution business is further divided into operating units which utilize the borders of the nine provinces in South Africa as a boundary. Each operating unit is responsible for all distribution networks contained within their boundary including operation, maintenance as well as building of new infrastructure. KwaZulu-Natal Operating Unit (KZN OU) supplies predominantly rural networks which have long line lengths and large customer bases with scattered loads along the feeder. Contrarily, other areas such as Gauteng operating unit supplies densely populated cities and towns resulting in networks which have shorter lengths and are usually meshed systems, allowing easy switching between networks. MV rural networks from KZN OU will be discussed in further detail and simulated in the reliability studies.

In KZN OU all occurrences of faults events are captured on a Network and Equipment Performance System (NEPS) which is thereafter used to monitor the performance of networks [58]. Raw fault event data extracted from NEPS was obtained for a five-year period from January 2012 until December 2016 for the entire KZN OU, with a section displayed in Figure A-1. Analysis of historical data allows the most common faults and their characteristics to be determined. From a study of all fault data, commonly occurring faults which occur on the networks are contained in Figure 3-1 and are due to various equipment type failures. Planned outages for the purpose of maintenance and construction also contribute significantly to the SAIDI and SAIFI of the OU [59]. For Distribution feeders, momentary interruptions are disregarded in the analysis as the power is usually restored soon after the momentary occurrence. Momentary interruption events have duration longer than three seconds but less than five minutes. While events where the customer was disconnected for a period greater than five minutes are classified as sustained interruptions and contribute to the feeder KPIs [60].

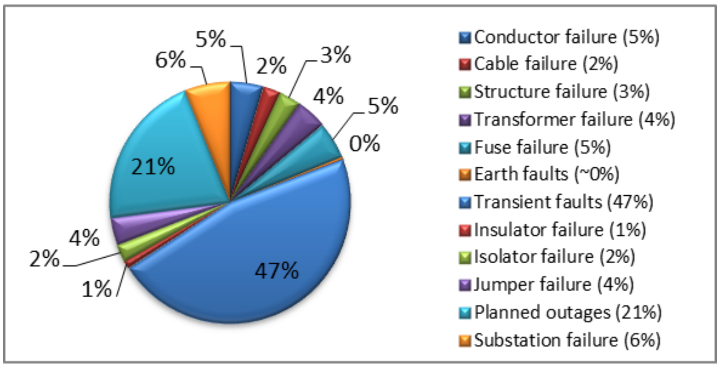

Figure 3-1: Common causes of outages on KZN OU networks [58]

3.1.1 Overall outage duration

The average duration of the fault can be determined as in Figure 3-2. After a fault occurs, it needs to be reported by a customer unless some network visibility exists. The measured outage duration starts at the time when the fault has been captured and is used for the purposes of calculating the utility KPIs. Where no network visibility exists, the overall outage duration is dependent on the customer reaction time to report the fault. Network visibility may exist by means of substation Remote Terminal Unit (RTU) and reclosers with possible integrated RTU. The RTU allows for remote control as well as live monitoring of the feeder or recloser. Thus, RTU enabled technology allows real-time notification of faults and reduces travel time to faults as remote switching may be utilized [61].

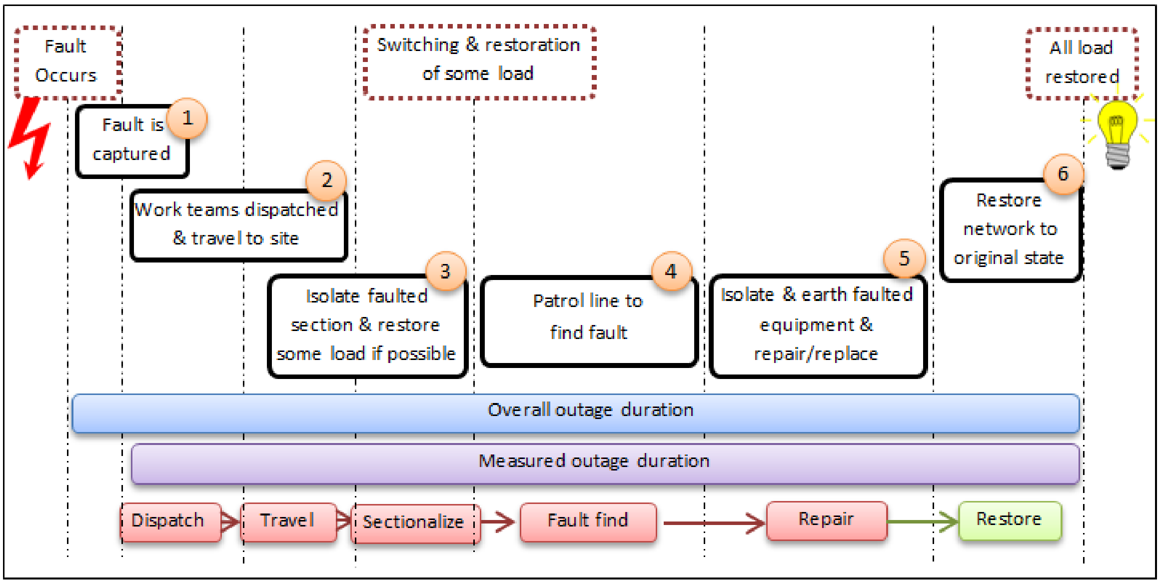

Figure 3-2: Process to restore supply after occurrence of a fault [61]

Once the fault has been captured, a works order is issued which allows the operator to perform work on the network. The operator is required to travel to operate the isolator or disconnector to isolate the fault if possible. The travel time is reliant on the distance which the operator has to travel to the network and possible prevailing weather conditions. The network is subdivided into smaller sections until the minimum number of customers is affected by the outage. Once sectionalizing is complete there may be partial restoration of power on the network and the affected network would have been isolated. The operator fault finds by patrolling the sectionalized line to visually identify the defect. The fault finding time is thus dependent on the length of the network which the operator is required to search. Once the exact location and cause of failure are identified, the faulted equipment is either repaired or replaced. This time is determined by the type of fault and may also be dependent on availability of spare equipment. Thereafter the power is restored; the network returned to its original state and concludes the measured outage duration [61].

3.1.2 Simulation model methodology

Reliability assessments may be conducted using various mathematical methods including the use of stochastic models, state sequencing methods and failure effect analysis (FMEA) [62]. Failure models define how equipment on the electrical system can fail, how prone they are to failure, and in the event of a failure the time required to complete repairs [63]. The failure models may be based on historical data of the electrical system or from data trends present in the electrical utility. In the case that there is a combination of one or more concurrent events and a specific load condition, it is referred to as the system state. FMEA is where the system state is analyzed in response to the faults, to determine if it will lead to load interruptions and their extent. FMEA considers post-fault operational scenarios which include fault clearance by tripping of fuses or protection breakers, opening switches, closing normally open switches to allow power restoration as well as load shed. Reliability indices may then be determined from the FMEA and system state [64].

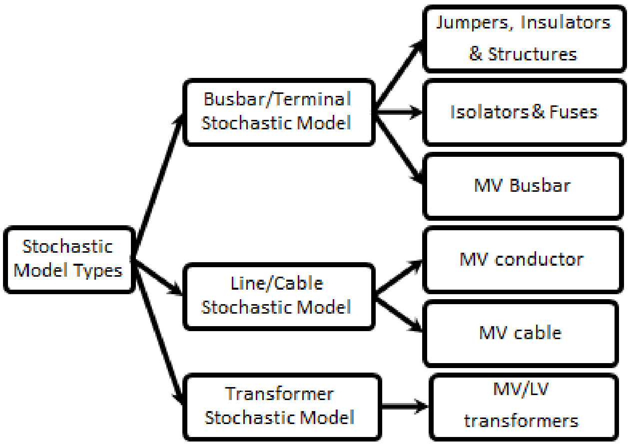

Figure 3-3: Types of stochastic models

The DigSILENT PowerFactory simulation model requires stochastic failure models to be assigned to certain elements on the network. A quantity is said to be stochastic when it has a random probability distribution. A stochastic model is a statistical representation of the failure rate and repair duration for any power system component. The stochastic model types of interest to MV networks include lines, bars and transformers as in Figure 3-3 [63]. Predictive reliability modelling will aid the utility in determining shortcomings and making technical decisions for both planned and existing networks, thus the component failure rates and mean time to repair need to be as accurate as possible.

3.1.3 Component failure rates and repair duration

Failure rates of components change during the course of its lifespan as in Figure 3-4 which displays the 'bathtub curve'. Equipment has early life failure which may occur during installation but with time the failure rate decreases. Aging failure which is due to wear and tear on equipment increases with time towards the end of the component's useful life. Random failure occurs during the component's useful life and has a constant failure rate which will be utilized for reliability studies [65].

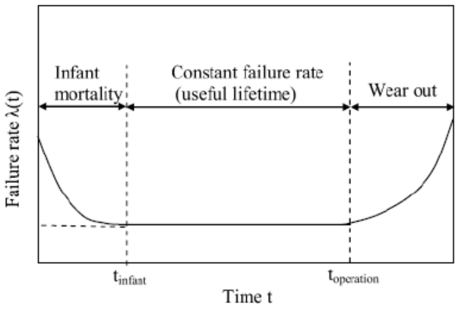

Figure 3-4: The bathtub curve [22]

Each stochastic model requires input parameters of the failure data which includes frequency of interruptions per annum and repair duration in hours. The component failure rate (λ) is determined by (3-1). This utilizes the actual number of component failures as a function of the component base to determine the interruptions per annum (1/a) [15]. The traditional repair duration of components may be determined by using mathematical equations which calculate the mean time to failure and the mean time to repair per annum as in (3-2) and (3-3). The availability and unavailability of the component may be determined by (3-4) and (3-5) as a fraction of time [63].

$$\lambda = \frac{number\ of\ component\ failures}{component\ base \times years} \tag{3-1}$$

$$MTTF = \frac{1}{\lambda} \tag{3-2}$$

$$MTTR = \frac{total\ outage\ duration}{number\ of\ component\ failures} \tag{3-3}$$

$$P = \frac{MTTF}{MTTF + MTTR} \tag{3-4}$$

$$Q = \frac{MTTR}{MTTF + MTTR} \tag{3-5}$$

where

$\lambda =$ failure rate

$MTTF$ = mean time to failure

$MTTR$ = mean time to repair

P = availability

Q = unavailability

The current KZN OU practice determines the yearly failure rate of components utilizing the total number of failures which occur on all networks in the area as a function of the entire component base within the whole area. Thus, the component failure rate is an average estimate dependent on the area in which it is situated. The network is classified according to environmental exposure, which has a direct effect on network performance. Environmental considerations include lightning, vegetation and corrosive pollution and are ranked from low to high impact. The repair duration used is a standard time in hours across all areas, which is estimated for each component type from literature [66]. Some average values of component failure rates and repair duration per area are contained in Table A-1.

The limitation with using blanket failure rates and repair durations is that the reliability output parameters will not be specific to the network but rather an average representation of any distribution network. The actual performance of the network whether poor or above average is not taken into consideration and the age and maintenance history of the network are also not factored in. Thus, it is more accurate to determine component failure rates per feeder utilizing historical data in order to perform meaningful reliability analysis [67].

The component base required to calculate the failure rate as in (3-1) is determined from the quantity of equipment present only on the network of interest. The data containing the actual number of transformers, isolators and fuses can be extracted. The length of the overhead conductor as well as the length of cable can also be extracted from existing data. For transient and earth faults, the line length in kilometers will be used as the component base. There is no easy means with which to determine the physical number of MV structures which are on the field as this information is not documented. The number of MV structures can be estimated by using the line length, assuming a structure exists every 100 meters for any overhead line. Jumpers and insulators are fitted onto structures hence the estimated number of structures may also be used as the component base for jumpers and insulators. Protection devices can be assigned a probability of failure percentage which is the average total that fault clearance operations will fail. Only one feeder breaker at the substation exists per network, but there may be multiple reclosers along the length of the line [66].

Similarly, the conventional means of determining the repair duration, which utilizes the sum of the hours spent on repairs divided by the number of failures to provide an average repair time, was not utilized. Figure 3-5 represents all occurrences of structure related faults and their duration for the entire KZN OU. As can be seen in Figure 3-5 some faults occur often and are of an extremely short duration, while some faults occur rarely and have an extremely long duration, thus compromising the average value for repair duration.

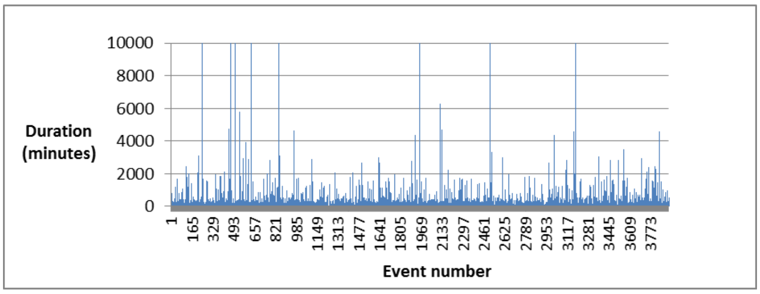

Figure 3-5: Fault event duration of structures over KZN OU [58]

The repair duration can instead be determined per network, per component type, using historical fault data captured on NEPS. A bell-shaped distribution can be utilized to determine the most frequent occurring repair duration for different fault types [62], [68]. Due to the large number of faults and their various durations, the data needs to be evaluated in order to determine the event duration to be utilized. This can be calculated using the mean (μ) and standard deviation (σ) of the data [69].

$$\mu = \frac{sum\ of\ event\ durations}{N} \tag{3-6}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{3-7}$$

where N = number of events

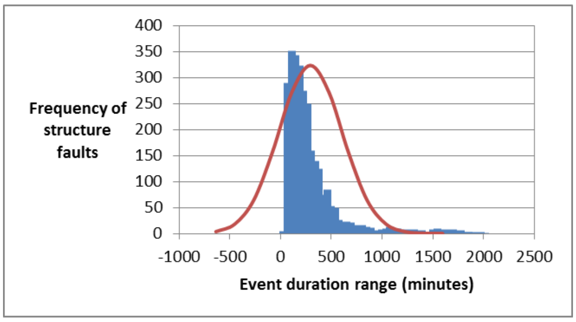

Figure 3-6: Frequency of structure related faults and the normal distribution curve

Figure 3-6 displays a plot of the structure faults which have occurred within KZN OU. It considers the frequency of faults occurring within different event duration ranges. The normal distribution curve has also been plotted which allows the most likely duration of any outage to be determined. The distribution data for event duration denotes that the majority of structure fault events have a shorter duration, and fault events with a longer duration occur less often. The most likely repair duration for all component failure types can be calculated in the same way for all networks. The average repair time determined from the normal distribution curve will be input into the stochastic model. Statistical analysis also accommodates for irregular events; with extremely long or short duration time; as the repair time is considered as outlying data. Utilizing equations to calculate the repair duration includes all irregular data which may compromise the result.

3.1.4 Reliability assessment parameters

The performance of a network may be measured by several reliability indices including system availability, duration and frequency of outages among others. The SAIDI and SAIFI of a network directly affect the customer and are thus considered in the study as continual effort is made by the utility to improve these KPIs [70] [71].

System Average Interruption Duration Index (SAIDI): Indicates the average interruption duration; measured in either minutes or hours; which any customer on the network would experience per annum. SAIDI may be improved by decreasing the duration of interruptions or by minimizing the number of sustained interruptions.

$$SAIDI = \sum \frac{customer\ interruption\ duration\ per\ annum}{total\ number\ of\ customers\ served} \tag{3-8}$$

System Average Interruption Frequency Index (SAIFI): Indicates on average how often any customer on the network would experience an interruption per annum. SAIFI may be improved by decreasing the number of sustained interruptions which customers experience.

$$SAIFI = \sum \frac{total\ number\ of\ customer\ interruptions\ per\ annum}{total\ number\ of\ customers\ served} \tag{3-9}$$

The reliability indices which are an output from the simulations can be compared to the data previously captured by the utility for SAIDI and SAIFI from the actual network performance. The real performance results act as a benchmark to ensure the accuracy of the simulation and output results [72].

3.2 Network optimization by reconfiguration

Reconfiguration makes small changes to the MV network ensuring the radial structure is maintained and will alter the KPIs of the network in either a positive or adverse manner. This is done by closing a normally open switch and opening an upstream switch while also ensuring that the feeder remains within expected voltage and thermal limits [18], [60]. The Particle Swarm Optimization (PSO) algorithm is an efficient means to determine the status of the switches in the network. Since the switches in a distribution network can only be in the open or closed state, which can be described as the binary values of either 1 or 0, Binary Particle Swarm Optimization (BPSO) can be used to provide the optimal network configuration.

3.2.1 BPSO algorithm - network reconfiguration

For BPSO a number of particles (Np) are engaged to find the optimal solution, with their movement guided by both the individual and global knowledge of the particles. The number of elements in the vector is equal to the number of switches in the network (Nswitches). The particle's position is determined by the velocity in that instant and position at the previous instant [47].

$$x_i(t) = x_i(t-1) + v_i(t) \tag{3-10}$$

where

x_i = position vector

v_i = velocity vector

The particle's velocity is updated by the experience of individual particles and the performance of other particles in the neighborhood.

$$v_i(t) = v_i(t-1) + \varphi_1.r_1.\left(\mathbf{pbest}_i - x_i(t-1)\right) + \varphi_2.r_2.\left(\mathbf{gbest} - x_i(t-1)\right) \tag{3-11}$$

where

φ_1 = individual acceleration constant

φ_2 = social acceleration constant

r = random number between 0 and 1

pbest = best position vector

gbest = best position vector of all particles

The maximum and minimum values of the velocity vector components are limited as follows to avoid oscillations around the solution with v_{max} being limited to 4.

$$v_{ij} = \begin{cases} -v_{max} & \text{if } v_{ij} < -v_{max} \\ v_{max} & \text{if } v_{ij} > v_{max} \end{cases} \tag{3-12}$$

Since the position vector can only take on binary values of 0 or 1, the elements are updated with each iteration.

$$x_{ij}(t) = \begin{cases} 1 & \text{if } p_{ij} > 0.6 \\ 0 & \text{otherwise} \end{cases} \tag{3-13}$$

where p_{ij} = random decimal number between 0 and 1

A fitness function is then needed to evaluate if the solution found by the particles is suitable at each stage of the iteration. The fitness function J(x) is expressed as follows [8].

$$J(x) = \begin{cases} K & \text{if the configuration is not feasible} \\ w_1 J_1 + w_2 J_2 & \text{if the configuration is feasible} \end{cases} \tag{3-14}$$

where

K = a large number

w = weighting value

J_1 = SAIDI

J_2 = total power loss

If the network configuration is not feasible, a large number is assigned to the fitness function. Feasible solutions ensure radial operation of the distribution network and that no voltage or thermal violations occur. While optimizing the reliability of the system is the main objective, the effect of system losses is monitored simultaneously and a multi-objective problem is formulated. Reconfiguration options to maximize reliability and secondly to minimize losses are explored. A weighting value can be assigned to both measures of the fitness function to optimize one parameter or to ensure comparable results.

The BPSO was coded using DigSILENT Programming Language (DPL), which was chosen as it saves the time consuming process of linking PowerFactory to another programme such as MATLAB to perform the optimization. The parameters in Table 3-1 are adjustable but were chosen as they allow for good performance and execution time of the algorithm. In order to achieve the optimal reliability of a feeder the process outlined in the flowchart as in Figure 3-7 was followed and tested on three different case study networks [73]. The pseudocode of the BPSO algorithm is contained in Appendix A.

Table 3-1: BPSO Parameters

Parameter	Optimal value
Number of particles (Np)	1*Nswitches
Individual acceleration constant (φ_1)	2
Social acceleration constant (φ_2)	2
Iterations to stop if no better solution is found (Ni)	1*Nswitches
Maximum number of iterations	100

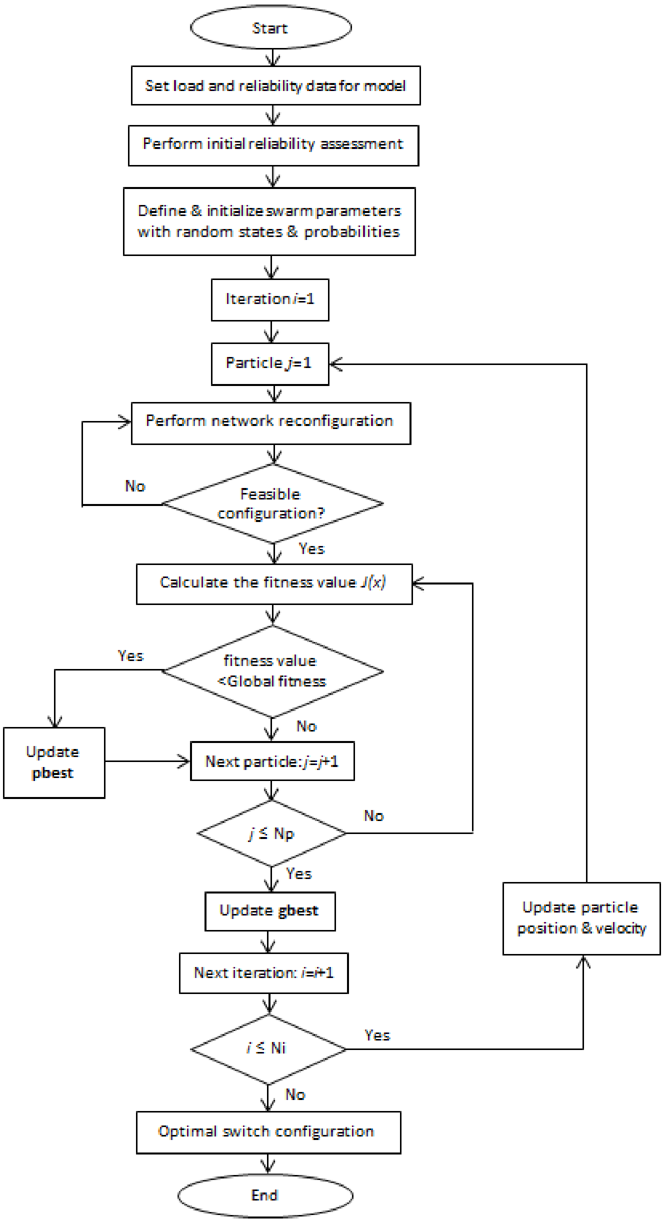

Figure 3-7: Flow diagram of BPSO algorithm

3.3 Optimizing sectionalizing devices and placement

The key factors which have an effect on reliability parameters include the restoration time after the occurrence of a fault, the number of faults which occur and the customers affected. While it is difficult to reduce the number of faults a network experiences, the restoration time and number of affected customers may be reduced by the installation of devices such as sectionalizing switches or reclosers. In order to optimize the effects there needs to be a balance between the cost and the improvement in reliability [74].

3.3.1 Mathematical formulation

Adding an additional device to a distribution network reduces the number of customers affected by an outage and may also reduce the restoration time for faults. Additional switches or reclosers on the network require an initial capital cost, installation costs as well as annual maintenance until the switch reaches the end of its useful lifespan. Hence, additional devices reduce the reliability indices but also increase the investment cost on the network. The location and number of devices to be installed may be optimized while improving the reliability KPIs of the network.

The Energy Not Supplied (ENS) is the total amount of energy on average which is not provided to the loads on the system and in measured in units of MWh/a [44], [75].

$$ENS = \sum_{i=1}^{ni}\sum_{j=1}^{nj}\sum_{k=1}^{nk} L_{ik} r_j \lambda_j \tag{3-15}$$

where

ni = number of load steps

nj = number of outage events

nk = number of load points isolated due to contingency j

L_{ik} = load at k for the i^{th} step of load duration curve at load point k

r_j = average outage time of contingency j

λ_j = average failure rate of contingency j

The system expected outage cost may be explained by (3-16) which is measured in Rands/annum.

$$ECOST = \sum_{i=1}^{ni}\sum_{j=1}^{nj}\sum_{k=1}^{nk} L_{ik} C_{jk}(r_j) \lambda_j \tag{3-16}$$

where $C_{jk}(r_j)$ = outage cost of customer class k due to outage j with the outage duration of r_j

In order for the utility to obtain maximum benefit from the installation of additional devices on any network, it is essential to minimize the total costs as in (3-17). Installation costs are dependent on the number of devices and are a summation of the capital equipment costs and labour costs. Maintenance costs are an estimate of the expenditure encompassed by the utility to maintain the additional equipment on the network.

The fitness function is used to minimize the costs of the utility as in (3.17).

$$J(x) = \sum_{i=1}^{ni}\sum_{j=1}^{nj}\sum_{k=1}^{nk} L_{ik} C_{jk}(r_j) \lambda_j + \sum Installation\ cost + \sum Maintenance\ costs \tag{3-17}$$

Table 3-2: Costs of sectionalizing devices

	Capital cost	Interest rate	Maintenance cost	Life span
Switch	R30 236	6.5%	2%	25 years
Recloser	R353 394	6.5%	2%	25 years

Constraints to consider in the optimization are the minimum voltage of the networks, the thermal loading of the lines and to maintain radial configuration of the feeder at all times. The capital and maintenance costs and estimated life span for sectionalizing devices on a distribution network are contained in Table 3-2 [76].

3.3.2 BPSO algorithm - optimizing sectionalizing devices

Due to the numerous positions where devices may be installed along the network, it would be difficult to determine the optimal location and number of devices. The BPSO algorithm was further used for this task due to its suitability for large search spaces. It is an effective algorithm to determine the optimal number of additional devices to be added to a network and their locations while considering financial feasibility. While manual switches have no limitations to where they can be placed on the network or a maximum number per network, reclosers are subject to protection co-ordination. A network is limited to having a maximum of four reclosers in a series configuration to allow for grading of the reclosers and thus effective protection [61].

In order to implement BPSO for reclosers, the distribution network is divided into zones, where the length per zone can be determined by the user. The length of connected line elements, including the backbone and tee-offs, from the source and along the feeder is summated until the specified length is reached. This portion of the feeder is allocated as a zone with the remaining lines of the feeder being allocated to zones similarly until the entire feeder is divided into zones of the specified length. A maximum of one recloser per zone is thereafter added to the network, while ensuring that the limitation of four reclosers in series per feeder is not exceeded. Each section of line within a zone is a potential location for an additional recloser to be added, at either the start or end terminal of the line. These positions are chosen at random using the BPSO algorithm due to the large search space. The random selection of the zone, line and terminal of the line does not limit the possible positions for the device placement on the network. The tool automatically adds the protection device to the network at the established locations and the objective function is calculated for each iteration, thereafter removing the device. This continues until the global optimal solution is reached where the aim is to minimize the objective function thus improving reliability and increasing savings. Additional switches on the network are added in a similar manner to the reclosers, where the switch is placed at random by the BPSO algorithm at either the start or end terminals of the line. However; switches are not limited to a maximum number of devices per network or per zone. Figure 3-8 displays the BPSO process to optimize reliability on the feeder for additional device placement.

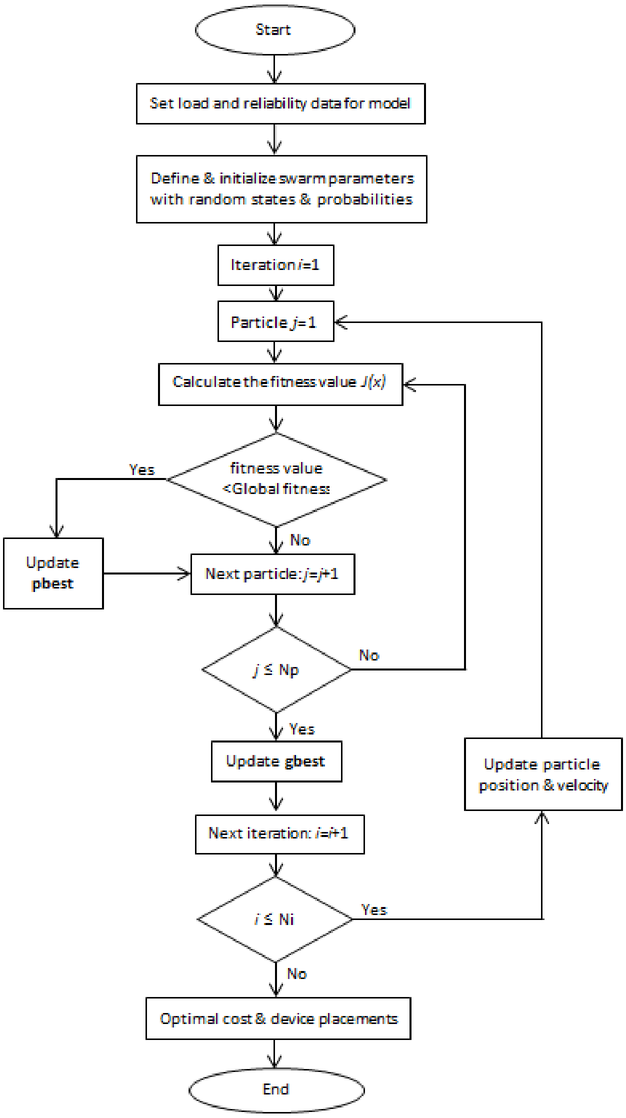

Figure 3-8: Flow diagram of BPSO algorithm for additional device placement

3.4 Conclusion

The methodology used to optimize network configuration and device placement was outlined. The steps taken to obtain network models which could be used to perform accurate reliability evaluations were discussed. A weighted objective function for network reconfiguration was used to minimize SAIDI or minimize system losses with the constraint for the network to remain radial and network voltage and thermal loading to remain within permissible limits. An objective function for protective device placement was established considering capital and operations costs as well as the network ENS costs with a constraint on the number of reclosers and areas to which they can be added. The steps to implement the BPSO algorithm were outlined with the expectation to minimize the objective function in the cases of network reconfiguration and additional device placement. The implementation of the network reconfiguration methodology and algorithm is tested in Chapter 4.

4 Reliability Evaluation of Distribution Networks considering Reconfiguration

This chapter assesses the effects of network reconfiguration on real distribution networks using three different case studies. The networks are simulated and reliability evaluation conducted using DigSILENT PowerFactory software. The reliability indices output from the simulation model will be compared to historical data and practical performance of the network to ensure they are similar. Reconfiguration of the network is performed using BPSO on each case study utilizing the existing switches available on the network. The results on reliability indices, operational limits and network efficiency are discussed.

4.1 Network analysis

In KZN OU the MV networks cover a large expanse with both coastal and inland areas and supply a mix of residential, commercial and industrial customers. The weather conditions and environmental exposure in each of these areas vary greatly. KZN OU contains three zonal areas which have been divided geographically to form the Empangeni, Pietermaritzburg and Newcastle Zone as in Figure 4-1. The type of networks as well as their environmental exposure is unique within each of these areas and they experience all types of faults. The case studies utilize networks from KZN OU, but the same methodology may be applied to any network with similar characteristics.

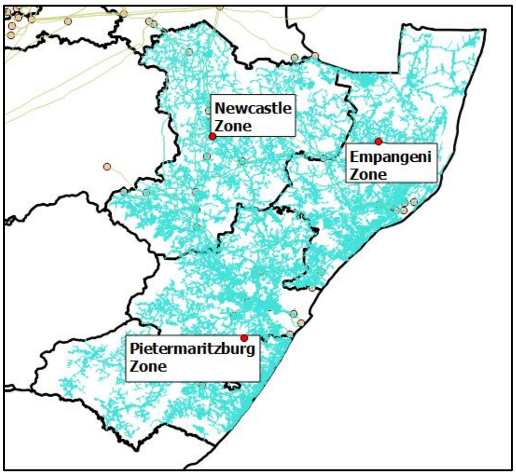

Figure 4-1: Geographical overview of KZN OU and zonal areas

The following feeders as in Table 4-1 were chosen from the various areas as case studies due to their long line length, high customer base and high SAIDI and SAIFI values. They are also complex feeders which contain ring feeds but are operated as a radial line to reduce short circuit current and for functionality of protection schemes [77]. The networks have sectionalizing switches which are switches that are normally closed and tie switches which are normally open during normal operation of the network. Sectionalizing switches are mainly used to isolate a specific area or restore load when possible during maintenance or outages [18].

Table 4-1: Feeders chosen for analysis

Feeder	Area	Line Length	Number of Customers
Umzali NB71	Pietermaritzburg	157 km	4322
Driel NB5	Newcastle	106 km	2137
Mhlatuze NB7	Empangeni	380 km	6464

4.1.1 Case study 1 - Driel NB5

Driel NB5 is an 11 kV overhead line network supplied from Driel 132/11 kV Substation. The network is situated in the Newcastle area and supplies the Woodford and Rookdale areas which comprises both densely populated towns as well as scattered rural load as in Figure 4-2. The three-phase feeder consists of mainly Hare, Mink and Fox Aluminium conductor steel-reinforced (ACSR) conductor types. The feeder supplies a total of 2137 customers, including three Large Power Users (LPUs) and the remaining customers made up of Small Power Users (SPUs) and Prepaid Power Users (PPUs). LPUs are customers who usually have a dedicated transformer and require supply from above 100 kVA to a few MVA of load. The numerous residential households are referred to as SPUs and PPUs. There are 144 transformers with an installed capacity of 8398 kVA, and the peak load of the feeder is approximately 3085 kVA. Driel NB5 has five existing reclosers, 191 sectionalizing or normally closed switches and eleven tie or normally open switches which exist on the network.

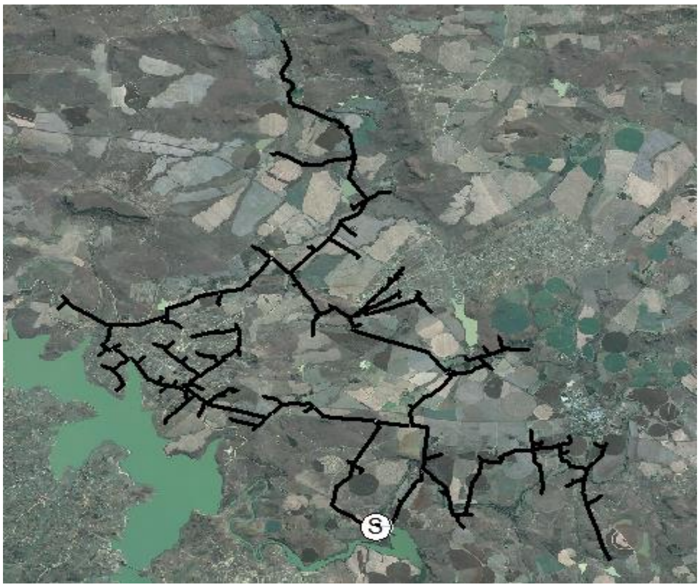

Figure 4-2: Driel NB5 geographic overview

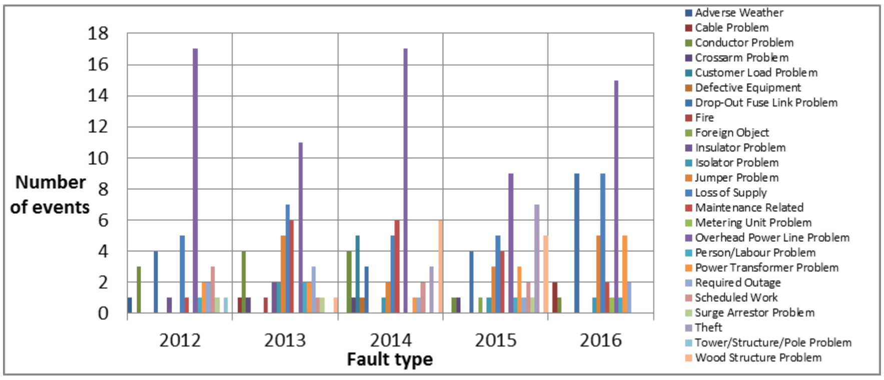

Figure 4-3: Causes of sustained interruptions on Driel NB5

Figure 4-3 displays the number of sustained interruptions per year recorded on Driel NB5 according to the fault type. The highest number of events is linked to insulator failure each year. Figure 4-4 displays historical SAIDI and SAIFI values for Driel NB5 for each month over the past five years, which consider the financial year from March 1st to February 28th each year. The network did not perform very well in the period from 2013 to 2015 which sees a steady increase in the number of faults and the duration of outages experienced by customers each month. The year 2014 had the maximum number of fault events, 58, and the longest combined duration of outages totaling 332 hours. Thereafter the SAIDI and SAIFI improve from the year 2015 onwards. In the year 2016 the number of faults has decreased and the total customer interruption duration is halved to 164 hours possibly due to maintenance or refurbishment of the network. The actual SAIDI and SAIFI trend values for 2016/2017 will provide a benchmark to compare the simulation results and ensure that the output is realistic.

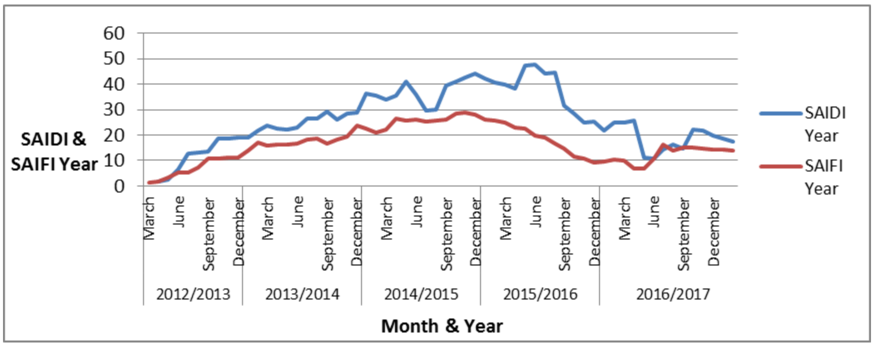

Figure 4-4: Driel NB5 SAIDI and SAIFI trends

The different types of equipment found on a MV feeder have unique failure rates and repair times. Hence, each type of equipment was assigned a stochastic model with the calculated failure rate and restoration time. For purposes of the PowerFactory model an average time of 90 minutes to switch disconnectors was used. This is inclusive of the time required for the operator to travel to site, performing switching, and allow for partial power restoration if possible. Reclosers have been set to operate after one minute duration.

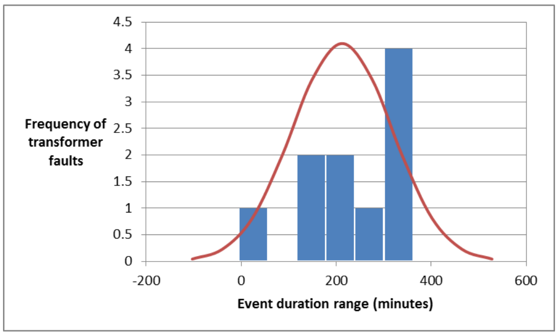

Figure 4-5: Frequency of MV/LV transformer faults and the normal distribution curve

The frequency of MV/LV transformer faults on Driel NB5 and the distribution curve as in Figure 4-5 indicates the average restoration time in minutes. There are a few faults which occur with a shorter duration and a few having a long duration closer to 400 minutes; however; the normal distribution curve indicates the most likely event duration is 3.33 hours. A similar plot and process may be followed to determine the average restoration time for all fault types. The tangible equipment count per feeder may be determined from the simulation model. The actual number of faults may be counted from the raw fault data, and the failure rate may be calculated from (3-1) for each fault type. The failure rates and repair duration in hours calculated for the various equipment types for Driel NB5 are contained in Table 4-2. In comparison to the average failure rates and repair durations in Table A-1, Driel NB5 is more prone to transformer and conductor failure than the average network in the Newcastle area. However, the restoration time is quicker for both failure types than the average rate, reiterating the benefit of determining unique failure rates and repair durations for each network.

Table 4-2: Driel NB5 failure rates and repair duration utilized in model

	Failure rate	**Restoration time**
Transformer failure	0.0347	3.33
Conductor failure	0.358	1.06
Transient faults	0.372	-
Earth faults	0.0094	-
Cable failure	0.1226	8.33
Fuse & Isolator failure	0.1366	0.65
Jumper failure	0.014	1.48
Insulator failure	0.002	0.85
Structure failure	0.015	4.82
Breaker fail-to-operate	0.0571	-
Substation failure	0.002	18.6

Figure 4-6 displays the single line diagram of Driel NB5. The network comprises of one ring-feed and four existing normally open points and numerous switches. The switches are referred to as S-links and have an “S” preceding a unique number.

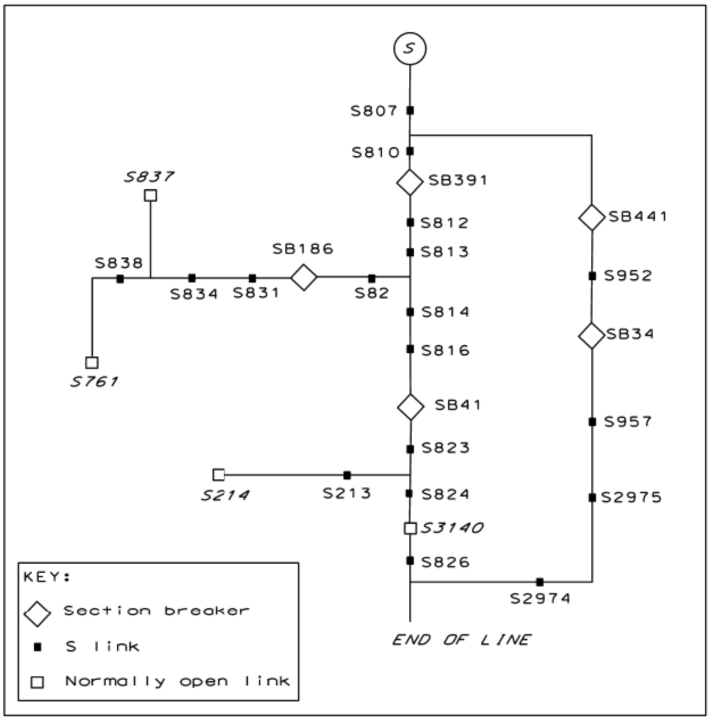

Figure 4-6: Single line diagram of Driel NB5

The percentage reliability improvement after reconfiguration may be calculated as follows [78].

$$SAIDI\ improvement = \frac{SAIDI_{original} - SAIDI_{new}}{SAIDI_{original}}\ x\ 100 \tag{4-1}$$

$$SAIFI\ improvement = \frac{SAIFI_{original} - SAIFI_{new}}{SAIFI_{original}}\ x\ 100 \tag{4-2}$$

Table 4-3: Optimal switch configuration for Driel NB5

	Original Configuration	**Maximum reliability w_1= 1, w_2= 0**	**Minimum losses (kW) w_1= 0, w_2= 1000**
NOP	S3140	S2974	S3140
SAIDI	26.357	25.096	26.357
SAIFI	18.969	18.128	18.969
Minimum voltage (p.u)	0.933	0.927	0.933
Maximum loading (%)	56.22	56.22	56.22
Losses (kW)	155.539	165.04	155.539

The optimal switch configurations for Driel NB5 for maximum reliability and minimal losses are contained in Table 4-3. The weighted objective function to obtain the maximum network reliability is optimized by closing S3140 and creating the new normally open point (NOP) at S2974. This leads to an improvement in SAIDI of approximately 5%. This is due to the reconfiguration which isolates the town load from the rural load as far as possible resulting in improved reliability. The down time of the feeder is reduced from 26.357 hours/year to 25.097 hours/year. However, the minimum voltage of the network is compromised with the reconfiguration hence the new topology was flagged during simulation as not feasible. With the network configured for maximum reliability, the system losses also increase. Maintaining the current system configuration achieves the minimum losses for the system. Driel NB5 is not a suitable network to be reconfigured as the existing topology is satisfactory.

4.1.2 Case study 2 - Umzali NB71

Umzali NB71 is a 22 kV overhead line network supplied from Umzali 132/22 kV Substation. The network is situated in the Pietermaritzburg area, near Umzimkhulu town and supplies mainly rural load as in Figure 4-7. The three-phase feeder has a line length of 148.6 km and consists of mainly Hare, Mink and Fox ACSR conductor types. The feeder supplies a total of 4322 customers consisting of only SPUs and PPUs. There are 173 transformers with an installed capacity of 9114 kVA, and the peak load of the feeder is approximately 1930 kVA. Umzali NB71 has two existing reclosers, 238 sectionalizing or normally closed switches and six tie or normally open switches which exist on the network.

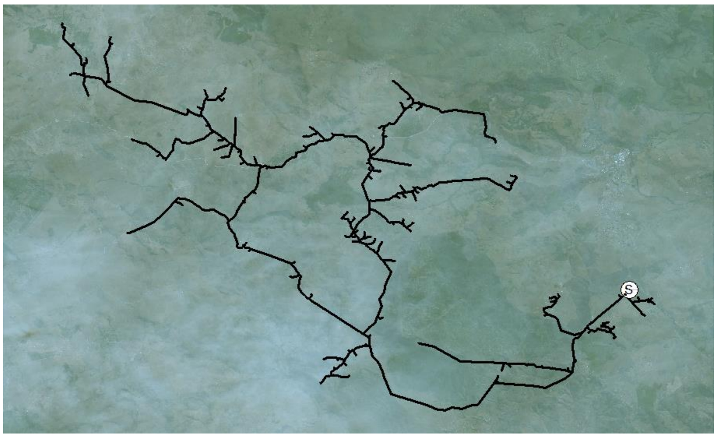

Figure 4-7: Umzali NB71 geographic overview

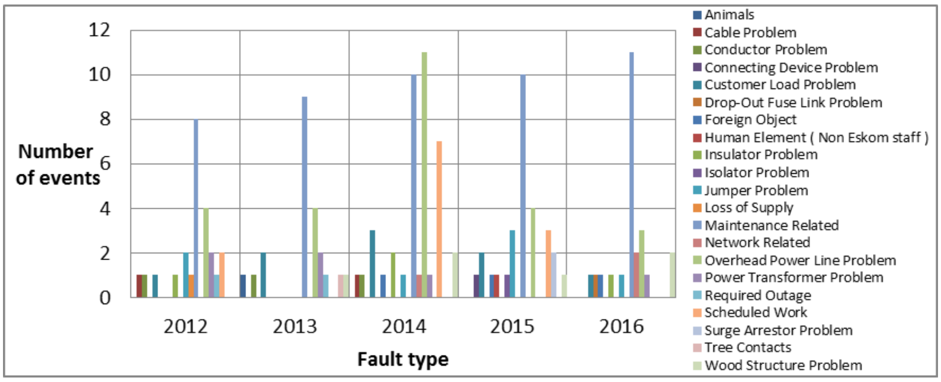

Figure 4-8: Causes of sustained interruptions on Umzali NB7

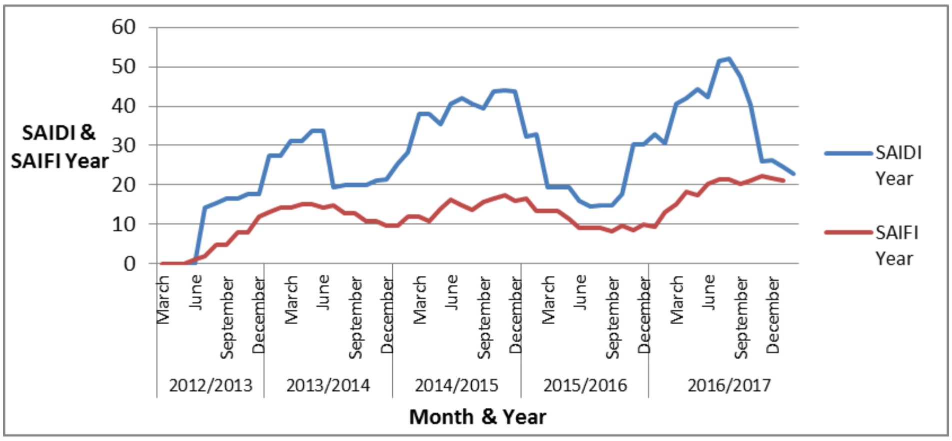

Figure 4-9: Umzali NB71 SAIDI and SAIFI trends

Table 4-4: Umzali NB71 failure rates and repair duration utilized in model

	Failure rate	**Restoration time**
Transformer failure	0.052	5
Conductor failure	0.0335	5.83
Transient faults	0.1476	-
Earth faults	0.0001	-
Cable failure	0.0134	5.83
Fuse & Isolator failure	0.00862	3.33
Jumper failure	0.004	1.08
Insulator failure	0.002	1.33
Structure failure	0.0033	4.82
Breaker fail-to-operate	0.001	-
Substation failure	0.0025	18.6

The number of events has remained fairly low and constant on Umzali NB71 as in Figure 4-8. Jumpers and insulators are the main cause of failure on this network. Figure 4-9 displays historical data of the

SAIDI and SAIFI values for Umzali NB71 over the past five financial years. The SAIDI and SAIFI have increased each year due to poor performance of the network. The duration of customer interruptions has spiked each year with 2016 totaling 116 hours of outages. The failure rates and repair durations were calculated in the same manner as case study 1. Table 4-4 is a summary of the failure rates and restoration time which are specific to Umzali NB71 components. The transformer and conductor failure rates are higher than the average network in Pietermaritzburg. The transformer repair duration is equal to the average networks restoration time, while the conductor restoration time is considerably longer for Umzali NB71. The single line diagram of Umzali NB71 is displayed in Figure 4-10 where the network contains only one ring feed.

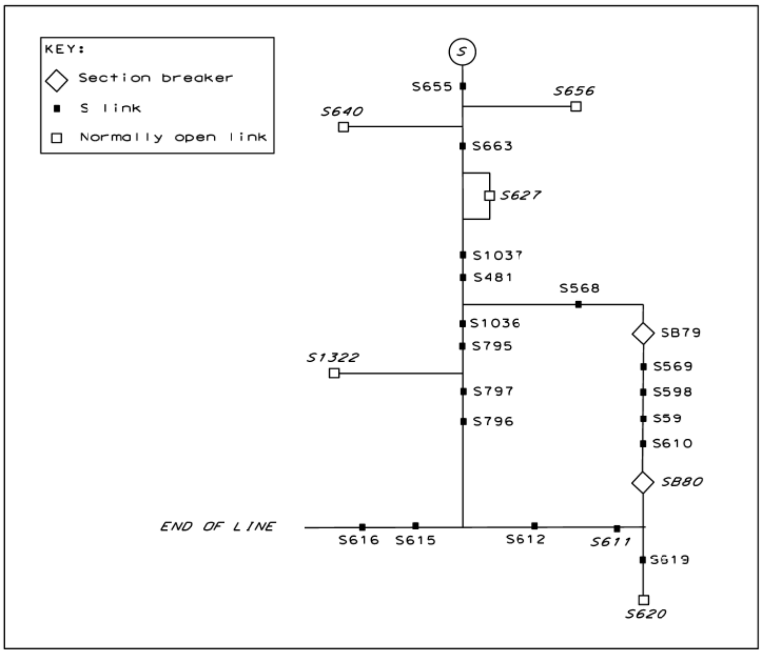

Figure 4-10: Single line diagram of Umzali NB71

Table 4-5: Optimal switch configuration for Umzali NB71

	Original configuration	**Maximum reliability** w_1= 1, w_2= 0	**Minimum losses** w_1= 0, w_2= 1000
NOPs	SB80	S1036	S611
SAIDI	26.493	21.265	24.907
SAIFI	14.273	10.872	13.327
Minimum voltage (p.u)	0.997	0.989	0.997
Maximum loading (%)	33.47	33.46	33.47
Losses (kW)	75.590	73.10	65.08124

Table 4-5 displays results for two feasible reconfiguration options determined using BPSO, one for maximum reliability and one for minimum losses. Creating a new NOP at S1036 reduces the SAIDI by almost 20% and the SAIFI by 24%. The system down-time is reduced by 5 hours/year and results in significant improvements in reliability. The voltage and line loading on the network remain within feasible limits and the system losses are also reduced slightly. Hence, reliability can be improved significantly while the expenditure is negligible. The proposed configuration to obtain minimum losses on the system does improve the loss value slightly but worsens the reliability as the network SAIDI and SAIFI increase. The reconfiguration option to maximize system reliability is a feasible solution for the utility.

4.1.3 Case study 3 - Mhlatuze NB7

Mhlatuze NB7 is a 22 kV overhead line network supplied from Mhlatuze 88/22 kV Substation. The network is situated in Empangeni, supplying the Upper Nseleni area consisting of mainly rural load as in Figure 4-11. The three-phase feeder has a line length of 379.14 km and consists of mainly Oak and Fox ACSR conductor types. The feeder supplies a total of 6464 customers consisting of LPUs, SPUs and PPUs. There are 573 transformers with an installed capacity of 23881 kVA, and the peak load of the feeder is approximately 4260 kVA. Mhlatuze NB7 has eight existing reclosers, 566 sectionalizing or normally closed switches and sixteen tie or normally open switches which exist on the network.

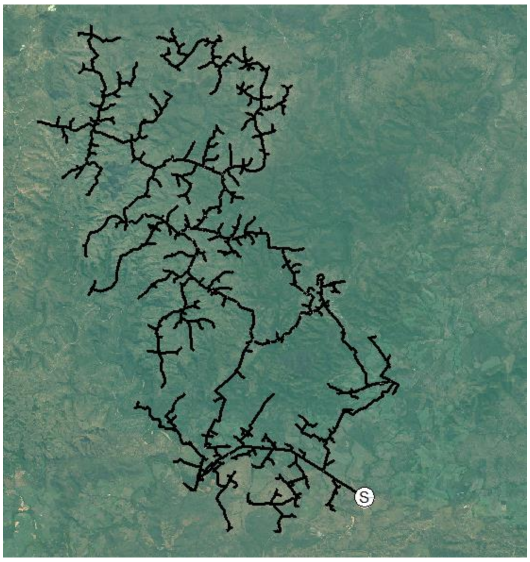

Figure 4-11: Mhlatuze NB7 geographic overview

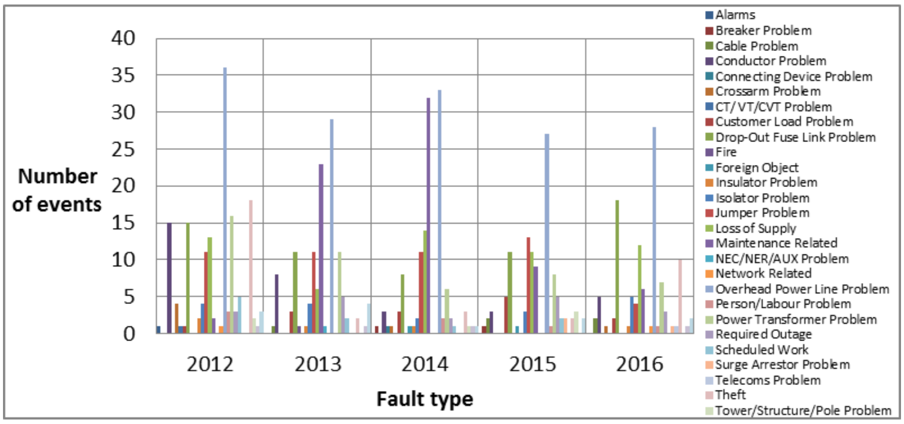

Figure 4-12: Causes of sustained interruptions on Mhlatuze NB7

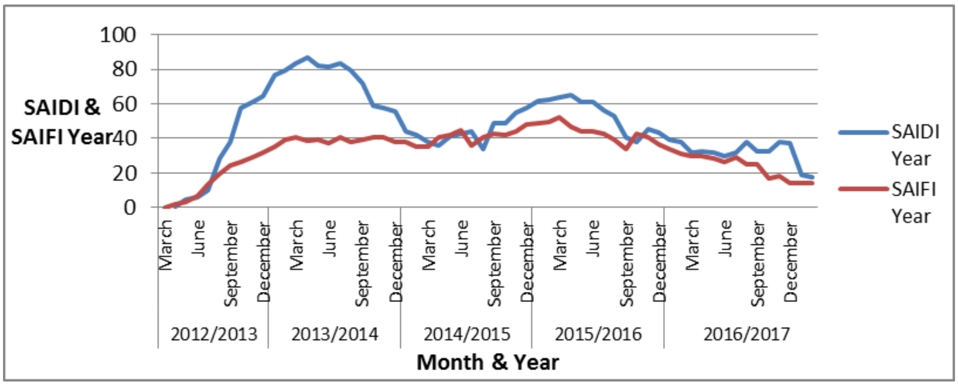

Figure 4-13: Mhlatuze NB7 SAIDI and SAIFI trends

The number of events has remained high on Mhlatuze NB7 over the five-year period as in Figure 4-12. There have been multiple incidences of faults caused by fire and overhead conductor. The number of events is also considerably higher in comparison with Driel NB5 and Umzali NB71. This can be attributed to the much longer line length and higher number of customers in comparison to the networks from the previous two case studies. The duration of customer interruptions peaked in 2015 with a total of 1260 hours of outages. This is expected due to the long distances which operators need to travel to isolate the faults. The large number of customers affected also contributes significantly to the SAIDI and SAIFI figures. Figure 4-13 displays historical SAIDI and SAIFI data for Mhlatuze NB7 over the past five financial years. The SAIDI and SAIFI improve in the 2016/2017 financial year, and these values will be used as a benchmark to compare the simulation output results. From the fault data the failure rate and repair duration per component can be determined for Mhlatuze NB7 as in Table 4-6. Mhlatuze NB7 has a higher isolator and conductor failure rate than the average distribution network in the Empangeni area as in Table A-1. The restoration time for transformer and conductor faults is similar to the average restoration time.

Table 4-6: Mhlatuze NB7 failure rates and repair duration utilized in model

	Failure rate	Restoration time
Transformer failure	0.025	4.83
Conductor failure	0.204	2.25
Transient faults	0.226	-
Earth faults	0.0026	-
Cable failure	0.0087	6.58
Fuse & Isolator failure	0.105	1.5
Jumper failure	0.0124	1.08
Insulator failure	0.0013	6
Structure failure	0.0058	2.6
Breaker fail-to-operate	0.2857	-
Substation failure	0.23	5.78

The single line diagram of Mhlatuze NB7 is contained in Figure 4-14. It contains three ring-feeds and due to the number of available paths for power distribution there are many feasible options for reconfiguration with the optimal solution determined by the BPSO algorithm.

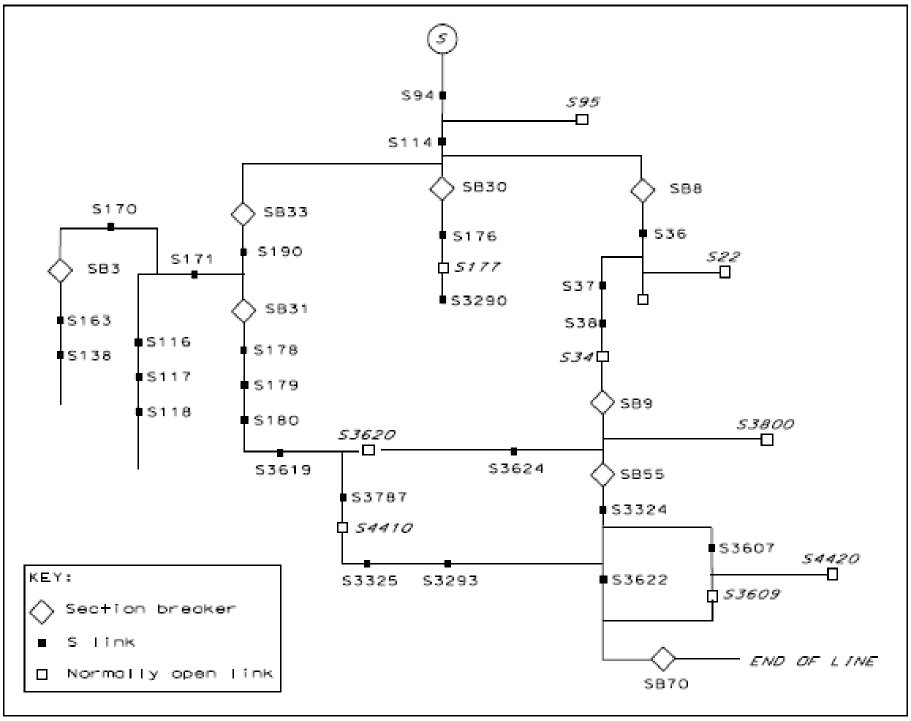

Figure 4-14: Single line diagram of Mhlatuze NB7

Table 4-7: Optimal switch configuration for Mhlatuze NB7

	Original configuration	**Maximum reliability w_1= 1, w_2= 0**	**Minimum losses w_1= 0, w_2= 1000**
NOPs	S3620, S4410, S3609	S3293, S3608, S3624	S3292, S3608, S3620
SAIDI	41.694	38.015	43.518
SAIFI	23.532	21.177	24.835
Minimum voltage (p.u)	0.976	0.957	0.957
Maximum loading (%)	35.46	35.62	35.47
Losses (kW)	340.665	294.171	287.599

The reconfiguration option presented in Table 4-7 shows a significant improvement in both SAIDI and SAIFI by 8.8% and 10% respectively when maximizing reliability. The network voltage and thermal loading remain within feasible limits after reconfiguration. The network also remains radial and the system losses are reduced. On the contrary, optimizing the network to minimize losses worsens the network reliability. This is also a feasible network to be reconfigured as reliability can be maximized at no expense to the utility and furthermore the losses will reduce resulting in financial savings for the utility.

4.2 Conclusion

BPSO allows the optimal configuration of the network to be determined where the switch logical state is changed between open and closed. It is a fast and effective algorithm taking all constraints into consideration to determine the optimal solution. Each network has a different number of switches and thus the size of the search space differs. For a larger search space, the computation time is increased, but the algorithm provides practical results which can be easily implemented.

The solution fitness is calculated for each possible network configuration until the optimal case is found dependant on the weighting of the objective function. The configuration options to achieve maximum reliability versus minimum losses are different in all cases evaluated. With the key objective being reliability improvement, all three case studies have shown that it is possible to improve the power supplied to customers; however; not all cases satisfy the technical conditions specified. It also shows significant improvement in reliability and in some cases a reduction in network losses. The largest reliability improvement is on Umzali NB71 which is a large and dense network. The BPSO algorithm has been validated for network reconfiguration and is a useful tool which can be utilized on all networks. The methodology and algorithm for the placement of additional devices to further improve reliability are tested in Chapter 5.

5 Improving reliability by additional devices

This chapter discusses the cost implications of outages which occur on distribution networks and the variation due to customer types. The BPSO algorithm is then applied to the reconfigured networks from the three case studies to place additional switches or reclosers on the networks. The objective function considers the reliability improvement and costs associated with the protection devices in order to obtain the most feasible solution.

5.1 Customer interruption costs

The duration of an outage on a network can be related to the cost associated with the outage and is referred to as the customer damage function. The type of customers connected influence the customer damage function and in turn the customer interruption costs associated with the outage [44]. The customer damage functions for common customer types found on the distribution networks are found in Figure 5-1. Residential and manufacturing customers have a similar impact which is minimal in comparison to customers such as trade, community services and general government consumers [60].

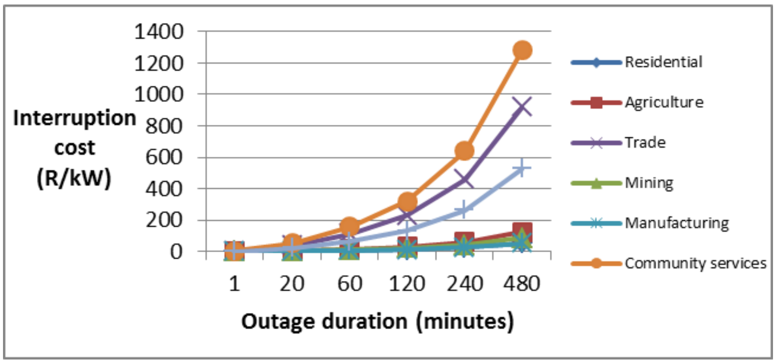

Figure 5-1: Customer damage functions for common customer types [79]

Considering the case study networks, Umzali NB71 supplies mainly residential customers and a few small agricultural customers. Driel NB5 supplies some community services and trade customers but mainly supplies residential load in the area. Mhlatuze NB7 supplies residential, agricultural, community services, construction, trade and general government customers in the area. Thus, the impact and loss of revenue due to outages on Mhlatuze NB7 are significantly greater than Umzali NB71 or Driel NB5 as displayed in Figure 5-2.

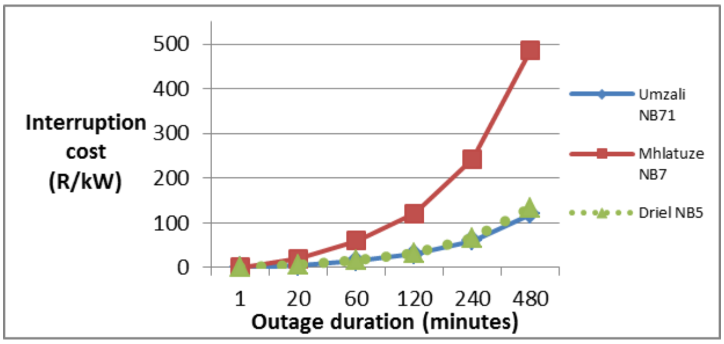

Figure 5-2: Customer damage functions per network

5.2 Network analysis

Umzali NB71 and Mhlatuze NB7 previously reconfigured for maximum reliability are used again in the reconfigured state as case study networks. Driel NB5 is used in this case study with the original network configuration. The BPSO algorithm is used to optimally place switches and reclosers to determine the effects of additional devices on the network reliability. The benefit to cost of each solution will be considered to determine the most financially feasible option which maximizes reliability while minimizing costs to the utility.

5.2.1 Case study 1 – Driel NB5

The annual income of the feeder as in (5-1) may be used as an estimate of the income generated by the feeder. The energy charge utilized; as the network supplies mainly small residential customers; is the standard non-authority rate of 127.33 c/kWh in South Africa [80].

$$Annual\ feeder\ income = Load\ \times hours\ \times power\ factor\ \times energy\ charge \qquad (5\text{-}1)$$

The Driel NB5 typical daily load profile is shown in Figure 5-3 from 12 am which corresponds to hour zero. The load factor is the ratio of the average load experienced at the specific hour in relation to the peak load experienced by the feeder. By utilizing the daily load profile of the feeder it allows the annual feeder income to be calculated more accurately as it considers the diversified load of customers at both low and high load conditions. Considering the average load profile for Driel NB5 over a 24-hour period, the income for the feeder is approximately R12 825 297 per annum.

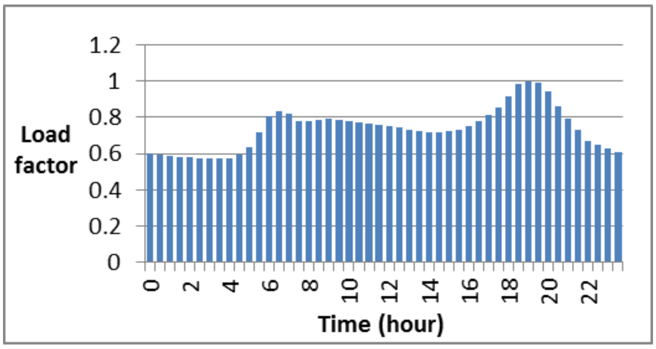

Figure 5-3: Driel NB5 average 24 hour load profile

Using the BPSO algorithm to optimally place switches on Driel NB5, Figure 5-4 displays the effects of the additional switches on ENS and SAIDI respectively. In both cases as the number of additional switches increases, the network reliability improves. The system failure frequency is not affected by switches hence it is not documented.

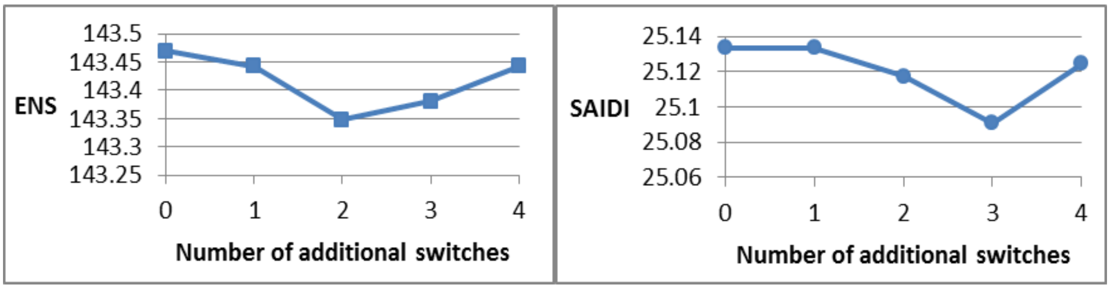

Figure 5-4: ENS and SAIDI values for Driel NB5 with additional switches

Table 5-1 lists the cost and benefit values with respect to the number of additional switches. ECOST is dependent on the reliability cost and worth assessment completed on the network. The utility costs are dependent on the number of devices added and is a summated cost inclusive of capital, maintenance and installation costs. The total cost is a summation of ECOST and the utility cost. The benefit is determined by the difference between the ECOST of the existing network with zero additional switches and the ECOST in each case with additional switches. A ratio of the benefit in Rands to the total cost is determined to establish the most feasible option. For Driel NB5 the outage costs are lowest with three additional switches while the investment costs are highest with four additional switches. A solution which provides balance between the outage and investment costs and preferred by both the customer and utility is required.

Table 5-1: Results for additional switches on Driel NB5

No. of switches	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R2 387 321.85	R0.00	R2 387 321.85	R0.00	-
1	R2 386 889.41	R30 840.72	R2 417 730.13	R432.44	0.00017
2	R2 385 311.11	R61 681.44	R2 377 982.48	R2 010.74	0.00084
3	R2 385 849.91	R92 522.16	R2 374 090.80	R1 471.94	0.00062
4	R2 386 883.62	R123 362.88	R2 510 246.50	R438.23	0.00017

The relationship between reliability benefit and cost to the utility is required to determine the most feasible solution. Figure 5-5 displays the benefit to cost ratio curve for Driel NB5 where the optimal number of additional switches is two, thereafter the cost to benefit ratio begins to decrease. The total cost for this case is R2 377 982.48 in comparison to the higher total cost of R2 378 321.85 with no additional investment. This is due to the outage cost which reduces with increased switches. With the additional switches the SAIDI improvement is 0.06% and the ENS improvement is 0.08%. Figure 5-6 displays a geographic overview of Driel NB5 and the optimal positions to place the additional two switches. The first switch separates a densely populated area on the network. The second switch is situated towards the tail end of networks. The BPSO provides a solution which satisfies the reliability as well as economic considerations of the optimization problem.

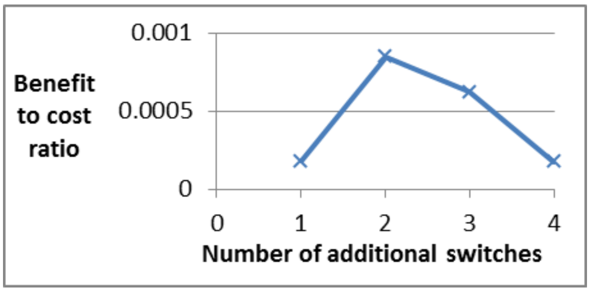

Figure 5-5: Benefit to cost analysis of additional switches on Driel NB5

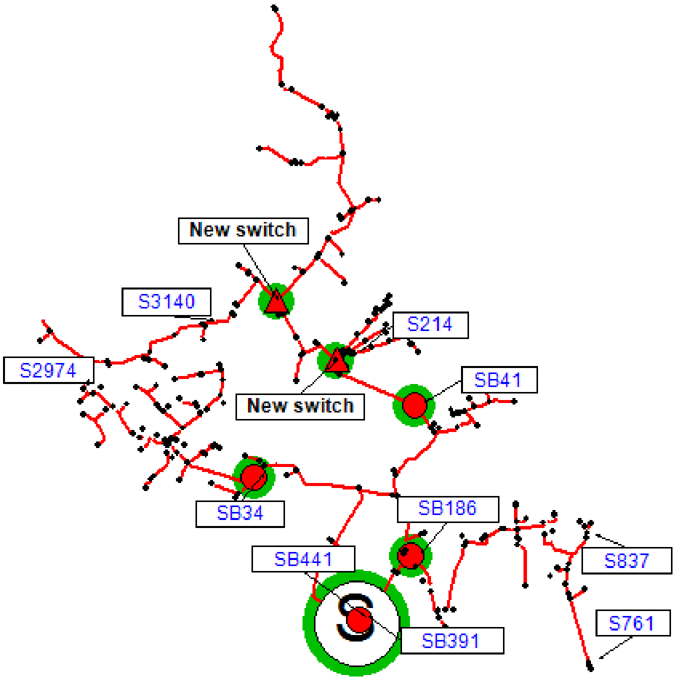

Figure 5-6: Optimal placement of switches on Driel NB5

Similarly Figure 5-7 displays the effects of adding additional reclosers on ENS and SAIDI respectively. Table 5-2 and Figure 5-8 display the cost and benefit per additional recloser installation. With the addition of the first and second recloser the customer interruption cost is reduced. The optimal number of reclosers is two, thereafter the cost to benefit ratio begins to decrease. The SAIDI and ENS improvement are 18.78% and 21.77% respectively.

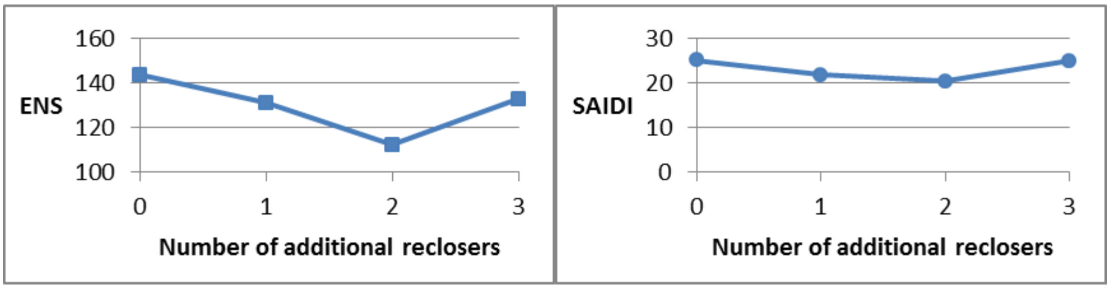

Figure 5-7: ENS and SAIDI values for Driel NB5 with additional reclosers

Table 5-2: Results for additional reclosers on Driel NB5

No. of reclosers	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R2 387 321.85	R0.00	R2 387 321.85	R0.00	-
1	R2 181 095.87	R360 461.88	R2 541 557.75	R206 225.98	0.08114
2	R1 908 964.84	R720 923.76	R2 629 888.60	R478 357.02	0.18189
3	R2 207 764.94	R1 081 385.64	R3 289 150.58	R179 556.91	0.05459

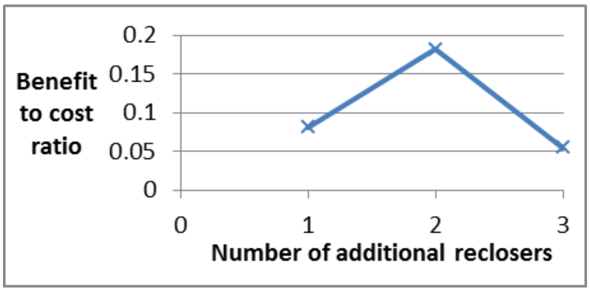

Figure 5-8: Benefit to cost analysis of additional reclosers on Driel NB5

Figure 5-9 displays the optimal locations of the additional two reclosers to be placed on Driel NB5. The first additional recloser is placed in a similar location to the switch, aiming to separate the highly loaded area. The second recloser is positioned to accommodate for the zoning of the feeder into sections which allows for protection co-ordination. Fast power restoration is achieved by automatic devices, which is critical for reliability improvement. The benefit of installing reclosers in terms of reliability optimization thus outweighs that of manual switches on Driel NB5. The recloser allows for improved continuity of supply as transient faults can be eliminated on the rural network.

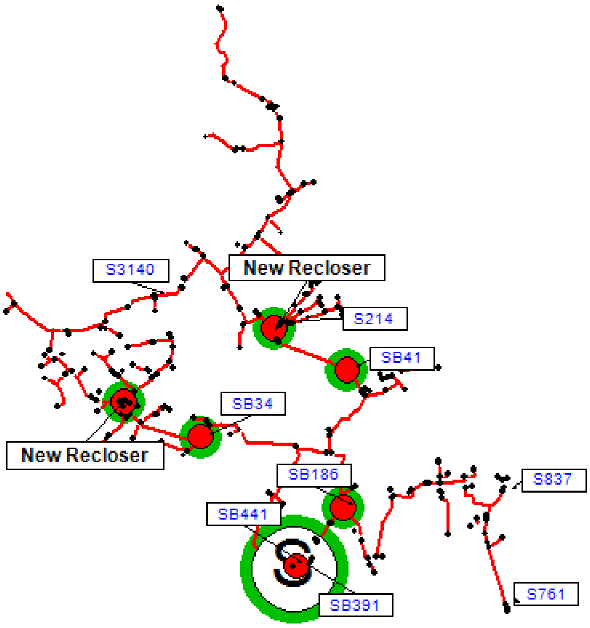

Figure 5-9: Optimal placement of reclosers on Driel NB5

The discounted future benefit (DFB) can be calculated as in (5-2) in order to compare the cost of installing additional devices to the present value of future benefit on the network [50]. Detailed calculations to determine the DFB are contained in Table A-2 in Appendix A.

$$DFB = \sum_{t=0}^{t} \frac{ECOST_{original} - ECOST_{optimized}}{(1+i)^{t}} \qquad (5\text{-}2)$$

where t = year

The DFB of additional switch installation is R26 538 while the DFB of reclosers is R6 313 297 which is more beneficial.

5.2.2 Case study 2 – Umzali NB71

The same methodology used for Driel NB5 was utilized for Umzali NB71 to determine the optimal devices and location with the BPSO algorithm. Figure 5-10 displays the average load profile for Umzali NB71 over a 24-hour period. Umzali NB71 consists of mainly residential load as can be seen by the morning and evening peak experienced on the network [81]. The estimated income from Umzali NB71 per year is R9 800 278.

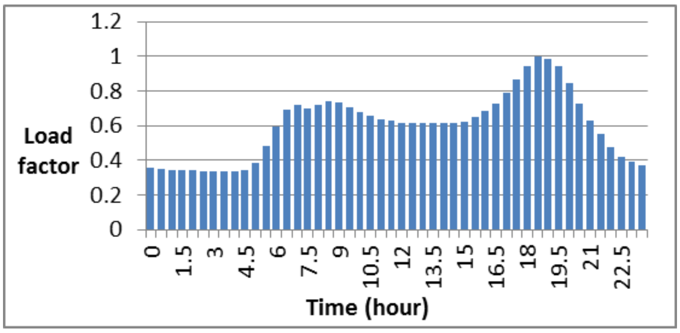

Figure 5-10: Umzali NB71 average 24 hour load profile

Figure 5-11 shows the decrease in ENS and SAIDI per additional switch added to Umzali NB71. Table 5-3 provides the cost and benefit values while Figure 5-12 displays the benefit to cost curve. With additional switches the outage costs reduce but not significantly. The optimal number of additional switches is three as it reduces the outage time in an economic way. The improvement in SAIDI is a minimal 0.16% and in ENS the improvement is 0.26%. The DFB of switch installation is R50 252. Figure 5-13 displays the optimal positions of switches with two located towards the tail end of the network and a third switch on the backbone, not far from the network source.

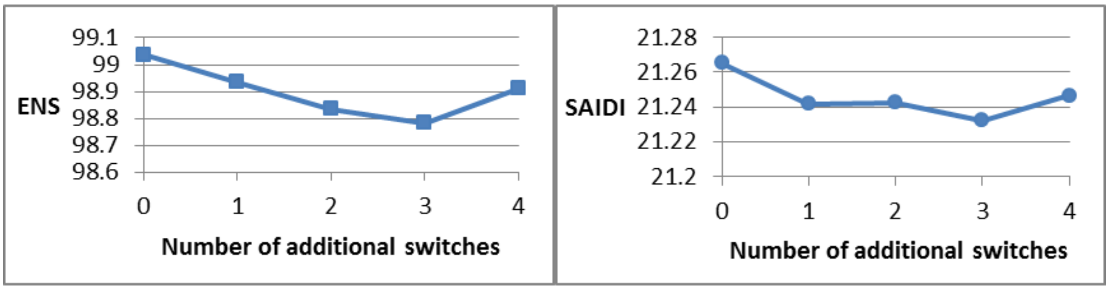

Figure 5-11: ENS and SAIDI values for Umzali NB71 with additional switches

Table 5-3: Results for additional switches on Umzali NB71

No. of switches	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R1 491 489.21	R0.00	R1 491 489.21	R0.00	-
1	R1 489 970.90	R30 840.72	R1 520 811.62	R1 518.31	0.00099
2	R1 488 456.20	R61 681.44	R1 550 137.64	R3 033.00	0.00195
3	R1 487 681.61	R92 522.16	R1 580 203.77	R3 807.60	0.00240
4	R1 489 616.67	R123 362.88	R1 612 979.55	R1 872.54	0.00116

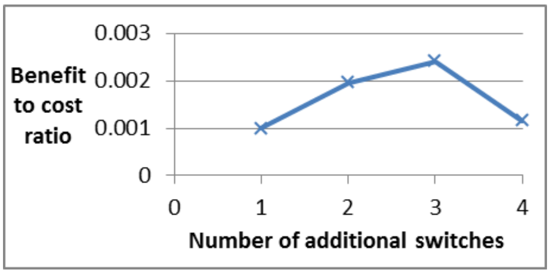

Figure 5-12: Benefit to cost analysis of additional switches on Umzali NB71

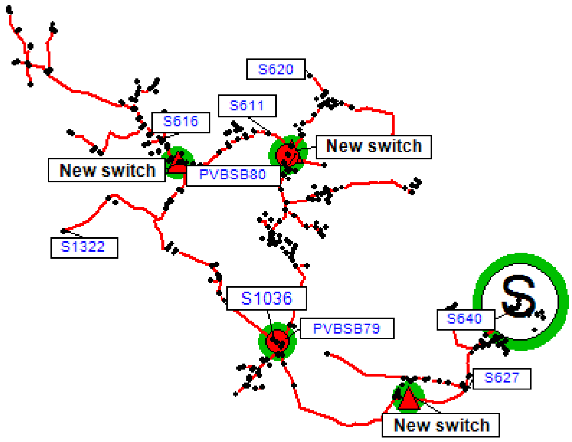

Figure 5-13: Optimal placement of additional switches on Umzali NB71

Figure 5-14 displays the effects of adding additional reclosers on the ENS and SAIDI of Umzali NB71. With each additional recloser placement there is a steady improvement in both ENS and SAIDI but with the fifth recloser, the ENS and SAIDI cannot be reduced further due to restrictions on the placement. The simulation and monetary results of each case are displayed in Table 5-4. As per the benefit to cost analysis in Figure 5-15 the optimal number of additional reclosers is four and the SAIDI improves by 21.27% and ENS by 11.47%. The DFB for four reclosers is R2 257 708.

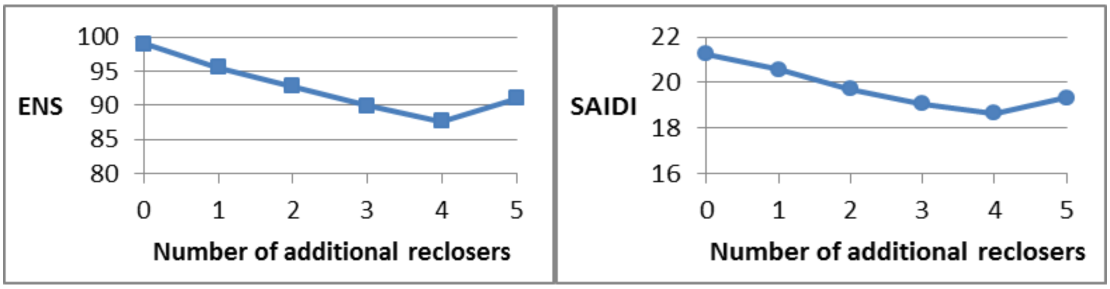

Figure 5-14: ENS and SAIDI values for Umzali NB71 with additional reclosers

Table 5-4: Results for additional reclosers on Umzali NB71

No. of reclosers	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R1 491 489.21	R 0.00	R1 491 489.21	R0.00	-
1	R1 438 759.93	R360 461.88	R1 799 221.81	R52 729.28	0.02930
2	R1 396 968.58	R720 923.76	R2 117 892.34	R94 520.63	0.04462
3	R1 353 635.01	R1 081 385.64	R2 435 020.65	R137 854.20	0.05661
4	R1 320 423.18	R1 441 847.52	R2 762 270.70	R171 066.03	0.06192
5	R1 369 845.40	R1 802 309.40	R3 172 154.80	R121 643.81	0.03834

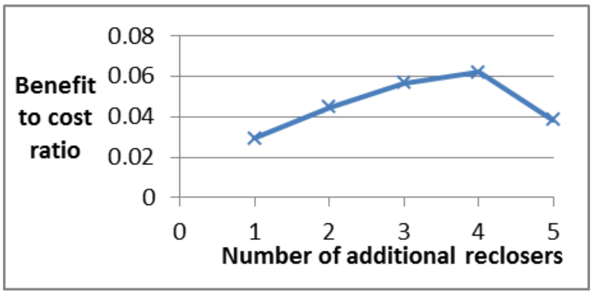

Figure 5-15: Benefit to cost analysis of Umzali NB71 with additional reclosers

The optimal reclosers locations are displayed geographically in Figure 5-16 with an allocation of one recloser per defined zone. The first recloser is positioned on the backbone close to the network source. The other two reclosers are distributed evenly to improve performance. The limitation of four reclosers placed in a series configuration is not exceeded also considering the existing reclosers on the network.

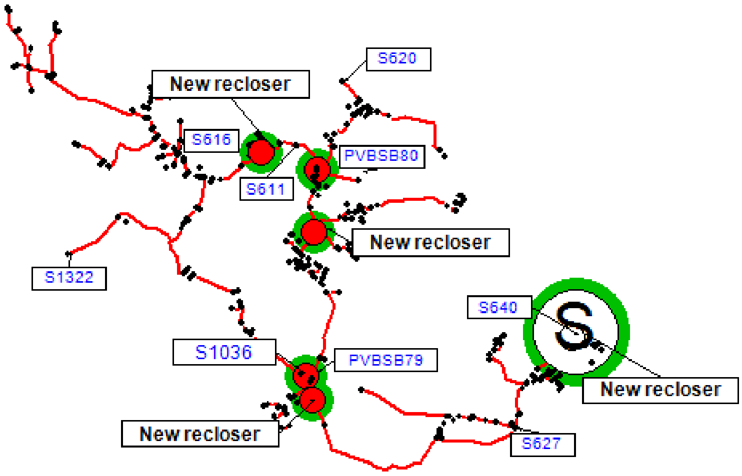

Figure 5-16: Optimal placement of reclosers of Umzali NB71

5.2.3 Case study 3 – Mhlatuze NB7

The same methodology used for Driel NB5 and Umzali NB71 was utilized for Mhlatuze NB7 to determine the optimal number of devices and location. Figure 5-17 displays the average load profile for Mhlatuze NB7 over a 24-hour period. The profile differs to the other networks due to the large amount of LPUs which are supplied by Mhlatuze NB7 causing a more steady power consumption throughout the day. The estimated income from Mhlatuze NB7 is R22 422 714 per annum.

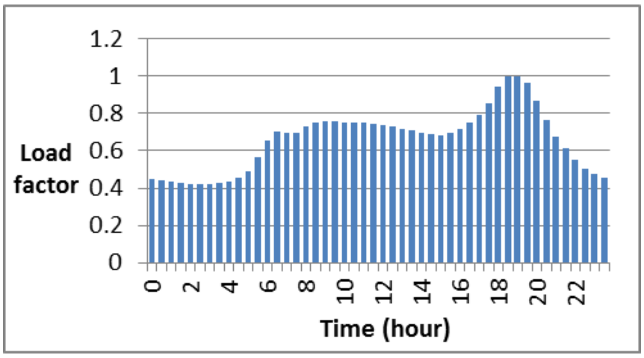

Figure 5-17: Mhlatuze NB7 average 24 hour load profile

Implementing the BPSO algorithm to place additional switches on Mhlatuze NB7 yielded the reliability KPIs displayed in Figure 5-18. The results and analysis determined from Table 5-5 and Figure 5-19 indicates six additional switches to be added to the network, with a fixed cost of R185 044.32. After the addition of six switches the variation in ENS and SAIDI is negligible. The SAIDI and ENS improvement are 0.28% and 0.24% respectively. The DFB is R670 463, which is substantial in relation to the other case studies for additional switches, due to the large CDF on Mhlatuze NB7.

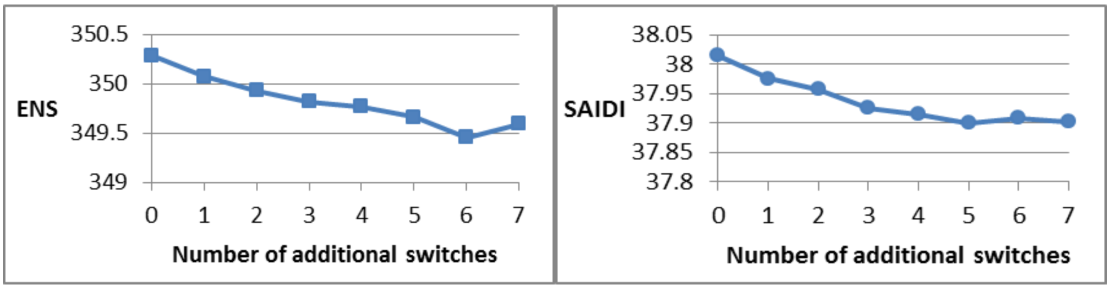

Figure 5-18: ENS and SAIDI of Mhlatuze with additional switches

Table 5-5: Results for additional switches on Mhlatuze NB7

No. of switches	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R21 329 066.25	R0.00	R21 329 066.25	R0.00	-
1	R21 316 162.08	R30 840.72	R21 347 002.80	R12 904.16	0.00060
2	R21 307 344.06	R61 681.44	R21 369 025.50	R21 722.19	0.00101
3	R21 300 353.73	R92 522.16	R21 392 875.89	R28 712.52	0.00134
4	R21 297 511.83	R123 362.88	R21 420 874.71	R31 554.42	0.00147
5	R21 291 009.60	R154 203.60	R21 445 213.20	R38 056.64	0.00177
6	R21 278 265.40	R185 044.32	R21 463 309.72	R50 800.85	0.00236
7	R21 286 690.23	R 215 885.04	R21 502 575.27	R42 376.02	0.00197

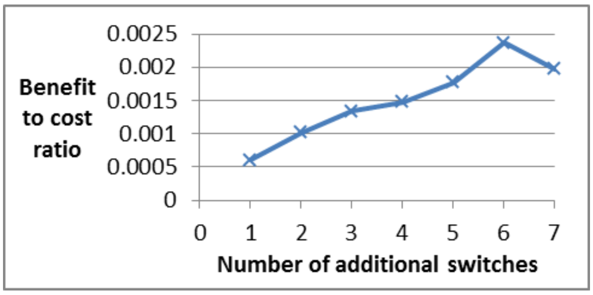

Figure 5-19: Benefit to cost analysis of Mhlatuze NB7 with additional switches

Figure 5-20 presents the locations of six additional switch positions on Mhlatuze NB7, along with the existing switches and reclosers. Four additional switches are located on the left leg of the network with the remaining two closer to the source.

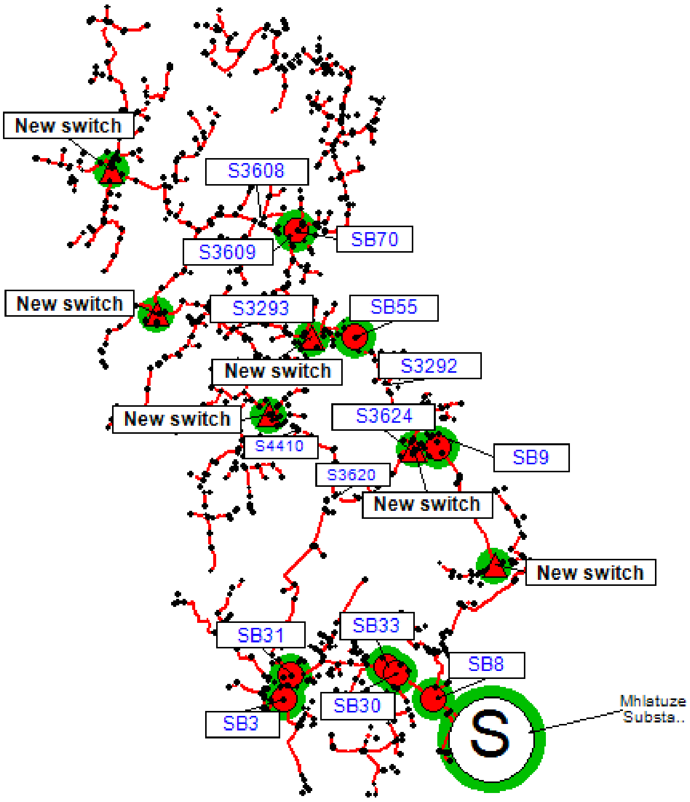

Figure 5-20: Optimal placement of switches on Mhlatuze NB7

Figure 5-21 displays the decrease in ENS and SAIDI with each additional recloser on Mhlatuze NB7. The optimal number of reclosers is three, which has the largest benefit to cost ratio as displayed in Table 5-6 and Figure 5-22. This results in an approximate 10% reduction in the SAIDI and ENS values for the network. The improvement in SAIDI is less than the previous case studies as the network already has a substantial amount of existing reclosers meaning that protection of critical loads are likely already in place.

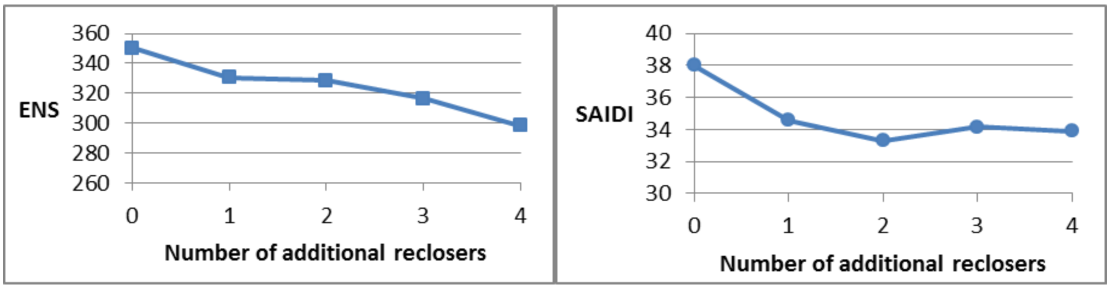

Figure 5-21: ENS and SAIDI of Mhlatuze NB7 with additional reclosers

Table 5-6: Results for additional reclosers on Mhlatuze NB7

No. of reclosers	ECOST	Utility Costs	Total Cost	Benefit	ΔBenefit/ΔCost
0	R21 329 066.25	R0.00	R21 329 066.25	R0.00	-
1	R20 114 017.46	R360 461.88	R20 474 479.34	R1 215048.79	0.05934
2	R19 994 582.72	R720 923.76	R20 715 506.48	R1 334 483.53	0.06441
3	R19 257 167.59	R1 081 385.64	R20 338 553.23	R2 071 898.66	0.10187
4	R18 171 782.36	R1 441 847.52	R19 613 629.88	R1 715 436.37	0.08746

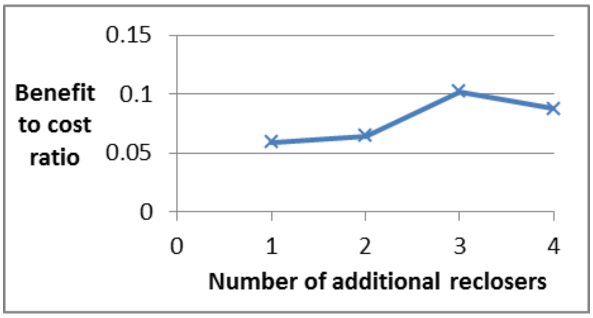

Figure 5-22: Benefit to cost analysis of Mhlatuze NB7 with additional reclosers

Figure 5-23 shows the locations of the proposed additional reclosers along with the existing reclosers on the network. The reconfiguration of the network and change in normally open points allows more reclosers to be added while still adhering to the maximum of four reclosers placed in series and allowing effective grading of the protection. The three reclosers are positioned similarly to the four additional switches on the left leg of the network. The analysis demonstrates the relationship between additional reclosers on the network and improvement in reliability. The DFB is close to R27.3 million, which is the most beneficial of all cases tested and can be attributed to the mixture of commercial, agricultural and community service load present on the network.

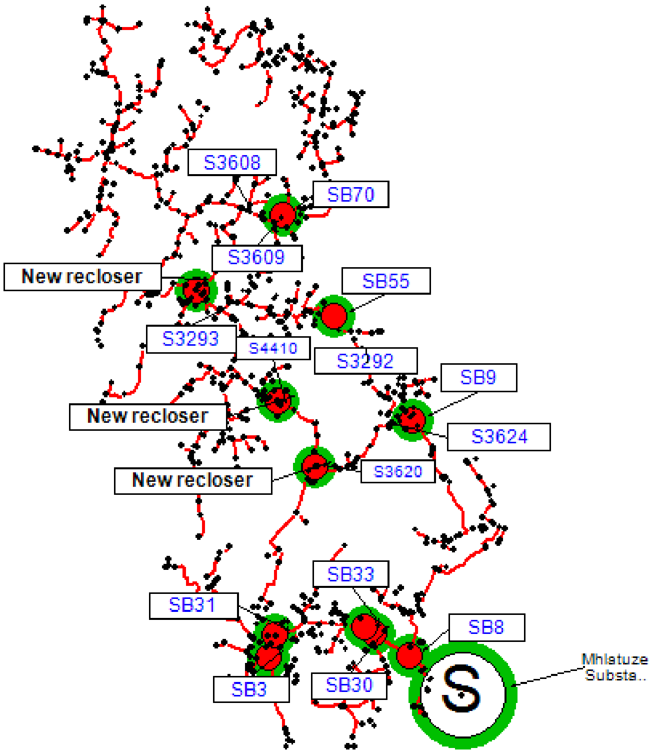

Figure 5-23: Optimal placement of reclosers on Mhlatuze NB7

5.3 Conclusion

The integration of the tool created which utilizes BPSO for optimization of protection devices is tested on three real case study networks. The approach taken considers investment costs, maintenance requirements as well as outage costs in the objective function to obtain the optimal network reliability. The fitness of each solution was assessed using the objective function. Mhlatuze NB7 has the maximum benefit with the placement of additional devices. This is due to the largest customer damage function of the network as well as the loop switches present in the network. When faults occur, the additional sectionalizing devices can be used to isolate the faulted section of network and create alternate paths to restore power to other customers, thus maximizing reliability. The function of the switches and reclosers are both protective and ideally the devices should be most effective at only specific locations on the network. However, the positions of the switches and reclosers are not expected to be the same as the switches have no restrictions and can be placed anywhere which will yield the maximum benefit to the network. The reclosers are restricted to an allocated zone to allow for effective protection co-ordination as well as a limit to the maximum number of reclosers which can be placed in a series configuration. The reliability improvement with the addition of reclosers was greater than with additional switches in all cases tested. Validation of the algorithm using the case study networks, prove that it is an effective tool which can be used on real distribution networks to place protection devices in locations which were not previously considered.

6 Conclusion and suggestions for future work

6.1 Conclusion

The research work undertaken has focused on predicting and thereafter improving the South African distribution network reliability. An algorithm based on Binary Particle Swarm Optimization was implemented to optimize distribution network reconfiguration as well as supplemental device placement on the system. The effects on reliability, network performance and system efficiency were considered. The methodology was applied to three distribution networks in KwaZulu-Natal, each with diverse topology, environmental exposure and causes of failure.

Feeder performance is directly affected by factors such as age, maintenance and environmental exposure. Reliability studies are usually performed by using average component failure rates and repair durations. However, this does not take into account the unique characteristics of each network, and the resultant reliability indices reflect average network performance. A methodology was proposed to determine specific component type failure rates and repair durations unique to each feeder. The component types included transformers, lines, cables, jumpers, insulators and isolators. This was accomplished using historical fault data which is readily available where the cause of failure and time to restoration is documented for each event. The repair duration determined by statistical analysis provides a more robust value as it considers all fault events in a bell-shaped distribution where outlying data is excluded if necessary. The percentage difference in average and calculated failure rates and repair durations in some cases are 97% and 90% respectively. Failure effect analysis and Monte Carlo simulation was thereafter used to determine the reliability parameters of practical distribution networks. The output results are measured against recorded reliability parameters available for the distribution network to act as a benchmark for the simulation results. The calculation of failure rates provides results which are closer to the historical reliability data and hence more accurate predictive reliability modelling.

Thereafter the concept of network reconfiguration was tested to change the topology of the networks and determine the effects on SAIDI and SAIFI. BPSO was successfully used to optimize the network to maximize reliability and as a secondary objective to minimize losses. Reconfiguration consisted of adjusting the normally open and normally closed points on the network, while still maintaining the radial nature of the network. Practical operational constraints including the voltage and thermal capabilities of the network were also taken into consideration. The reconfiguration options proposed with no capital expenditure result in improvements of up to 20% on SAIDI and 24% on SAIFI. The algorithm was similarly tested to optimize system losses by network reconfiguration. While the objective was met and losses reduced in some cases from approximately 341 kW to 288 kW, the reconfiguration had an adverse effect on reliability where the SAIDI and SAIFI of the network increased. In two of the tested cases the reconfiguration to maximize reliability simultaneously resulted in a reduction of losses. Hence, the primary objective function to maximize reliability is preferred when performing network reconfiguration. The results obtained from reconfiguration are encouraging and will allow power utilities to provide improved reliable supply without the need for capital intensive investment and expenditure.

Further improvement of reliability was considered by strategic placement of additional devices on the distribution networks. Utilizing value based planning; the objective is to minimize costs while achieving maximum improvement in reliability. In order to quantify investment decisions, the customer interruption costs were determined per network to obtain an accurate outage cost per network. The customer damage functions for each network varied due to the type of customers present on each network. BPSO was again used to optimally place and locate switches and reclosers on the practical networks. The results initially show a steady improvement in reliability indices with each additional device added to the networks. However, in all cases saturation is reached where there is no further reliability improvement with the additional device installation. This is where a benefit to cost ratio is used to determine the trade-off between capital expenditure and reliability improvement.

For additional switch placement in some cases the SAIDI improves from 38.02 h/Ca to 37.90 h/Ca. The discounted future benefit is R670 463 over the 25-year period for the installation of the manual switches. The results show that the discounted future benefit of adding additional reclosers to a network is close to R27 million over a 25-year period and the improvement in SAIDI is up to 10%. The financial benefit of device installation is higher in the third case study as the customer damage function is much larger on this network, due to the mix of agricultural, community services and commercial load. Thus, the impact of outages and loss of revenue are significant in comparison to networks supplying residential loads. SAIDI is also improved by 21% in the second case study using the previously reconfigured network. The benefit of installing reclosers far outweighs the benefit of installing sectionalizing switches in all cases tested. The reclosers have a greater impact on reducing the power restoration time to isolate faulted equipment as opposed to performing manual switching. Based on the case studies presented, utilizing the BPSO algorithm to determine the number of devices and their optimal placement on a network ensures an economically feasible approach is used to improve reliability.

Based on the findings from this research, it is recommended that reconfiguration on networks should be implemented as a basic measure for reliability improvement of distribution networks. Thereafter additional devices should be placed in their optimal positons to further improve reliability and profitability of the electric utility. BPSO is an efficient and accurate algorithm to be used for both reconfiguration and optimal device placement. The methodology proposed was tested on large and complex networks and produced promising results. The algorithm can thus be further utilized to optimize other distribution networks of a similar nature.

6.2 Future work

The aspects of reliability improvement by network configuration and additional device placement have been well investigated. Further research and development can be conducted considering other aspects to improve reliability.

While the BPSO algorithm has performed well to determine optimal solutions, other algorithms can also be tested using the same networks and objective functions which will allow the algorithm efficiency and output results to be compared. If mixed methods are utilized, it is possible to further improve the objective function and reduce the computation time of the algorithm to yield superior results.

The possibility of load transfer between neighboring meshed distribution networks; prevalent in urban areas; can improve reliability significantly and should be considered in future studies. With the ability to evaluate non radial systems, transmission systems and networks containing distributed generation could also be considered for optimization. The presence of distributed generation such as rooftop photovoltaic systems on rural networks is increasing. Their effects on system reliability along with an economic analysis also need to be investigated in future research work.

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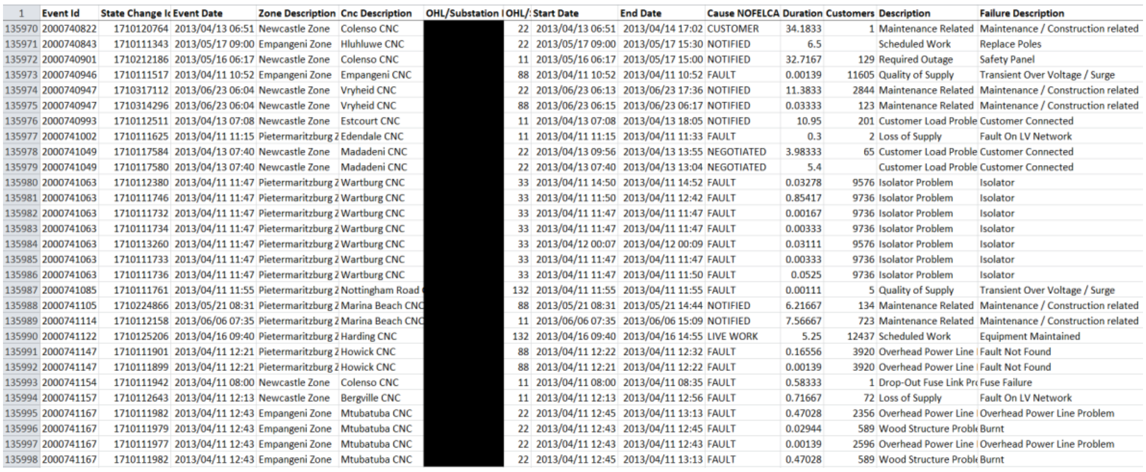
Appendix A



1	Event Id	State Change I	Event Date	Zone Description	Cnc Description	OHL/Substation I	OHL/	Start Date	End Date	Cause NOFELCA	Duration	Customers	Description	Failure Description
135970	2000740822	1710120764	2013/04/13 06:51	Newcastle Zone	Colenso CNC	[redacted]	22	2013/04/13 06:51	2013/04/14 17:02	CUSTOMER	34.1833	1	Maintenance Related	Maintenance / Construction related
135971	2000740843	1710111343	2013/05/17 09:00	Empangeni Zone	Hluhluwe CNC	[redacted]	22	2013/05/17 09:00	2013/05/17 15:30	NOTIFIED	6.5		Scheduled Work	Replace Poles
135972	2000740901	1710212186	2013/05/16 06:17	Newcastle Zone	Colenso CNC	[redacted]	11	2013/05/16 06:17	2013/05/17 15:00	NOTIFIED	32.7167	129	Required Outage	Safety Panel
135973	2000740946	1710111517	2013/04/11 10:52	Empangeni Zone	Empangeni CNC	[redacted]	88	2013/04/11 10:52	2013/04/11 10:52	FAULT	0.00139	11605	Quality of Supply	Transient Over Voltage / Surge
135974	2000740947	1710317112	2013/06/23 06:04	Newcastle Zone	Vryheid CNC	[redacted]	22	2013/06/23 06:13	2013/06/23 17:36	NOTIFIED	11.3833	2844	Maintenance Related	Maintenance / Construction related
135975	2000740947	1710314296	2013/06/23 06:04	Newcastle Zone	Vryheid CNC	[redacted]	88	2013/06/23 06:15	2013/06/23 06:17	NOTIFIED	0.03333	123	Maintenance Related	Maintenance / Construction related
135976	2000740993	1710112511	2013/04/13 07:08	Newcastle Zone	Estcourt CNC	[redacted]	11	2013/04/13 07:08	2013/04/13 18:05	NOTIFIED	10.95	201	Customer Load Proble	Customer Connected
135977	2000741002	1710111625	2013/04/11 11:15	Pietermaritzburg Z	Edendale CNC	[redacted]	11	2013/04/11 11:15	2013/04/11 11:33	FAULT	0.3	2	Loss of Supply	Fault On LV Network
135978	2000741049	1710117584	2013/04/13 07:40	Newcastle Zone	Madadeni CNC	[redacted]	22	2013/04/13 09:56	2013/04/13 13:55	NEGOTIATED	3.98333	65	Customer Load Proble	Customer Connected
135979	2000741049	1710117580	2013/04/13 07:40	Newcastle Zone	Madadeni CNC	[redacted]	22	2013/04/13 07:40	2013/04/13 13:04	NEGOTIATED	5.4		Customer Load Proble	Customer Connected
135980	2000741063	1710112380	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 14:50	2013/04/11 14:52	FAULT	0.03278	9576	Isolator Problem	Isolator
135981	2000741063	1710111746	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 11:50	2013/04/11 12:42	FAULT	0.85417	9736	Isolator Problem	Isolator
135982	2000741063	1710111732	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 11:47	2013/04/11 11:47	FAULT	0.00167	9736	Isolator Problem	Isolator
135983	2000741063	1710111734	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 11:47	2013/04/11 11:47	FAULT	0.00333	9736	Isolator Problem	Isolator
135984	2000741063	1710113260	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/12 00:07	2013/04/12 00:09	FAULT	0.03111	9576	Isolator Problem	Isolator
135985	2000741063	1710111733	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 11:47	2013/04/11 11:47	FAULT	0.00333	9736	Isolator Problem	Isolator
135986	2000741063	1710111736	2013/04/11 11:47	Pietermaritzburg Z	Wartburg CNC	[redacted]	33	2013/04/11 11:47	2013/04/11 11:50	FAULT	0.0525	9736	Isolator Problem	Isolator
135987	2000741085	1710111761	2013/04/11 11:55	Pietermaritzburg Z	Nottingham Road	[redacted]	132	2013/04/11 11:55	2013/04/11 11:55	FAULT	0.00111	5	Quality of Supply	Transient Over Voltage / Surge
135988	2000741105	1710224866	2013/05/21 08:31	Pietermaritzburg Z	Marina Beach CNC	[redacted]	88	2013/05/21 08:31	2013/05/21 14:44	NOTIFIED	6.21667	134	Maintenance Related	Maintenance / Construction related
135989	2000741114	1710112158	2013/06/06 07:35	Pietermaritzburg Z	Marina Beach CNC	[redacted]	11	2013/06/06 07:35	2013/06/06 15:09	NOTIFIED	7.56667	723	Maintenance Related	Maintenance / Construction related
135990	2000741122	1710125206	2013/04/16 09:40	Pietermaritzburg Z	Harding CNC	[redacted]	132	2013/04/16 09:40	2013/04/16 14:55	LIVE WORK	5.25	12437	Scheduled Work	Equipment Maintained
135991	2000741147	1710111901	2013/04/11 12:21	Pietermaritzburg Z	Howick CNC	[redacted]	88	2013/04/11 12:22	2013/04/11 12:32	FAULT	0.16556	3920	Overhead Power Line	Fault Not Found
135992	2000741147	1710111899	2013/04/11 12:21	Pietermaritzburg Z	Howick CNC	[redacted]	88	2013/04/11 12:21	2013/04/11 12:22	FAULT	0.00139	3920	Overhead Power Line	Fault Not Found
135993	2000741154	1710111942	2013/04/11 08:00	Newcastle Zone	Colenso CNC	[redacted]	11	2013/04/11 08:00	2013/04/11 08:35	FAULT	0.58333	1	Drop-Out Fuse Link Pr	Fuse Failure
135994	2000741157	1710112643	2013/04/11 12:13	Newcastle Zone	Bergville CNC	[redacted]	11	2013/04/11 12:13	2013/04/11 12:56	FAULT	0.71667	72	Loss of Supply	Fault On LV Network
135995	2000741167	1710111982	2013/04/11 12:43	Empangeni Zone	Mtubatuba CNC	[redacted]	22	2013/04/11 12:45	2013/04/11 13:13	FAULT	0.47028	2356	Overhead Power Line	Overhead Power Line Problem
135996	2000741167	1710111979	2013/04/11 12:43	Empangeni Zone	Mtubatuba CNC	[redacted]	22	2013/04/11 12:43	2013/04/11 12:45	FAULT	0.02944	589	Wood Structure Probl	Burnt
135997	2000741167	1710111977	2013/04/11 12:43	Empangeni Zone	Mtubatuba CNC	[redacted]	22	2013/04/11 12:43	2013/04/11 12:43	FAULT	0.00139	2596	Overhead Power Line	Overhead Power Line Problem
135998	2000741167	1710111982	2013/04/11 12:43	Empangeni Zone	Mtubatuba CNC	[redacted]	22	2013/04/11 12:45	2013/04/11 13:13	FAULT	0.47028	589	Wood Structure Probl	Burnt

Figure A-1: Example of fault data captured on NEPS

Table A-1: Some average failure rates and repair durations per area [61]

	Newcastle	Pietermaritzburg	Empangeni	All
	Failure rate	Failure rate	Failure rate	Restoration time
Transformer failure	0.0254	0.0264	0.0293	5
Conductor failure	0.0142	0.0182	0.0182	2
Isolator failure	0.0044	0.0065	0.0077	0.35

Discounted Future Benefit (DFB) Calculations

$$DFB = \sum_{t=0}^{t} \frac{ECOST_{original} - ECOST_{optimized}}{(1+i)^t}$$

Table A-2: DFB calculations for each case study

	Switches	Reclosers
Driel	$DFB = \sum_{t=0}^{25} \frac{\text{R2 387 321.85} - \text{R2 385 311.11}}{(1+0.065)^{25}}$ $DFB = R26\,537.50$	$DFB = \sum_{t=0}^{25} \frac{\text{R2 387 321.85} - \text{R1 908 964.84}}{(1+0.065)^{25}}$ $DFB = R6\,313\,296.85$
Umzali	$DFB = \sum_{t=0}^{25} \frac{\text{R1 491 489.21} - \text{R1 487 681.61}}{(1+0.065)^{25}}$ $DFB = R50\,252.24$	$DFB = \sum_{t=0}^{25} \frac{\text{R1 491 489.21} - \text{R1 320 423.18}}{(1+0.065)^{25}}$ $DFB = R2\,257\,708.38$
Mhlatuze	$DFB = \sum_{t=0}^{25} \frac{\text{R21 329 066.25} - \text{R21 278 265.40}}{(1+0.065)^{25}}$ $DFB = R670\,463.36$	$DFB = \sum_{t=0}^{25} \frac{\text{R21 329 066.25} - \text{R19 257 167.59}}{(1+0.065)^{25}}$ $DFB = R27\,344\,633.10$

Pseudocode of BPSO algorithm

```
For each particle
Initialize particles
End

Do
    For each particle
        Calculate the fitness value
        If the fitness value is better than the best fitness value in history Then
            Set the current particle position as the new best fitness value
    End For

    Select the particle with the best fitness value of all particles as the best global position
    For each particle
        Update the particle velocity
        Update the particle position
    End For
While less than maximum number of iterations
```