

**OPTIMISING THE NUMBER AND POSITION OF RECLOSERS ON A MEDIUM
VOLTAGE DISTRIBUTION LINE TO MINIMISE DAMAGE ON EQUIPMENT**

by

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Submitted in partial fulfilment of the requirements for the degree
Master of Engineering (Electrical Engineering)

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

31 August 2014

ACKNOWLEDGEMENTS

I am grateful to my supervisors, colleagues and family for their encouragement and support without which I could not have completed this thesis.

I would like to express my gratitude to my dissertation supervisor, Dr. R. Naidoo and co-supervisors Professor R. Bansal and Stuart van Zyl for their guidance and support.

A special note of appreciation goes to my colleagues, Anura Perera, for the technical assistance provided and Paul Keller, for the mentorship and inspiration he has provided.

I would like to thank my parents and my husband, Rinesh for their continuous patience, love and support.

Rinu Thomas

August 2014

SUMMARY

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Keywords: Recloser, damage factor, customer outage, kVA outage, investment costs, genetic algorithm, optimisation, reliability

The optimal placement of reclosers on overhead lines in a medium voltage distribution network is known to improve the reliability of a power system. Traditionally, recloser placement studies have not considered the effect of greater numbers of reclosers on network damage during faults or the effect of positioning on protection settings. Recloser positions that enhance the reliability of the system may not necessarily improve other problematic operational aspects, such as the damage to equipment and the risk of incorrect tripping due to the sudden increase in loading.

This research seeks to prove the hypothesis that:

Recloser placement studies with the additional consideration of protection-related factors such as equipment damage and the risk of false tripping will result in different recloser positions compared to when the priority is only on improving reliability indices and cost.

A tool is developed to assess the reliability indices, cost, damage and the risk of false tripping and it determines the best recloser positioning based on the priority given to each factor considered. Using this tool, observations are made on the effect of the added factors of damage and the risk of false tripping on recloser positioning.

The addition of the protection-related factors to the objective function is unique in its ability to realise the value of recloser positions that cater for minimizing the damage factor and the possibility of tripping on load. In the absence of these factors, the value of certain recloser positions would not be identified as they would not improve reliability or cost factors. The importance of reliability and cost are not overruled by the addition of the protection-related factors.

The consideration of protection-related factors in the planning process of optimising recloser placement ensures that the protection of the overhead line is optimal and is not compromised in any way. This would inherently have a positive effect on the lifespan of the equipment on the feeder and the reliability of the feeder in the long-term.

OPSOMMING

DIE OPTIMALISERING VAN DIE POSISIE EN DIE AANTAL HERSLUITERS OP 'N MEDIUMSPANNING-DISTRIBUSIEVOERDER OM DIE SKADE AAN TOERUSTING TE VERMINDER.

deur

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Dit is bekend dat die optimale plasing van hersluiters op mediumspanning-oorhoofse distribusievoerders die betroubaarheid van die netwerk verbeter. Normaalweg word die effek van 'n groter aantal hersluiters op die beskadiging van die netwerk gedurende foute nie in ag geneem nie. Die effek van die plasing van hersluiters op die beveiligingsverstellings word ook nie in ag geneem nie. Hersluiterposisies wat die betroubaarheid van die netwerk verbeter, sal nie noodwendig ander probleme, soos beskadiging van toerusting en 'n verkeerde breker wat klink as gevolg van 'n hoë las, op die netwerk verbeter nie.

Hierdie navorsing poog om die volgende hipotese te bewys:

Wanneer addisionele beveiligingsfaktore, soos die beskadiging van toerusting en die klinkrisiko in ag geneem word tydens hersluiter-plasingstudies, sal dit ander posisies aanwys as wanneer die prioriteit slegs is om die koste en betroubaarheidsindekse te verbeter.

'n Sagteware toepassing is ontwikkel om die betroubaarheidsindekse, koste, skade en die risiko van 'n klink te evalueer. Die toepassing voorsien dan die beste hersluiteerposisie, gebaseer op die gewig, toegeken aan elkeen van die voorafgaande faktore. Deur van dié toepassing gebruik te maak, kan waarnemings gemaak word van die effek wat die addisionele faktore op die skade aan toerusting en die klinkrisiko het.

Deur die beveiligingsfaktore in die doelfunksie by te sit, word unieke waardes geheg aan die resultate in hul vermoë om die beskadigingsfaktor en die risiko van 'n las-klank te verminder. Wanneer die beveiligingsfaktore nie in ag geneem word nie, sal sekere posisies nie geïdentifiseer word nie, omdat dit nie die betroubaarheid en kostefaktore verbeter nie. Die belangrikheid van die betroubaarheid en kostefaktore word nie deur die byvoeging van die beveiligingsfaktore uitgeskakel nie.

Die inagneming van die beskermingsgeoriënteerde faktore in die beplanningsproses van die optimalisering van die hersluiteerplasing verseker dat die beskerming van 'n oorhoofse voerder optimaal is en nie in enige mate in gedrang is nie. Inherent sal dit dus nie net die lewensduur van die toerusting verbeter nie, maar ook oor 'n lang tydperk die betroubaarheid daarvan.

LIST OF ABBREVIATIONS

kVA	kilo Volt-Ampere
MAIFI	Momentary Average Interruption Frequency Index
MV	Medium Voltage
NERSA	National Energy Regulator of South Africa
NI	Normal Inverse
RSLI	Reticulation Supply Loss Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

There are approximately 305500 km of overhead MV distribution networks in South Africa [1]. The National Energy Regulator of South Africa (NERSA) has increasingly been driving emphasis on the improvement of network reliability [2]. This has driven significant investment in reclosers. In the South African context, specifically within Eskom, the urgency of improving network reliability has led to a large number of additional reclosers being installed, with up to ten having been installed on some overhead lines, also known as feeders. The term recloser has been substituted for automatic circuit recloser for simplicity. A recloser automatically interrupts and recloses an alternating current circuit and it locks out after a predefined sequence of opening and reclosing [3]. A recloser is equipped with non-directional overcurrent, earth fault and sensitive earth fault protection, which is used to protect the feeder. Reclosers are frequently used in preference to fuses because fuses blow to isolate transient and permanent faults and need to be replaced manually to restore supply. Reclosers restore the network automatically if the fault is transient and only require manual restoration for permanent faults [4].

Although there has been increased investment in reclosers due to the focus on improvement of network reliability indices, the primary purpose of protection on reclosers in a power system is to detect abnormal conditions, locate the position of faults and promptly remove the faulty equipment from service. Both network reliability and protection of the network are dependent on the number and placement of reclosers. In the planning stages of recloser placement, the drive to improve reliability should therefore not compromise the protection of the network.

An increase in the number of reclosers minimises the customer interruption costs and improves the network reliability [5]. This is achieved by isolating the downstream section of the faulted network, which would reduce the impact of a fault on the rest of network.

The number of customers, the kVA base and the length of line are important considerations during the planning of a recloser installation so as to optimise return on investment [6]. A number of researchers have developed methods to calculate the optimal number and placement of reclosers on an MV feeder, offsetting improvements to reliability against investment cost [6]-[16].

Recloser placement studies have traditionally not considered the effect of greater numbers of reclosers on network damage during faults or the effect of positioning on protection settings. The requirement for devices in series to co-ordinate has the result that upstream devices, where fault currents are highest, operate in the longest time. Upstream reclosers are intentionally time delayed to ensure that the recloser closest to the fault trips first to minimise the number of customers affected [17]. Larger numbers of protective devices in series can thus give rise to slower fault clearance and thus greater damage as a result of faults being left on the network longer. The result includes localised damage at the fault point as well as potential damage to upstream devices (specifically power transformers). This will lead to a shortened lifespan and a higher probability of failures. In the longer term, having more reclosers on a network with just traditional considerations could worsen network reliability and increase maintenance costs.

Fault currents cause huge amounts of thermal energy, which can cause extensive damage to equipment and risk to human life if not cleared quickly. By minimizing the fault duration and therefore the energy released, reclosers greatly reduce the damage caused to lines, the surrounding equipment and the environment. The fault duration is dependent on the settings of the recloser, which are in turn dependent on the number of reclosers as well as the position of reclosers. The optimisation of the number and placement of reclosers can thus not be done without considering the associated negative impact on fault clearance.

On the contrary, having too few devices may lead to nuisance tripping under normal load conditions. This is because each recloser must be set sensitive enough to detect faults at the intended reach of the recloser. The intended reach is defined as the furthest point upto which the recloser should detect faults should the downstream recloser fail, and is

dependent on the positions of the other reclosers in the network. Setting the recloser in this manner could result in tripping for load currents, because the current pickup value of the recloser may be set below the emergency rating of the overhead conductor. In order to avoid such nuisance tripping, the current pickup value is often rather set to the emergency rating of the line, compromising the sensitivity of the recloser to a fault at the intended reach. If the recloser is not set sensitive enough to detect a fault at its intended reach, there is a possibility that the fault will remain on the network undetected. Undetected faults can result in damage of the equipment and pose a risk to human safety.

Neither of the above factors has been considered in optimisation studies undertaken so far. The protection settings on distribution networks are highly dependent on the number and placement of reclosers. This has a direct impact on the practicality of the application of protection settings that minimise the damage caused to the network under fault conditions whilst ensuring that feeders are not tripped under load conditions.

The placement of reclosers solely based on the optimisation of network reliability and cost may not necessarily address the need to protect the feeder from damage and unnecessary tripping on load due to the constraints of protection settings. A well-protected feeder implies an improved lifespan and a lower probability of failures of equipment on the feeder, lowering maintenance and replacement costs in the long term. The potential benefits of improvement of reliability indices and optimised operational costs in the long term, makes it increasingly important that the effects of the abovementioned factors are included as criteria for recloser placement.

1.1.2 Research gap

The consideration of the impact of the recloser number and placement on protection settings needs to be prioritized in order to minimise the damage caused to the network under fault conditions and to ensure that the feeder does not trip under load conditions. In previous studies, reliability indices and cost have been optimised in isolation from this consideration.

The research gap will be addressed by minimising equipment damage during fault conditions and the risk of tripping for load, in addition to the cost of investment in reclosers, and the probable loss of supply to customers. The loss of supply to customers is quantified in terms of the number of customers affected and the total amount of load interrupted. How the recloser number and placement vary due to different priorities applied to the abovementioned factors will be studied.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

Previous work by other authors has investigated the optimal number and placement of reclosers to improve network reliability yet minimise investment cost. The aim of this research is to build on this work by considering two additional factors in the optimisation algorithm:

- The damage caused to the conductor and other line equipment
- The risk of nuisance tripping due to heavy load as a result of settings constraints on reclosers

The research questions are as follows:

- How will recloser number and placement change based on the priority given to the various factors in the objective function?
- What is the suggested recloser number and placement with equal priority given to each factor in the objective function on a real network? For an actual distribution network, how do the actual device numbers and placements compare with those suggested by the algorithm?

A tool will be created to assess various factors such as the reliability indices, cost, damage and the risk of false tripping and determine the best recloser positioning based on the priority given to each factor considered. Observations are made on how recloser positioning is affected due to the added factors of damage and the risk of false tripping.

1.3 HYPOTHESIS AND APPROACH

This research seeks to prove the hypothesis that:

Recloser placement studies with the additional consideration of protection-related factors such as equipment damage and the risk of false tripping will result in different recloser positions compared to when the priority is only on improving reliability indices and cost.

The hypothesis describes the development of an improved recloser placement algorithm for radial distribution networks. The various aspects considered in the application of the algorithm are as follows:

- The complexity of the network model that the algorithm is applied to needs to be decided upon. The approach of previous studies on network model complexity should be analysed in terms of the limitations on the results of the optimisation algorithm.
- A program should be developed for the automatic creation of the network model based on provided data and for the application of the algorithm. Software packages in which to implement the algorithm need to be assessed for simplicity of implementation.
- Various optimisation methods from previous literature must be analysed. An optimisation method suitable for the problem of recloser placement must be identified.
- The formulation of objective functions in previous literature must be analysed and the method of measuring reliability indices and cost must be studied. The availability of actual data required to calculate factors of the objective function accurately must be assessed to decide on which approach should be used to calculate the reliability and cost factors.
- A suitable factor to represent the damage caused to the network and risk of nuisance tripping due to heavy load needs to be formulated to be included in the objective function to be optimised.
- An objective function must be developed that takes into account the risk of losing customers and load, the investment costs, the damage during fault conditions and the risk of false tripping.

- The results of the algorithm should be tested using different priority factors, and plausibility will be checked.
- Once the algorithm is validated, the program will be applied to a real life network and results will be analysed.

1.4 RESEARCH GOALS

The goal of this research is to check whether or not the tools that have been previously documented can be improved by additionally considering two protection-related factors. The impact of the damage factor and the risk of nuisance tripping due to heavy load will be studied by means of simulation. The addition of the abovementioned factors to the objective function could lead to a more balanced algorithm in terms of simultaneously minimising reliability indices, cost, damage to the network and the risk of nuisance tripping due to heavy load.

1.5 RESEARCH CONTRIBUTION

Much emphasis has previously been placed on optimisation of reliability indices. This has driven considerable investment in reclosers. This work seeks to test the concept that recloser placement driven by reliability indices only may deteriorate the effectiveness of network protection. Decreased effectiveness of network protection may lead to increased damage, and may be a contributor to decreased network reliability in the long run.

1.6 OVERVIEW OF STUDY

The structure of this thesis is guided by the research goals and the process that must be followed in order to evaluate the hypothesis. The chapters that follow are briefly outlined below.

Chapter 2 includes a review of available literature on network damage due to fault currents, various factors considered in the optimisation of recloser placement and various optimisation methods and simulation tools pertaining to the objectives of the hypothesis.

Chapter 3 explains the protection philosophy applied to MV distribution networks.

Chapter 4 develops the objective function to be optimised and introduces the protection-related factors, which have not been considered in previous studies for the optimisation of recloser placement. Modifications on the reliability and cost factors that have been considered in previous studies are discussed.

The general theory and the application of the genetic algorithm are explained in Chapter 5.

Chapter 6 explains the integration of concepts explained in Chapters 3, 4 and 5 in the development of the tool created for the optimisation of recloser placement. Discussions on the automated creation of the network model are included in this chapter.

Chapter 7 includes the validation of the optimisation tool to identify the individual impact of each factor of the objective function on recloser placement. Thereafter, the tool is applied to a real feeder and the results are analysed and compared to the actual placement of reclosers on the network.

Chapter 8 summarises the findings of the research and evaluates the hypothesis.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OBJECTIVES

Chapter 1 identified a number of areas related to the hypothesis that an improved objective function for the optimisation of recloser placement could be developed. This chapter includes a review of published information that provides background on previous studies on recloser placement and on how fault currents can cause damage to conductors. Four broad topics form the framework of the literature survey. The following topics are studied:

- Optimisation methods are evaluated for suitability of application to the recloser placement problem.
- Relevant studies reported by other researchers are analysed in terms of the factors included in the objective function.
- An understanding of distribution feeder protection is critical to the formulation of the protection-related factors that are to be added to the objective function.
- A comparison of software implementation of the project in various software packages must be done to ensure the efficient programming of the algorithm.

2.2 OPTIMISATION METHODS

The researchers in [6]-[16] employ various optimisation methods to optimise recloser placement. In all the optimisation methods used, the quality of the solution is determined by the value of the objective function. The objective function is an equation that consists of variables that need to be minimised or maximised [18]. All possible combinations of recloser numbers and positions form the search space of the solution. Each optimisation algorithm has a unique method of exploring the search space to find a near-optimal solution. All the methods discussed are more efficient than exhaustive enumeration in terms of computational time.

2.2.1 Simulated annealing

In [11], the simulated annealing algorithm is used for optimising the number and placement of switching devices. The idea of this algorithm originates from the process of annealing in metal work [11]. As a metal is heated and then cooled, the physical properties

of the metal change slowly during the cooling process and become fixed as it freezes, after which the metal retains its newly gained properties. Similarly, the algorithm employs a temperature variable to simulate the heating process. The algorithm begins by randomly generating an initial recloser placement and by setting the initial temperature variable high. The quality of the solution is assessed in terms of the value of the objective function. In each iteration, the existing recloser placement is modified by implementing a set of moves that are randomly selected, and the temperature variable is reduced by a predefined factor. If the value of the objective function has improved, the new configuration is accepted as the current solution. If the value of the objective function has deteriorated, the new configuration is accepted based on a probability component calculated from the difference of the objective functions and the temperature. If neither of the above conditions is met, the previous recloser placement is retained. The probability component is calculated such that it has a higher value when the temperature is high and when the difference between the values of objective functions at a fixed temperature is low. The acceptance of configurations that result in slightly worse solutions ensures that the algorithm can escape from converging at a local optimum in the early iterations of the algorithm. As the temperature variable reduces, so does the probability of accepting poorer solutions. This process is repeated until the value of objective function for the configuration does not change for a number of consecutive temperature reductions, which is indicative of the optimal configuration.

The consideration of all branches of the feeder in the optimisation problem creates a large search space, which makes the approach appropriate for the solution methodology. The convergence of the simulated annealing algorithm to the optimum solution of a problem is highly dependent on the selection of assumptions for the cooling schedule, the acceptance rate and the number of moves at each temperature [11]. The disadvantages of the algorithm are the difficulty in obtaining these problem-dependent parameters and its slow convergence speed [11].

2.2.2 Modified drop heuristic

The modified drop heuristic method is used to determine the number of protective devices and their positioning, so that the inconvenience caused to the customer is minimised [9]. To simplify the problem, the potential points of recloser placement are limited to nodes on the main line, or a connection point between the main line and one of the branches. Once the number of potential sites is chosen, the objective function value is calculated. Each device is temporarily removed and the objective function is recalculated. This is repeated until the largest cost minimisation is achieved. The modified drop heuristic was tested on ten networks and produced the best average improvement and the lowest standard deviation in comparison to the kVA.km method and the back parse method. This is observed since the placement of devices is limited to the main line in the other methods. The disadvantage of the modified drop heuristic is that when a possible solution is dropped, it can not be reinstalled again, irrespective of whether it becomes economical at a later stage [9].

2.2.3 kVA.km method

This method is used to determine the number of protective devices and their positioning, so that the inconvenience caused to the customer is minimised [9]. The kVA.km rating is defined as the product of the length of the line and the energy usage in the network at each evaluation point [9]. Once the kVA.km ratings for all the evaluation points are calculated, the position that yields the biggest value or where the product exceeds a prescribed bound is chosen as the position for the placement of the device [9]. The success of this method is highly dependent on a suitable selection of the prescribed bound for each case that is studied. The value of the bound is network dependent and it varies as the number of reclosers on the network change. A guideline on how the bounds were selected for each case is absent in [9].

According to the logic of this method, a node connected to a very long network and a high load is the most optimal position for a recloser. The shortfall of this method is that a node connected to a long network, where the probability of faults is high, and where the load

connected is low may not necessarily be considered as a potential position for a recloser. It will only be considered as a potential position if the connected length of the network is extremely long. The major drawback of the kVA.km method is that it tends to select placement on the main line only [9]. This is due to the fact that the largest length coverage and connected load is typically on the main line of the feeder. This method is found to behave less satisfactorily in comparison to other optimisation methods due to this limitation [9].

2.2.4 Back parse method

The back parse method is used in [16]. The cumulative value of the objective function is assessed at each point of evaluation and if the value is greater than a prescribed threshold, a device is placed at that node. This algorithm iterates through all possible recloser positions from the end points of the feeder till the source is reached. The back parse method is found to perform better than the kVA.km method, but worse than the modified drop heuristic. The result of this method is highly dependent on the threshold that needs to be determined, which is network dependent. This aspect of the method is similar to the dependency of the kVA.km method on the bound parameter. A lower threshold results in excessive placement of devices, which would violate the financial constraints.

2.2.5 Tabu search

In [7] and [9], the tabu search is utilised to determine the protective device placement.

The tabu search employs adaptive memory, which enables an economical and effective search of the solution space. The initial recloser placement is provided or randomly selected. The neighbourhood of the existing recloser placement is explored by moves of certain elements of the given recloser placement. If the objective function of the new configuration has a better value than the previous configuration, the new configuration is accepted to be the best candidate. The adaptive memory of the algorithm is achieved by storing each move into various memory types based on certain rules. Recent moves are stored in the short-term memory, also called the tabu list, which ensures that the move is not reversed. Selection from the tabu list is allowed if the aspiration criterion is met. The

aspiration criterion is typically dependent on the difference in the objective values of the old and new configurations. The intermediate-term memory stores the moves that depict promising areas of the search space, which biases the search into this area. The long-term memory stores all previously explored configurations and forces the search into previously unexplored areas of the search space.

All branches from the main line are considered in the algorithm, which ensures good results. The consideration of all branches considerably increases the run-time of the algorithm. The tabu search typically moves to recloser position configurations of lower energy, but is permitted to make uphill moves to enable the escape from local minima [7].

2.2.6 Genetic algorithms

In [12] and [13], the problem of protection device placement is formulated as a binary integer non-linear programming problem that is solved using genetic algorithms.

A randomly created population of recloser placement configurations is created and evaluated according to the objective function. Configurations with the best values of objective function are considered as elite and are selected as the parent generation. Children vectors are produced by combining the recloser positions of the parent vectors or by the random change of a single element in one parent vector. A comparison of the objective function between the parent vectors and children vectors is done and the best configurations form the new generation. This process is repeated until the stopping criterion is reached. The vector with the best objective function after a fixed number of iterations is considered to be the optimal solution.

Genetic algorithms have been found to be a good tool to solve mixed, combinatorial problems, but they tend to be computationally expensive. They are less prone to converging at local optima, unlike gradient search methods. Since the output of the objective function is the only requirement of the algorithm, the complexity of the problem does not depend on the form of the objective function or its constraints.

2.2.7 Overview of optimisation methods

Complete enumeration is the assessment of all possible combinations, and where the best combination is chosen as the solution. This would be a very time consuming exercise. Every optimisation method discussed would converge to a solution faster than complete enumeration, but the quality of the solution may differ based on its ability to escape local optima and the suitability of the network dependent parameters required for the efficient convergence of the algorithm for the specific problem.

The genetic algorithm is not dependent on the form of the objective function and thus multi-dimensional, non-differential, non-continuous problems can be solved. The genetic algorithm is used in this study due to its suitability to solve multi-objective problems and its ability to find good solutions in potentially-large search spaces.

2.3 OPTIMISATION OF RECLOSER PLACEMENT

Optimisation studies based on different factors are summarised in Table 2.1 in terms of the purpose of the study, the optimisation method, the factors that are optimised and data required for the study. Researchers [6]-[8] use models based on real-life networks, while [10]-[11] and [16] use hypothetical systems.

The results of Table 2.1 indicate several factors that are considered in the optimisation process of recloser placement. The individual studies consider a number of different combinations of these factors in their objective functions, yet it is difficult to distinguish the individual influence of different factors on recloser placement.

2.3.1 Reliability

Most utilities' reliability measures are customer based measures. All the studies listed in Table 2.1 have at least one factor in the objective function that addresses the reliability of the system. This is due to the fact that the performance of MV distribution networks is measured by reliability indices, such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). ESKOM is obliged

to submit periodic reports to NERSA on these reliability indices according to NRS048 [19]. The inconvenience caused to the customer is well captured by SAIDI and SAIFI.

SAIDI is the average outage duration for each customer served and is calculated by Equation 2.1.

$$\text{SAIDI} = \frac{\sum U_i \times C_{\text{affected}}}{C_{\text{total}}} \quad (2.1)$$

where C_{affected} is the number of customers affected as a result of a fault at a specific position, C_{total} is the total number of customers, U_i is the repair time for a fault at location i .

SAIFI is the average number of interruptions that a customer would experience. SAIFI is calculated according to Equation 2.2.

$$\text{SAIFI} = \frac{\sum \lambda \times C_{\text{affected}}}{C_{\text{total}}} \quad (2.2)$$

where C_{affected} and C_{total} are the same as defined in (2.1) and λ is the failure rate of the length coverage of the recloser.

To calculate either of these parameters, the failure rate of the network following every potential recloser position and the restoration time for each interruption event must be known. This information must thus be supplied as inputs to the application that optimises recloser placement. In [8], [10] and [12]-[14], the objective function is dependent on the failure rate of equipment and the restoration time of interruption events, SAIDI and SAIFI are included in the objective function. The limitations of obtaining accurate failure rates for each branch and the restoration time for each interruption event of a real feeder in the South African context makes the use of these parameters in the objective function impractical.

Momentary Average Interruption Frequency Index (MAIFI) tends to be less reported than SAIDI and SAIFI, but is included in the objective functions of [8] and [13].

The risk of an outage scenario is included as a factor in the objective function of [6]. The risk of an outage scenario is given as the product of the Value of Lost Load (VoLL) and probability of an outage. In [6], the probability of an outage is equivalent to the ratio of the length of the feeder covered by the recloser and the total length of the feeder and VoLL is estimated as a specific cost per kilowatt hour to quantify the financial losses that customers suffer given a loss of supply. As the number of reclosers on a feeder increases, the risk of an outage for the different sections of the feeder decreases, but not significantly. The objective function in [6] is modified slightly and discussed further in Chapter 4 for use in the objective function developed for this study.

The cost of interruption focuses on the monetary aspects of customer outages. References [7], [11], [14] and [15] consider the placement of protective devices in order to minimise the cost of interruption in terms of the customer outages, the time needed for repairs and restoration. The assumptions made in the development of the objective function in [11] are as follows:

- Each load on the network must be defined as either a residential, commercial or industrial customer.
- A fixed repair time of four hours and a fixed switching time of 1.5 hours are assumed for every permanent fault. The author of [11] does not state the basis of these assumptions. This could possibly be the average periods for the repair time and the switching time.
- The repair costs and switching costs of residential, commercial and industrial customers during permanent faults are derived from a utility customer cost damage function shown in [20], which was relevant in Canada in 1998.
- The cost of an interruption for any type of customer during a permanent fault is assumed to be one dollar.

- The permanent and temporary failure rates of each section of the feeder must be known. In this study, the permanent and temporary failure rates were assumed to be equal for every section of the feeder. If the failure rates on every section are assumed to be equal, the length of the section is what determines which section has a higher probability of faults.

A considerable amount of data is required and a number of assumptions need to be made to ensure the accuracy of the calculated cost of interruptions. The cost of interruptions is not directly proportional to SAIDI, although both indices are dependent on the duration of an outage. In calculating the cost of interruptions, distinguishing the type of customer is important, whereas SAIDI only considers the number of customers. Recloser placement, based on the minimisation of the cost of interruptions, would give higher priority to commercial customers in comparison to residential customers due to the difference in cost according to the customer cost damage function shown in [20]. The minimisation of the cost of interruption would thus not imply the minimisation of SAIDI.

2.3.2 Cost

The cost of the protective devices to be installed is considered as a factor in the objective function [6], [7], [11] and [14], where the tradeoff between the cost of a recloser and the value of lost load is evaluated. The cost factor limits the number of reclosers on the network. It opposes the tendency of the reliability factors to increase the number of reclosers. The results of [6] show that the addition of a recloser at a specific position is only justified if the reduction in the risk of an outage scenario is high enough. The practical limitation of installing many reclosers is cost and the co-ordination between the reclosers [6], [10].

2.3.3 Co-ordination between the reclosers

The co-ordination between reclosers is not a common factor considered in many recloser placement studies. Authors in [6] acknowledge the problem of co-ordination between reclosers as a constraint that must be considered in the future. In [10], all possible combinations of placement where co-ordination is not possible must be identified

beforehand and the constraint of allowing a maximum of one recloser in both positions simultaneously is applied to the problem. The method of identifying recloser positions where co-ordination is not possible is not discussed in [10]. The automatic identification of these points is not discussed in [10], implying a manual process of identifying potential recloser positions that may not allow sound co-ordination between reclosers. The algorithm in [10] is tested on a hypothetical network, which is considerably simpler than an actual network. The identification of recloser positions that may not grade on a real network is impractical.

Table 2.1. Summary of recloser placement studies

Reference	Purpose	Candidate points for the placement of reclosers	Optimisation method	Factors considered in objective function	Data required for variables
[6]	Develops a technique to determine the most feasible number and location of reclosers to be installed.	Manually selected points were limited to the main line and secondary lines	Cost analysis	<ul style="list-style-type: none"> Investment costs Risk of an outage scenario 	<ul style="list-style-type: none"> Probabilities of a fault on a section of a feeder, which is dependent on the length of the section Cost of the outage, which is dependent on the load connected to the section Network topology Cost of reclosers
[7]	Presents a method to determine the optimal placement of control and protective devices on radial distribution feeders.	<ul style="list-style-type: none"> Main line and beginning of long secondary branches Beginning of branches with loads that can suffer reclosing effects and classified as special or areas subjected to a high number of temporary faults and that can suffer reclosing effects 	Reactive tabu search algorithm	<ul style="list-style-type: none"> Investment cost Cost of interruptions 	<ul style="list-style-type: none"> Connected load Permanent and temporary fault rates Costs associated with individual customer interruptions Network topology Cost of reclosers

[8]	Presents the optimisation of recloser placement to improve reliability	Main line and the beginning of all branches on the feeder	Genetic algorithm	<ul style="list-style-type: none"> • SAIFI • SAIDI • MAIFI 	<ul style="list-style-type: none"> • Failure rates • Connected customers • The restoration time for each interruption event • The number of interrupting device operations
[10]	Develops a method to determine the type and location of protective devices on a distribution feeder in order to minimise SAIFI.	Main line and the beginning of all branches on the feeder	Binary programming	<ul style="list-style-type: none"> • SAIFI 	<ul style="list-style-type: none"> • Connected load • Permanent and temporary fault rates
[11]	Presents a technique for sectionalising device placement in order to minimise customer interruption and investment costs.	Main line and the beginning and end of each section of the branches on the feeder	Simulated annealing	<ul style="list-style-type: none"> • Investment costs • Maintenance costs • Outage costs 	<ul style="list-style-type: none"> • System data • Failure rates • Repair times of the components • Customer cost interruption data • Cost of reclosers
[16]	Investigates the difference between the results of 3 different optimisation methods applied to the problem of recloser placement.	Main line and secondary branches	<ul style="list-style-type: none"> • Modified drop heuristic • Back parse method • kVA.km method 	<ul style="list-style-type: none"> • Inconvenience to customers 	<ul style="list-style-type: none"> • Fault rate • Line length • Customer numbers • Customer demand

2.4 DISTRIBUTION FEEDER PROTECTION

2.4.1 Protection of MV distribution feeders

Transient faults account for 70% to 80% of all faults on overhead distribution networks [6]. Typical causes of transient faults are lightning, phases in contact with each other due to windy conditions and contact with objects. These faults are temporary in nature and are normally cleared after one operation of the protective equipment, eliminating prolonged outages on the distribution system.

Typical causes of permanent faults are downed wires or tree branches making contact with the wires. The protection installed on the network isolates the fault and the equipment must be repaired before the supply is restored to the isolated portion of the network. Reclosure on permanent faults causes further damage to the network.

Every electrical utility has a protection philosophy that is used as a guideline for the application of protection settings. Protection philosophies for every piece of equipment are extensively explained in [17]. The application of the protection philosophies fulfils the purpose of protection which is to maintain the continuity of supply, to minimise damage and repair costs and to minimise risk to life. The protection settings of reclosers have a significant impact on the results of this study and will be further elaborated on in Chapter 3.

2.4.2 The impact of ineffective protection settings

Ineffective protection settings may result in unnecessary loss of supply, increased damage and repair costs and may pose a risk to life. Damage and risk to life are focussed on in this section.

Protection settings that are excessively delayed or that fail to detect a fault could cause the components of the feeder to overheat, resulting in permanent damage. The allowable sag, annealing, long term creep and the reliability of joints have an impact on the maximum

temperature at which a conductor can safely operate [21]. Permanent sag increases due to creep elongation of the conductor. This accumulates over time. The sag of an overhead line is determined as a function of the thermal-mechanical parameters of the installed conductor and the conductor temperature [22]. The conductor elongates during the metallurgical creeping of aluminium [22]. As a result, conductor sag increases which in turn reduces the clearance distance of the conductor to ground. Excessive sag can violate minimum statutory clearance requirements as it poses a risk to human lives and to the environment [21]. As the clearance distance between the conductor and ground reduces, the probability of instances of faults on the network will increase, which will have a negative impact on SAIDI and SAIFI.

In [23], the heat stored in the conductor is equated to the heat gained from the fault current and solar radiation less the heat lost from radiation and convection. The effect of the calculated temperature is used to determine an elongation model due to creep [22]. The model is dependent on temperature, mechanical tension, the time period and material coefficients. The only controllable parameter from the elongation model is the time duration that the conductor is exposed to the fault current. The ideal settings of protective devices must be sensitive enough to detect faults and trip fast enough to avoid elongation of the conductor.

The 1 s current rating of an overhead conductor is the maximum short-circuit current that the line can withstand for one second. This is derived from the temperature limit of the specific equipment. Permanent damage occurs wherever the energy exposure level or the let through energy exceeds the short time withstand rating of the conductor [22]. Equation 2.3 expresses the energy exposure of an overhead line as defined in [24]-[25].

$$E = I^2 t \quad (2.3)$$

where E is the energy exposure, I is the fault current and t is the duration of the fault current.

This equation is applicable to adiabatic conditions where the loss of heat due to radiation and convection are assumed to be insignificant due to the short time period of the fault current.

From Equation 2.3, the time that the conductor is exposed to the fault current is the only parameter that can be controlled without making any modifications in primary plant. A fault current limiter could be installed to reduce the fault current, but would require further investment. The time period the line and its components are exposed to the fault current is dependent on the settings of the protective devices (e.g. reclosers). The settings philosophy applied to the reclosers has a significant impact on the energy exposure of the feeder.

The energy exposure is most significant in the portion of the feeder closest to the source, where the fault current of the feeder is highest and where the energy limit could possibly be exceeded. The trip time has a significant effect on the energy exposure at high fault levels, near the source.

2.5 SOFTWARE IMPLEMENTATION

Most of the previous studies have been implemented in Matlab or optimisation packages specialised in the implementation of the optimisation methods discussed in Section 2.2. Due to the additional consideration of the damage factor on recloser placement, the ability to model real networks with the parameters of the actual conductor type is required since the fault level at each point of the network is a potential variable of the objective function. The implementation of a real network in Matlab is complex as each component must be modelled from first principles.

DIgSILENT PowerFactory is the simulation tool widely used in electrical utilities for modelling, analysis and simulation of the power system. It has an extensive database of electrical components, enabling the modelling of the network with the required parameters, such as the impedance of the line, based on the conductor type selected for the line. The provision of applying the relevant protection settings on reclosers modelled at specific

positions on the network allow for the protection-related factors to be assessed at each point on the network. This makes this tool the preferred option for the implementation of the algorithm.

2.6 CHAPTER IN PERSPECTIVE

The literature survey has provided background on how previous studies have approached the optimisation of recloser placement. None of the previous studies identified in the literature survey have attempted to include the effect of recloser placement on protection performance of a feeder. Consequently, the proposed approach seeks to give consideration to protection related factors in addition to the reliability and cost factors already considered in existing recloser placement studies. In this way, the damage to the network will be minimised.

The knowledge gained from previous studies is developed further in the detailed analysis of later chapters. Chapter 3 considers the protection settings philosophy that is implemented in the objective function and algorithm.

CHAPTER 3 PROTECTION SETTINGS

PHILOSOPHIES

Recloser placement has an impact on the application of suitable settings. In Section 2.3 it was seen that many authors on the topic of recloser placement focus on reliability and cost factors and have not considered the impact of recloser placement and numbers on protection settings. Sound understanding of protection settings philosophy for the MV distribution network is required for the development of the objective function detailed in Chapter 4 and for the implementation of the chosen optimisation method, which is described in Chapter 5.

3.1 RECLOSER SETTING PARAMETERS

Every recloser has a current pick-up and a time multiplier (TM). The current pick-up is the recloser setting at which, when exceeded, the recloser will operate or begin timing out. The time multiplier is the setting which determines the time that must lapse before the relay trips once the fault is detected. The manipulation of this setting allows for time grading to be achieved in the network. The current pick-up controls the sensitivity of the recloser and the time multiplier controls the operating time of the recloser.

Typically, most reclosers are set using the Normal Inverse (NI) characteristic. The trip time (TT) of the NI curve is determined by Equation 3.1 [17],

$$TT = \frac{0.14 \times TM}{\left(\frac{I_{\text{fault}}}{I_{\text{PU}}}\right)^{0.02} - 1} \quad (3.1)$$

where TT is the trip time of the recloser, TM is the time multiplier, I_{fault} is the fault current and I_{PU} is the current pick up setting.

From Equation 3.1 and Figure 3.1, it is evident that the trip time of the recloser reduces exponentially as the fault current increases if the recloser is set to a Normal Inverse or NI characteristic.

Reclosers with a definite time characteristic are set to trip after a specific time delay irrespective of the fault current. The difference between the Normal Inverse characteristic and the definite time characteristic is shown in Figure 3.1.

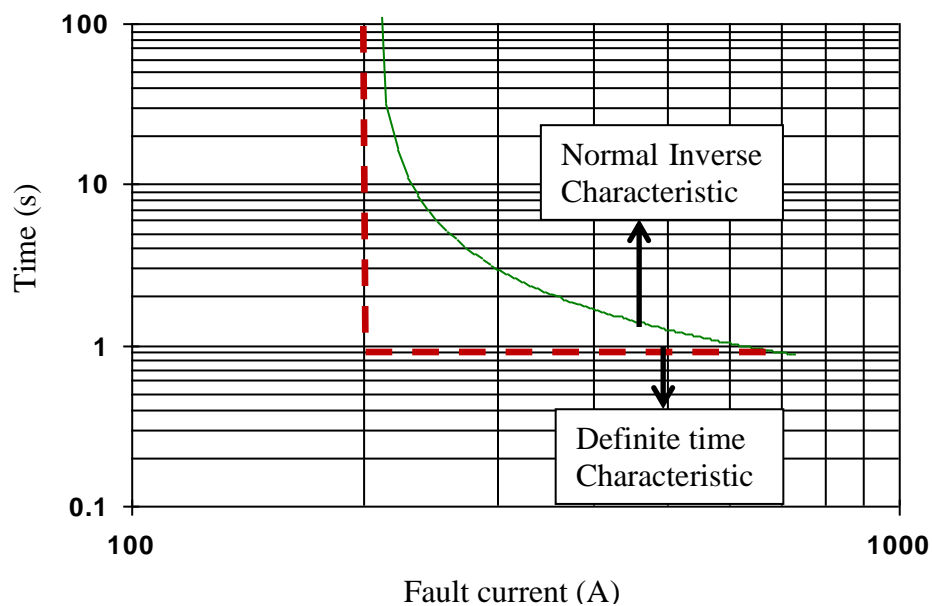


Figure 3.1. Normal Inverse and Definite Time Characteristic

Reclosers typically have overcurrent, earth fault and sensitive earth fault protection. Earth fault levels on the MV bus of the substations are low due to the installation of neutral earthing compensators, which limit the earth fault current nominally to 360 A per transformer [26]. Overcurrent fault current levels on the network vary according to the source impedance. As the source impedance reduces, the fault current will increase. The overcurrent element of a recloser, therefore, is considered to have a greater impact on the damage caused to the network due to the risk of exposing the network to high fault currents.

Overcurrent reclosers typically consist of the settings shown in Table 3.1.

Table 3.1. Summary of overcurrent elements on a recloser

Setting	Purpose
Delayed protection	<ul style="list-style-type: none"> Enables co-ordination between upstream and downstream devices
Instantaneous protection	<ul style="list-style-type: none"> Reduces damage caused by high fault currents; Prevents voltage depressions affecting customers on adjacent feeders
Autoreclose	<ul style="list-style-type: none"> Automatic restoration of supply if fault is temporary Automatic isolation of fault if fault is permanent

3.2 DELAYED PROTECTION SETTINGS

Suitable time-delayed overcurrent settings are applied to every recloser according to guidelines described in [17] and [27]:

- The pick-up should be set between 100 % and 120 % of the emergency rating of the conductor of lowest current rating within the overcurrent reach. The emergency rating is defined as the current rating at which the line can be safely operated during emergency conditions, without compromising the safety of the power line [28]. The purpose of overcurrent protection is to trip for faults and not for overload. Every feeder is designed with a conductor type suitable for the load requirements of the customers connected to it. If the recloser is set below the emergency rating of the conductor, there is a high probability that the feeder will trip for load conditions. This unnecessary loss of supply would negatively impact SAIDI.
- The pick-up should be sensitive enough to detect 80 percent of phase-to-phase fault current at the end of the intended reach, allowing for the bypassing of one immediate downstream recloser. Overcurrent protection must be sensitive enough to detect three-phase faults and phase-to-phase faults, which comparatively have a

smaller magnitude. Ensuring appropriate sensitivity to phase-to-phase faults would guarantee sensitivity to three-phase faults since the magnitude of phase-to-phase faults is always smaller than three-phase faults in MV distribution context. A safety margin of 80 percent is used in this case. The pick-up must also be low enough to detect all faults within the coverage of the immediate downstream recloser to cater for the contingency of the failure or the bypassing of the immediate downstream recloser. Figure 3.2 illustrates the furthest reach of recloser A. Recloser B must be able to detect faults at both Load 1 and 2, but if recloser B fails or is bypassed, recloser A must be able to pick up for a fault at both Load 1 and Load 2. Since the fault level is lower at Load 1 in comparison to Load 2, the pick-up must be set to 80 percent of the phase-to-phase fault at Load 1.

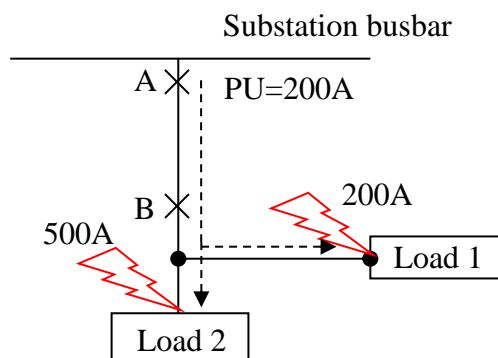


Figure 3.2. An illustration of the furthest reach

- The pick-up of a recloser must be set to 90 % of the pick-up of the upstream recloser. This ensures discrimination by current between two consecutive reclosers. The grading between two devices should be done at the maximum expected current at the point of overlap. Discrimination by time on radial networks is attained by setting the trip times of consecutive reclosers, such that the downstream recloser trips faster than the upstream recloser. The grading margin between reclosers is typically 400 ms - 500 ms due to circuit breaker operating times, recloser reset time, recloser overshoot and recloser time delay errors [27]. The required grading margin varies depending on the type of recloser that is

installed. The grading margin required between two numerical reclosers is 300 ms and between electromechanical reclosers is 400 ms.

The abovementioned guidelines can often be in conflict with each other and thus engineering judgement is required to decide on which criteria deserve precedence. An example of a conflicting situation is where the reach of a recloser is compromised to avoid load encroachment. From an operational and reliability perspective, ensuring that the line does not trip on load is critical. From a protection perspective, there is a small probability that some faults will not be detected, which could be a danger to human lives and to the equipment on the line. SAIDI and SAIFI will be negatively affected if precedence is given to the reach of the recloser and not to load encroachment. The structure of the feeder, the fault levels and recloser positions on the feeder have an impact on the existence of these situations of conflict between the criteria mentioned above. Of the abovementioned factors, the recloser number and positions can be varied to minimise the difference between the emergency rating of the line and the intended reach of the recloser. This will be discussed further in Chapter 5.

Various approaches exist in calculating the protection settings of reclosers on an MV distribution network. The bottom-up approach and the top-down approach are commonly used in utilities.

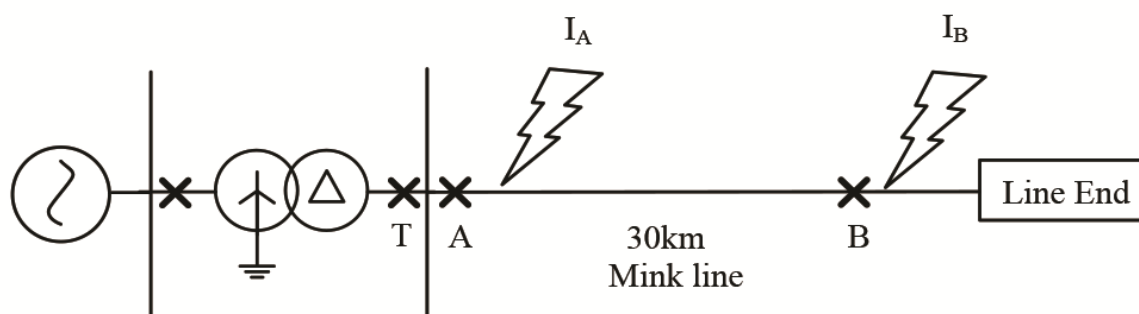


Figure 3.3. A sample feeder

The bottom-up approach entails setting the reclosers closest to the loads as fast as possible, with a minimum time multiplier. All upstream devices are graded with downstream reclosers. The trip time of the feeder circuit-breaker thus depends on the number of reclosers that need to be graded. The upper limit of the trip time for the feeder circuit-breaker is the trip time of the transformer minus the 400 ms grading margin. Recloser B in Figure 3.3 is set to a minimum time multiplier of 0.05 and the corresponding trip time for I_B is calculated. Recloser A should then be set to 400 ms slower than recloser B for I_B . The time multiplier of recloser A is calculated using Equation 3.1.

The top-down approach entails the setting of the feeder circuit-breaker 400 ms faster than the transformer's overcurrent protection at T in Figure 3.3. The transformer protection is typically set to 1.5 s for a busbar fault. All downstream reclosers are graded with upstream reclosers with a grading margin of 400 ms. Recloser A is set to trip in 1.1 s for a fault magnitude of I_A and the time multiplier is calculated using Equation 3.1. The trip time of recloser A is calculated for I_B . The time multiplier for recloser B is then calculated by setting the trip time 400 ms faster than the calculated trip time of recloser A for I_B . Recloser A should then be set to 400 ms slower than recloser B for I_B . The time multiplier of recloser A is calculated using Equation 3.1.

Although both methods of co-ordination are used commonly in utilities, the bottom-up approach allows less energy exposure than the top-down approach as the trip times of all reclosers are set as fast as possible.

3.3 INSTANTANEOUS PROTECTION SETTINGS

Most overcurrent reclosers are fitted with a high-set instantaneous element. Although the high-set is configured to trip instantaneously, the actual trip time is equivalent to the circuit-breaker operating time since the circuit-breaker is not capable of tripping instantaneously. The circuit-breaker operating time is defined as the time elapsed between the trip initiation and when the arc has actually been extinguished. The circuit-breaker operating time is assumed to be 80 ms [17].

The application of a high-set allows for a reduction in the tripping time at high fault levels. The instantaneous element or high-set on the feeder circuit-breaker is set so that it will not operate for the maximum through fault current seen by the successive recloser [17]. This philosophy ensures that the high-set will not trip instantaneously for faults beyond the successive recloser. A setting equal to 150 % of the fault current level at the downstream recloser position is assumed to cater for network modelling errors, recloser measurement errors and transient over reach [27].

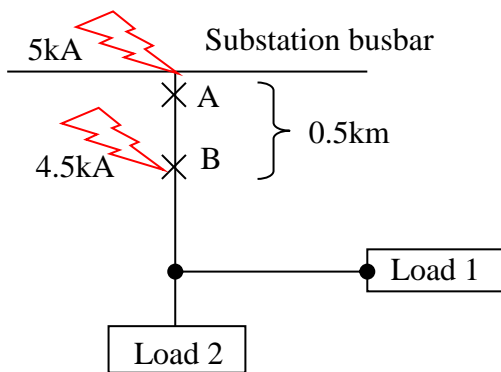


Figure 3.4. Case A: Application of a high-set

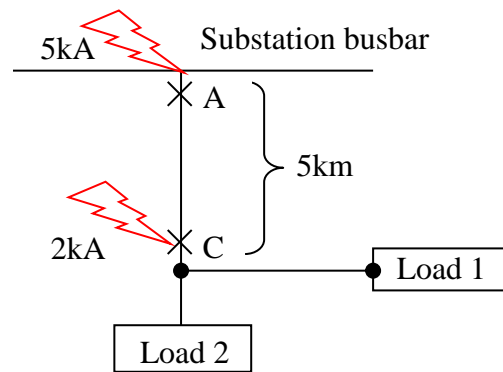


Figure 3.5. Case B: Application of a high-set

Instantaneous tripping is feasible only if there is a substantial increase in the magnitude of the short circuit current as the position of the short circuit moves from the downstream recloser towards the upstream recloser. The instantaneous high-set current pick-up of recloser A is set to either 150 % or 130 % of the fault level at the downstream recloser. If neither is possible due to small difference in fault currents, the high-set is deactivated. Figure 3.4 presents a situation where an instantaneous high-set cannot be applied to the feeder breaker since the fault level at A is only 10 % higher than the fault level at B. The instantaneous high-set of Recloser A in Figure 3.5 is set to 3 kA (1.5×2 kA). The location of downstream reclosers thus has an impact on the feasibility of the implementation of a high-set on reclosers.

The application of a high-set on the feeder breaker is very effective in reducing the let-through energy, where it is most critical. The lower the high-set is set, the lower the energy exposure of the feeder will be.

3.4 AUTO-RECLOSE PHILOSOPHY

A recloser is typically set to autoreclose twice in an attempt to re-establish connection. If the fault is detected even after the second autoreclose cycle, the recloser is set to lock-out, with no further attempts to re-establish connection. The faulted part of the network would be isolated and the remainder of the network is kept intact. If the recloser locks out, the permanent fault must be physically repaired by a technician. Inspection of the line beyond the recloser to locate the faulty portion of the line is time-consuming.

An auto-reclose philosophy of three trips to lock-out is assumed. This implies that the feeder will be exposed to a permanent fault current three times consecutively until the recloser locks out. It is assumed that the conductor will not dissipate heat significantly over the short time span of the auto reclose deadtimes. The energy exposure of a feeder for a permanent fault is thus three times that of a transient fault that is cleared with one auto-reclose cycle. A success rate of 89 % is reported for the first shot, 5 % for the second and 1 % for the third in [29]. All faults expose the network to the fault current till the first trip of the circuit. If a success rate of 89% is reported for the first shot, it implies that the remaining 11% of faults will remain on the network till the second trip. From the 11% of faults remaining on the system after the second trip, only 5% of faults will be cleared, implying that 6% of faults will remain on the network until the third trip. Using this as an assumption, the energy exposure for a fault at a specific point on the network is calculated as follows.

$$\begin{aligned}
 E &= (100\% \times I^2 t_1) + ((100\% - 89\%) \times I^2 t_2) + ((100\% - 89\% - 5\%) \times I^2 t_3) \\
 &= (100\% \times I^2 t_1) + (11\% \times I^2 t_2) + (6\% \times I^2 t_3)
 \end{aligned}
 \tag{3.2}$$

where E is the energy exposure, I is the short-circuit current and t_n is the duration of the short-circuit current with $n =$ trip 1, 2 or 3 respectively.

3.5 CHAPTER IN PERSPECTIVE

The philosophy described in this chapter is applied to each recloser modelled in DIgSILENT PowerFactory. Compromises based on engineering judgement are not made

in the implementation of the tool and the most conservative setting is applied to each recloser in the network.

Chapter 4 entails the development of the objective function. The protection-related factors in the objective function are dependent on the protection philosophy discussed in this chapter.

CHAPTER 4 THE MODIFIED OBJECTIVE FUNCTION

Chapter 3 discussed the protection settings philosophy which is expected to affect the results of the optimisation algorithm due to the addition of protection-related factors in the objective function. Sections 4.1 and 4.2 introduce the protection-related factors, which have not been considered in previous studies for the optimisation of recloser placement. Sections 4.3 to 4.5 include details on the selection of the reliability and cost factors that have previously been considered. Modifications to the reliability factors are made to suit the implementation of the optimisation algorithm and availability of data. The objective function consists of five factors that need to be minimised by means of the optimisation algorithm. Each factor is discussed in detail in this chapter.

Since the aim of the optimisation algorithm discussed in Chapter 5 is to minimise the value of the objective function, the smaller the value of the objective function is for a specific number and placement of reclosers, the more favourable the specified placement of reclosers is. Each factor in the objective function is normalised against a measure that is considered to be the worst case scenario. A value of 1 for any individual factor would imply that the selected recloser placement is detrimental to that factor. The factors to be minimised are the damage factor, the recloser investment costs, the risk of outages in terms of customer numbers and load size, as well as the risk of nuisance tripping due to heavy load.

4.1 DAMAGE FACTOR

The damage factor, D , is equivalent to the energy exposure of the MV distribution feeder that is quantified by Equation 2.3. It is determined as a function of the magnitude of the short-circuit current and the duration of the fault. The duration of the fault at each point of the feeder is dependent on the placement of reclosers and the settings allocated to the reclosers.

Once the placement of reclosers on the network is implemented, the reclosers are set according to the philosophy described in Chapter 3.

The following assumptions are made in the process of setting the recloser:

- An auto-reclose philosophy of three trips to lock-out is assumed.
- If the high-set implementation on a recloser is feasible, the high-set is activated. If the high-set is activated on the recloser, the first trip would be instantaneous and the other two trips would trip with an NI characteristic. The instantaneous overcurrent element of the recloser is designed to operate with no intentional time delay when the current exceeds the recloser setting, but in reality there is a slight time delay due to the breaker operating time. The period of an instantaneous trip is assumed to be 80 ms for calculation purposes.
- All reclosers on the network are assumed to be numerical and thus a grading margin of 300 ms is applied between consecutive reclosers.
- The bottom-up approach is used to set the reclosers.
- The minimum value of the current pick-up obtained from the three criteria detailed in Section 3.2 is utilised as the current pick-up of the recloser. This results in the most conservative setting, which would ensure comprehensive protection of the feeder, but could result in tripping on load if the fault current at the intended reach of the recloser is very low.

In deriving the damage factor, understanding the concept of the direct length coverage of a recloser is required. The direct length coverage of the reclosers is illustrated in Figure 4.1. Section LC_A and LC_B are the length coverages of reclosers A and B. The time that section LC_A is exposed to a fault current is dependent on the settings applied to recloser A and the same applies for section LC_B .

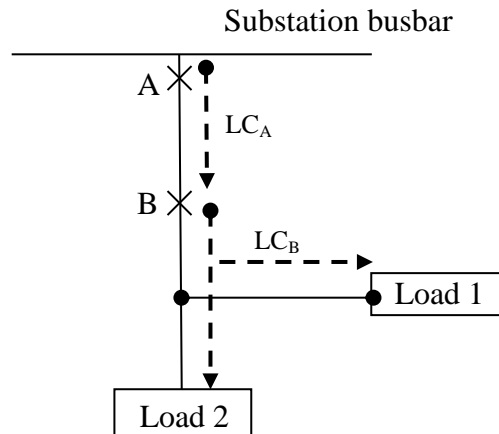


Figure 4.1. Illustration of the direct coverage of reclosers

Equation 4.1 is derived from Equation 3.2 and is applied to each recloser for the direct length coverage of the recloser.

$$D = \frac{1}{NF_1} \sum_{r_0}^{\eta} \int_{l_0}^{l_f} (I(l))^2 t_1(l) + 0.11 \times (I(l))^2 t_2(l) + 0.06 \times (I(l))^2 t_3(l) dl \quad (4.1)$$

Equation 4.1 can be discretized as follows. The energy exposure of the network is assessed at every 100 m of the network.

$$D = \frac{1}{NF_1} \sum_{r_0}^{\eta} \sum_{l_0}^{l_f} (I(l))^2 t_1(l) + 0.11 \times (I(l))^2 t_2(l) + 0.06 \times (I(l))^2 t_3(l) \quad (4.2)$$

where D is the damage factor, $I(l)$ is the short-circuit current at location l , r_0 is the first recloser, r_1 is the last recloser, l_0 is beginning of the length coverage of the recloser, l_f is the end of the length coverage of the recloser, $t_n(l)$ is the trip time of recloser r_n for a short-circuit current at location l with $n = \text{trip } 1, 2 \text{ or } 3$ respectively, NF_l is the normalisation factor.

Obtaining a normalisation factor for the damage factor is challenging as it is network dependent. The use of a constant value irrespective of the network would result in an

inconsistent weight of the damage factor. The normalisation factor NF_1 is set to the largest value for the damage function obtained from 200 simulated iterations of random placements of reclosers, where the recloser number is varied from the 2 reclosers to the maximum number of reclosers, specified by the user.

In the case of a recloser with the high-set element activated, Equation 3.2 can be simplified as:

$$\begin{aligned} E &= (100\% \times I^2 t_1) + (11\% \times I^2 t_2) + (6\% \times I^2 t_2) \\ &= I^2 t_1 + 0.17 I^2 t_2 \end{aligned} \quad (4.3)$$

where E is the energy exposure, I is the short-circuit current t_1 is the duration of the short-circuit current for an instantaneous trip and t_2 is the duration of the short-circuit current for a time-delayed trip.

If the high-set element is deactivated, Equation 3.2 can be simplified as:

$$\begin{aligned} E &= (100\% \times I^2 t_1) + (11\% \times I^2 t_1) + (6\% \times I^2 t_1) \\ &= 1.17 I^2 t_1 \end{aligned} \quad (4.4)$$

where E is the energy exposure, I is the short-circuit current and t_1 is the duration of the short-circuit current for a time-delayed trip.

4.2 RECLOSER PICKUP LIMITS

Minimising the difference between the emergency rating of the conductor and the recloser's time delayed current pick-up is vital for ensuring that the feeder does not trip on load. This factor is assessed to optimise the time delayed current pickup of reclosers by considering the philosophy to be sensitive enough to detect 80 % of phase-to-phase fault current at the end of the intended reach, allowing for the bypassing of one immediate downstream recloser. In Figure 4.2, recloser A must be able detect 80 % of phase-to-phase fault current at both Load 1 and Load 2. Since the fault current at Load 1 is smaller, the pickup of recloser must be set to the smaller value between the conductor emergency rating and 80 % of phase-to-phase fault current at Load 1. Assume that the feeder consists of Hare conductor, which has an emergency rating of 380 A. Although the conductor has the

capability to conduct 380 A, recloser A has to be set to 200 A, which is 80 % of phase-to-phase fault current at Load 1. This poses the threat of tripping on load.

With the addition of recloser B in Figure 4.3, the situation does not change, since the intended reach remains the same. This is due to the fact that the philosophy states that the bypass of the immediate downstream recloser should be catered for. Although recloser B will be set to detect a fault at Load 1, the case for when it is bypassed should be catered for.

With the addition of recloser B and recloser C in Figure 4.4, the intended reach of recloser A reduces from Load 1 to the location of recloser C. Recloser A should be set sensitive enough to detect a fault at recloser C, which is 400 A. Recloser A can be set to the emergency rating of the line, since the intended reach of the recloser is not a constraint anymore. Tripping for load conditions would not be an issue in this case.

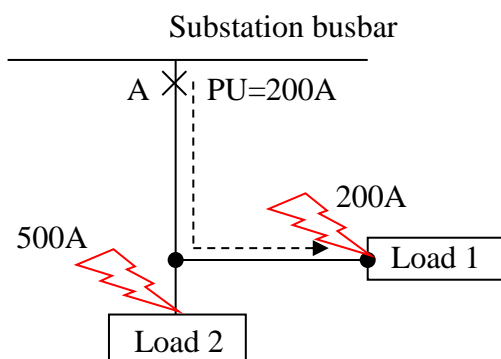


Figure 4.2. Furthest reach illustration with one recloser

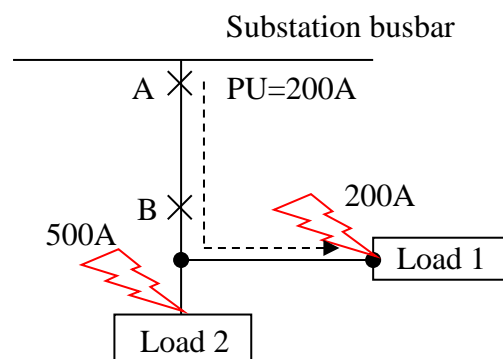


Figure 4.3. Furthest reach illustration with two reclosers

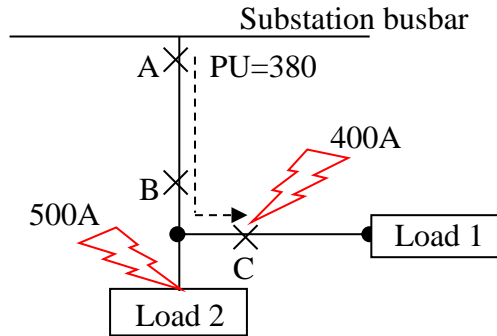


Figure 4.4. Furthest reach illustration with three reclosers

Setting the feeder breaker below the emergency rating of the conductor type has a ripple effect on the current pick-up of all downstream reclosers since all downstream reclosers must be set lower than the current pick-up of the feeder breaker to ensure grading by current.

Equation 4.5 shows the pickup limit factor of the objective function.

$$PU_{\text{limit}} = \frac{1}{NF_2} \sum_{r_0}^{r_n} \frac{LR - PU_r}{LR} \quad (4.5)$$

where PU_{limit} is the pickup limit factor, LR is the line rating of the conductor connected to the recloser, PU_r is the time delayed current pickup of the recloser, NF_2 is the normalisation factor, r_0 is the first recloser and r_n is the last recloser.

The normalisation factor NF_2 , is fixed at 0.5 as it is considered to be the worst case scenario. The worst case scenario is assumed to be when the difference between the emergency rating of the conductor and the recloser's current pick-up is 50% of the emergency rating.

4.3 RECLOSER INVESTMENT COSTS

The recloser investment cost, C , is determined by the ratio of the number of reclosers on the network to 10 reclosers. Equation 4.6 shows the investment cost factor of the objective function.

$$C = \frac{n_{sel}}{NF_3} \quad (4.6)$$

where n_{sel} is the actual number of reclosers allocated to the feeder and NF_3 is the normalisation factor.

The normalisation factor NF_3 is set to 10, as an investment of 10 reclosers is considered expensive on any feeder.

4.4 RISK TO CUSTOMERS

The assessment criterion of the risk to customer is based on the method used in [6]. A slight modification to the input of the equation is made in order to cater for the customer data that is available. The risk of outages in [6] is represented by Equation 4.7.

$$R_{cust} = \sum_{r_0}^{r_n} C_{outage} \times P_{fault} \quad (4.7)$$

where R_{cust} is the risk of an outage scenario on customers, C_{outage} is the cost of the outage as a result of a tripped recloser, P_{fault} is the probability of a fault on the line coverage of the recloser, r_0 is the first recloser and r_n is the last recloser.

In [6], the monetary value of the load lost is the data input at each load position. In this study, the number of customers is used as the data input at each load position. The probability of a fault occurring within a recloser's coverage is the quotient of the recloser's coverage portion of the feeder in terms of length and the total length of the feeder. This assumption is also applied in this study.

The risk of an outage scenario on customers, R_{cust} , is determined as a function of the probability of a fault occurring within a recloser's coverage and number of customers affected by the trip of a specific recloser, which is normalised to the total number of customers connected to the feeder. This factor is dependent on the recloser number and its location on the feeder. Equation 4.8 shows the customer risk factor of the objective function.

$$R_{\text{cust}} = \sum_{r_0}^{r_n} \frac{C_{\text{affected}}(r)}{C_{\text{total}}} \times \frac{L_{\text{coverage}}(r)}{L_{\text{total}}} \quad (4.8)$$

where C_{affected} is the number of customers affected as a result of a tripped recloser, C_{total} is the total number of customers, L_{coverage} is the length of the feeder for which the recloser provides direct protective coverage, L_{total} is the total length of the feeder, r_0 is the first recloser and r_n is the last recloser.

There is no need to normalise this factor as the worst case scenario of this factor is when there is only 1 recloser and all customers are disconnected should there be a fault anywhere on the network. The value of the risk factor is 1 in this case.

Minimising the risk of an outage scenario on customers ensures the minimisation of both SAIFI and SAIDI. The relationship between these factors is investigated further in Sections 4.4.1 and 4.4.2.

4.4.1 Impact on SAIFI

Equation 4.8 is compared to Equation 2.2 to show the relation between the risk of the loss of customers, R_{cust} , to SAIFI. SAIFI is dependent on the failure rate of equipment. A failure rate on a piece of equipment, λ , is defined as the number of failures in a period and is based on historical records of the network. The comparison of equations 4.8 and 2.2 reveal that the two measures are proportional to each other since the failure rate and the probability of faults are proportional to each other. The ratio of the number of customers

affected to the total number of customers is common to both equations. Minimising the risk to customers, R_{cust} , would thus minimise SAIFI at the same time.

4.4.2 Impact on SAIDI

SAIDI is dependent on the repair time of an interruption event at any point in the network. The repair time is generally dependent on the time taken to travel to the location of the recloser, to patrol the line beyond the recloser, to find the fault and to repair it. Of these four parameters, the only parameter that is dependent on the recloser placement is the time taken to patrol the line beyond the recloser that tripped. The time taken to patrol the line is directly proportional to the length of the line beyond the recloser, which is equivalent to the line coverage of the recloser.

The ratio of the customers connected to the section of line and the total number of customers is common to both Equations 2.1 and 4.8. Since the time taken to patrol the line is directly proportional to the length coverage of the recloser, SAIDI and the risk of an outage scenario for customers, R_{cust} , are proportional to each other. Minimising the risk of an outage in terms of customer numbers would thus minimise SAIDI.

4.5 RISK TO LOADS

Section 4.4 considers the risk to customers, irrespective of the size of the load. This factor caters for points on the network that do not necessarily have a high number of customers connected to it, but may have a large load connected to it. Customer numbers and the load size are not always directly proportional to each other and thus if priority needs to be given to large customers in terms of load size, the factor R_{load} will cater for this need. R_{load} , the risk of an outage scenario on loads, is determined as a function of the probability of a fault occurring within a recloser's coverage and load affected by the trip of a specific recloser, which is normalised to the total load connected to the feeder. The probability of a fault occurring within a recloser's coverage is dependent on the recloser's coverage portion of the feeder in terms of length and the total length of the feeder. Equation 4.9 shows the load risk factor of the objective function, R_{load} .

$$R_{\text{load}} = \sum_{r_0}^{r_n} \frac{kVA_{\text{affected}}(r)}{kVA_{\text{total}}} \times \frac{L_{\text{coverage}}(r)}{L_{\text{total}}} \quad (4.9)$$

where kVA_{affected} is the load affected as a result of a tripped recloser, kVA_{total} is the total load, L_{coverage} is the length of the feeder for which the recloser provides direct protective coverage, L_{total} is the total length of the feeder, r_0 is the first recloser and r_n is the last recloser.

There is no need to normalise this factor as the worst case scenario of this factor is when there is only 1 recloser and all loads are disconnected should there be a fault anywhere on the network. The value of the risk factor is 1 in this case.

4.6 OBJECTIVE FUNCTION

The total objective function combines equations 4.2 and 4.5, 4.7, 4.8 and 4.9. Weighting factors are added to the objective function to allow the user to apply various priorities on each factor. The objective function is as follows.

$$\min \quad J = w_1 D + w_2 C + w_3 R_{\text{cust}} + w_4 R_{\text{load}} + w_5 PU_{\text{limit}} \quad (4.10)$$

where w_1, w_2, w_3, w_4, w_5 are weighting factors that represent how the utility prioritises the respective criteria of minimisation of damage, investment costs, the number of customers affected, the size of the load affected and tripping on load respectively. D is the damage factor, C is the investment cost, R_{cust} is the risk of customer outages, R_{load} is the risk of load outages and PU_{limit} is the pick-up limit.

The system performance is determined by the result of the objective function, which is described in equation 4.10. The objective function is considered as the fitness function of this algorithm. The optimisation involves the adjustment of the recloser positions in order to minimise the five factors. In this way, the system performance is maximised.

4.7 CHAPTER IN PERSPECTIVE

The objective function described in this chapter is calculated for each combination of recloser placement in the processing of the optimisation algorithm, discussed in Chapter 5. It consists of five unrelated factors that are normalised to the worst case scenario. It is an improvement on the existing methods by way of its ability to:

- Include the effect of recloser placement on protection-related factors, in addition to reliability and cost factors.
- Allow the user to specify a weighting on each factor in the objective function based on the user's priority for each factor.

Since the aim of this study is to minimise the factors considered in the objective function, the recloser placement that produces the smallest value of the objective function is the optimal solution. The objective function is considered to be balanced and recloser positions that are favourable for reliability may not produce a favourable value for the objective function due to the addition of the protection-related factors to the objective function.

Chapter 5 explains the optimisation algorithm used to search the solution space to minimise the objective function. The general theory and the application of the genetic algorithm are elaborated upon in Chapter 5.

CHAPTER 5 APPLICATION OF A GENETIC ALGORITHM TO RECLOSER POSITIONING OPTIMISATION

The discussion of Chapter 4, regarding the objective function, will be used to measure the fitness of each candidate solution encountered in the optimisation process. Due to the extremely high number of combinations of recloser positions for various numbers of reclosers, the evaluation of every possible combination is not feasible. The implementation of an optimisation technique is thus required to explore the search space, without evaluating each combination in the search space. Various optimisation methods were analysed in Chapter 2 and the genetic algorithm was found to be suitable for the problem of recloser placement. Genetic algorithms tend to thrive in large search spaces that have many local maxima and minima. The general theory and the application of the genetic algorithm are explained in Sections 5.1 and 5.2.

5.1 THEORY

Genetic algorithms were created to mimic the process of evolution [18]. They are based on ideas of natural selection and genetics. Natural selection results in the ‘survival of the fittest’, as proposed by Charles Darwin. Where there is competition between individuals for any resource, the fittest individuals dominate over the weaker ones. The impact of genetics is that the fit individuals are considered to have ‘good’ genes and the offspring of two fit individuals have the possibility of being better than either parent. The phenomena of natural selection and genetics ensure the improvement of each successive generation.

The steps involved in the application of a genetic algorithm are as follows:

- A set of individuals is selected randomly from the search space. Each individual in this case would consist of a set of various recloser positions, which is a candidate solution.
- A fitness score, based on the objective function, is calculated for each individual. This represents the ability of an individual to compete or to qualify as a ‘parent’ for

the next generation. A predefined number of individuals with the highest fitness score are selected as parents. This process represents the survival of the fittest.

- The process of crossover is applied to the individuals that qualify as parents. Crossover represents mating between individuals, with high fitness scores. Firstly two parent individuals must be selected randomly and secondly, a random point of crossover must be selected. Figure 5.1 shows the process of crossover, where the randomly selected point of crossover is the third cell.

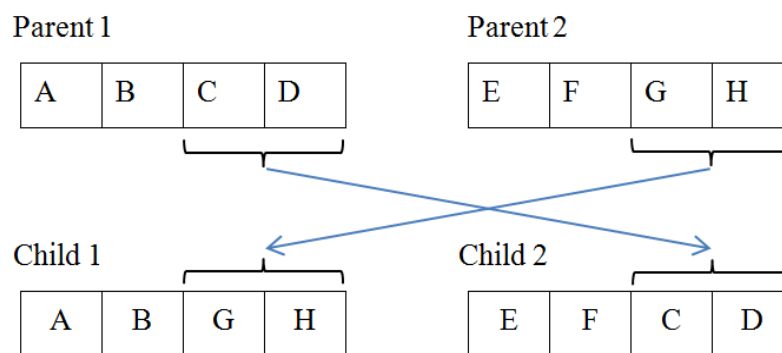


Figure 5.1. Illustration of crossover

Each cell of the parents represents a potential recloser position on the network. Binary crossover works by selecting a random cross point and then copying the data from one parent before the cross point and from the other parent after the cross point. Two children are created from each combination of parents. A new generation of individuals is created from this process.

- At times, the process of crossover results in individuals that already exist in the parent generation. The process of mutation is applied in these cases to introduce random modifications to the pool of individuals. A random position in the parent is selected to be replaced with a randomly selected recloser from the pool of all possible recloser positions.
- The fitness of the new generation is calculated and a predefined number of individuals with the best scores in the old generation and the new generation are stored as the new parent generation.

- This process is repeated until a certain number of generations are reached. The average fitness of each successive generation will tend to improve with the progression of this process of recombining portions of fit individuals.

Although genetic algorithms are randomised, they exploit historical data to focus the search into areas with superior performance within the search space.

5.2 THE APPLICATION TO RECLOSER POSITION OPTIMISATION

Two hundred random recloser placement combinations are created, protection settings are applied to each recloser in the set. A recloser model, which is available in the software package, is used on the network model. The relevant delayed and instantaneous protection settings are automatically applied to the recloser based on the philosophy detailed in Section 3.4. The process described in Figure 5.2 is applied to the feeder.

The genetic algorithm is not applied to the case where there are only one or two reclosers on the network since the search space is limited. The fact that there should always be a recloser at the substation implies there is only one solution in the case of the placement of one recloser. In the case where two reclosers are placed, there is only flexibility on the placement of the 2nd recloser. The fitness for every possible position of the 2nd recloser is assessed and the combination with the least value of the objective function automatically becomes the best solution for the case with only two reclosers. The genetic algorithm thus only caters for optimisation of recloser placement when the recloser count is three and above.

Figure 5.2 is a flow chart that describes the operation of the genetic algorithm.

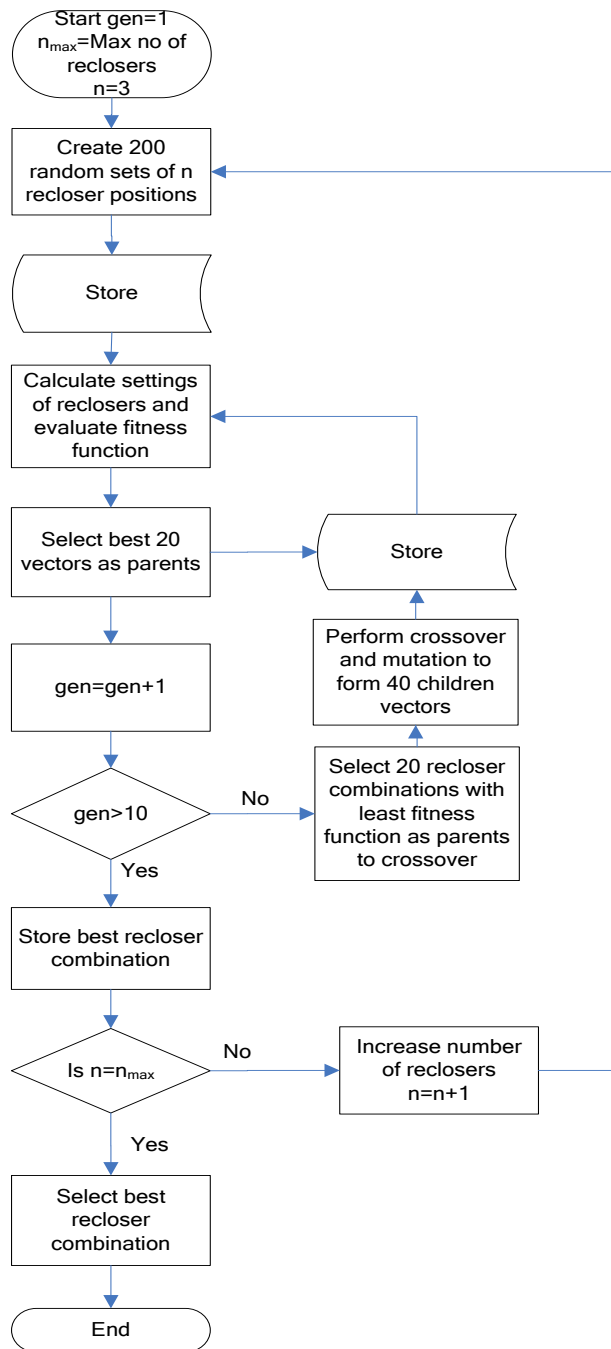


Figure 5.2. The operation of the genetic algorithm

The algorithm begins with randomly selecting 200 vectors, each consisting of n recloser placements on the feeder. Protection settings are automatically allocated to the reclosers based on the network structure and the recloser placement. The fitness function of each of

these vectors is evaluated and 20 vectors that have the minimum fitness value are selected and stored. The selected vectors are considered to be the parent vectors of the first generation of sequences created. The second generation of sequences is created by applying the process of crossover on the selected 20 parent vectors. The result of crossing over is 20 new vectors that are considered the children vectors. The children vectors are stored into the same matrix as the original parent vectors. The matrix now contains 40 vectors, consisting of 20 parent vectors and 20 children vectors. Twenty vectors with the least fitness function are selected from this matrix and form the parent vectors of the 2nd generation. Ten iterations will take place before the algorithm stops. The parent vector with the minimum fitness after 10 iterations is selected as the best recloser combination. The recloser number is increased and this process is repeated until the maximum number of reclosers, defined by the user is reached. The best results for each iteration done for each recloser number is compared and the option with the lowest objective function is deemed to be the best solution.

5.3 CHAPTER IN PERSPECTIVE

The method used for optimising the recloser placement based on the objective function discussed in Chapter 4 is presented in this chapter. The steps of the implementation of the genetic algorithm are discussed and the expectation of the algorithm is that it would converge to a solution where the overall value of the objective function is minimised. The individual factors of the objective function are not considered in isolation. If equal weightings are given to each factor in the objective function, there is a very low chance that any recloser position that is highly detrimental to a few factors in the objective function would be allowed to move to the next generation. This is due to the fact that the value of the objective function would be very high, lowering its chances of being selected as a parent for the next generation.

In Chapter 6, the integration of the tool created for the optimisation of recloser placement is discussed. The concepts discussed in Chapters 3, 4 and 5 are brought together in the implementation of the tool.

CHAPTER 6 INTEGRATION OF TOOL

The optimisation of recloser placement was implemented by applying a genetic algorithm to a specific feeder to minimise the value of the objective function discussed in Chapter 4. The aim was to create a generic tool that could be applied to any MV distribution feeder. The concepts explained in Chapters 3, 4 and 5 are to be applied to a real feeder.

The network model plays an important role in the results of the optimisation algorithm discussed in Chapter 5. In previous recloser optimisation studies, fault currents of the network were not considered and thus importance was not given to an accurate simulated model of the MV distribution feeder. Since the calculation of fault currents plays a pivotal role in the calculation of protection settings on the reclosers and for the calculation of the protection-related factors in the objective function discussed in Chapter 4, importance is given to the development of such a model of the feeder in DigSILENT PowerFactory.

6.1 NETWORK MODEL

Simplified models of the network were used in [6] and [11]. The use of simplified models of the network limits the number of potential recloser positions on the network. Most studies use the entire simulated network, but limit the potential recloser positions to the backbone and the beginning of secondary branches.

DigSILENT PowerFactory is a digital simulation and network calculation tool that is utilised to create the network model. A program was developed in DigSILENT PowerFactory to electrically model the network, based on the data provided, using the following components: source, terminals, lines and loads. Addendum B describes each program module of the created tool.

The following information is required for the program to create the network:

- An Excel spreadsheet with the pole numbers of every load on the network and the corresponding number of customers and load size, as shown in Addendum A, is

required. The pole number is the point at which a load is connected to the line. This file is to be kept open during the running of the program.

- The user is required to select the conductor type of the backbone and the branches of the feeder from the library of the software as shown in Figure 6.1. This is done on the ‘CreateNetwork’ module of the program.

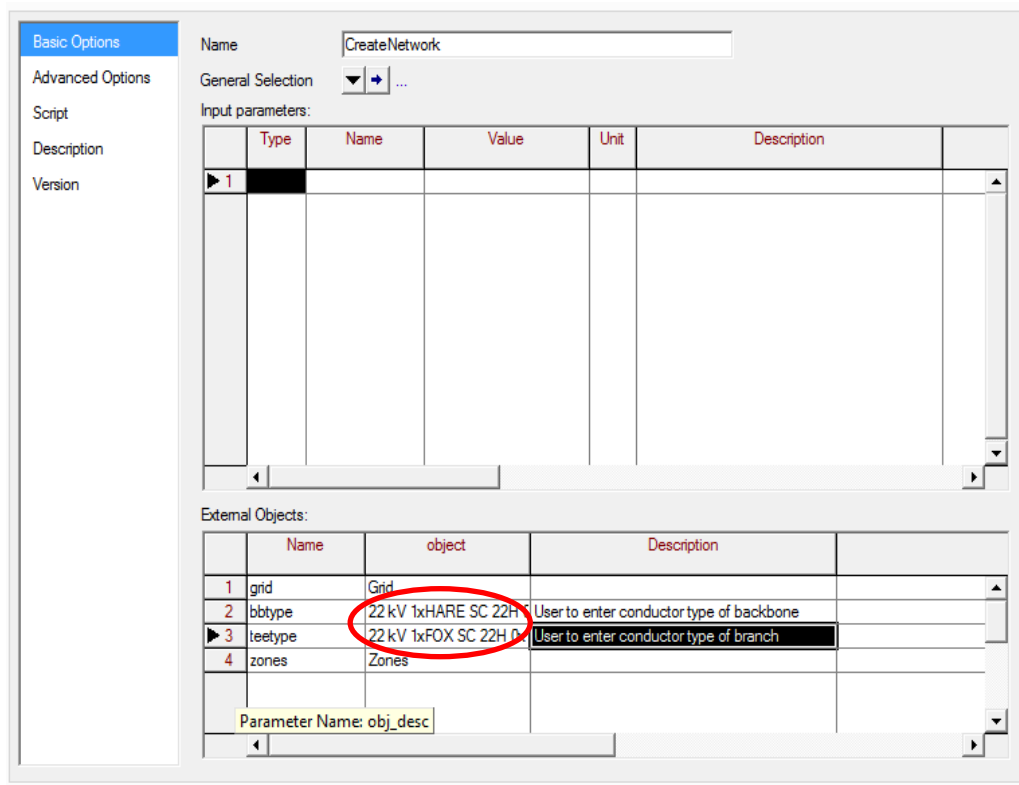


Figure 6.1. The selection of the conductor type for the backbone and the branches

- The user is required to enter the maximum number of reclosers to be considered in the ‘randRecloserPos’ module of the program. This is shown in Figure 6.2.

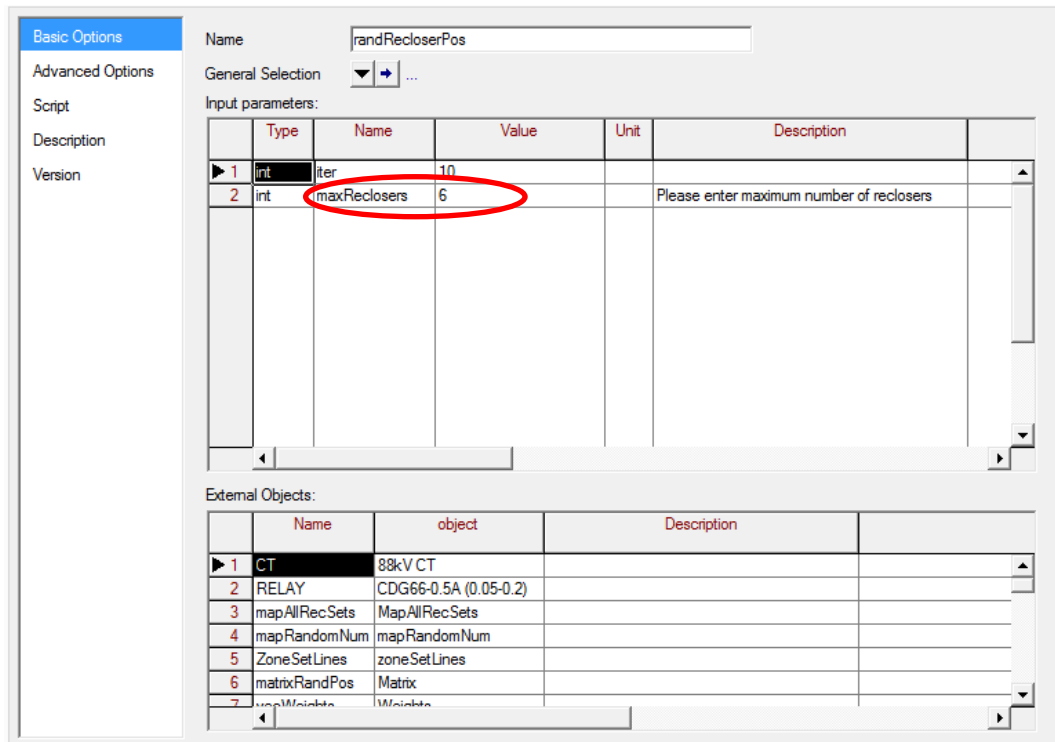


Figure 6.2. Display of where the user must enter the maximum number of reclosers to be considered.

The following information is requested as user inputs during the execution of the program to create the network:

- The first and last column of pole number information in the provided Excel spreadsheet is required. In Addendum A, the first column with pole number information is column 1 and the last column with pole number information is column 7.
- The column with the customer number data is required. In Addendum A, the column with this information is column 8.
- The column number of the load size data is required. In Addendum A, the column with this information is column 9.
- The fault level at the busbar of the substation is required.

The model of the network is automatically created in DIgSILENT PowerFactory once the program is executed, and fault simulations are possible at any point in this network. The

IEC60909 standard is used to simulate three phase faults throughout the network [30]. The fault study results are utilised in the allocation of relevant protection settings that are applied to each recloser on the network and to calculate the damage factor, discussed in Chapter 4.

The following assumptions are made in the creation of the network:

- The backbone of the feeder consists of a single conductor type and all the branches of the feeder consist of the same conductor type.
- The distance between each pole is 100 m. Using this assumption, the length of the conductor can be calculated. An example of the notation of a pole number describing the position of a load is 20/5, as shown in Figure 6.3. This shows that there is a secondary branch at the 20th pole (2 km) of the back bone. The stroke represents the position of the branch on the back bone of the feeder. The load is connected to the branch at its 5th pole (0.5 km). Using the assumption of the distance between each pole, the total distance between the load and the source can be calculated.

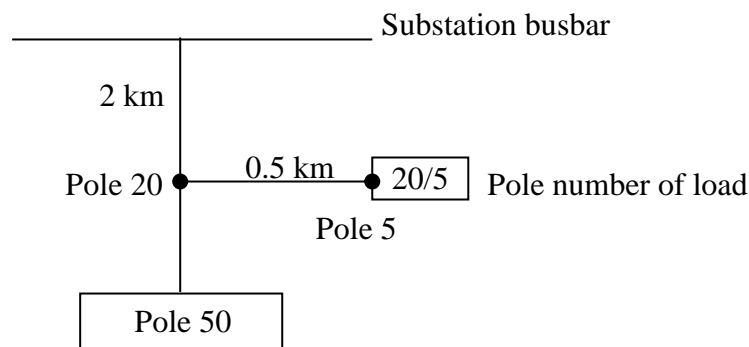


Figure 6.3. The figure shows the naming convention of loads on a feeder.

6.2 ALLOCATION OF LOAD TO TERMINALS

The sum of all loads and customer numbers beyond every terminal of the network is calculated and allocated to each terminal to identify terminals that have a high impact on the reliability of the network. From Figure 6.3, it is evident that the load and customer

number at Pole 20 is equivalent to the sum of the load and customer number at Pole 20/5 and Pole 50. Every terminal modelled in the network is allocated the number of customers and the load size that is connected to it, based on the data provided in the Excel spreadsheet shown in Addendum A. The values stored in each terminal of the network are utilised during the calculation of the objective function discussed in Sections 4.4 and 4.5.

6.3 DIVISION OF NETWORK INTO ZONES

The network is required to be divided into zones based on certain criteria. If a branch is identified as a zone, every terminal within the zone has the possibility of being allocated a recloser. The backbone is always considered as a zone, whether it meets the criteria or not.

In this study, an assumption is made that the length of any line is directly proportional to the probability of faults on the line. Only positions that would protect a line that has a reasonable probability of having faults is considered as a potential position for a recloser. The length of every branch is assessed and if it is longer than 10 km, the branch is stored as a zone. A separate zone is created for every 10 km of the branch since the maximum length for a zone is 10 km. The beginning terminal and end terminal of each section of line within a zone is considered as a potential position for a recloser.

This methodology does not limit the reclosers to be placed at the beginning of branches, as in [6]-[8], [11] and [16]. The beginning and end terminal of every section within a zone will be considered as potential positions for reclosers. Not only secondary branches will be considered as in [6] and [9], but all branches that meet the length criteria would qualify as a zone.

6.4 RANDOM ALLOCATION OF RECLOSERS

The maximum number of reclosers that can be allocated to any feeder is dependent on the user's input, but may be limited by the number of zones if the number of zones obtained from the network is less than the user's input. This is due to the fact that only one recloser can be allocated per zone. The random selection of a set of N reclosers is illustrated in Figure 6.4.

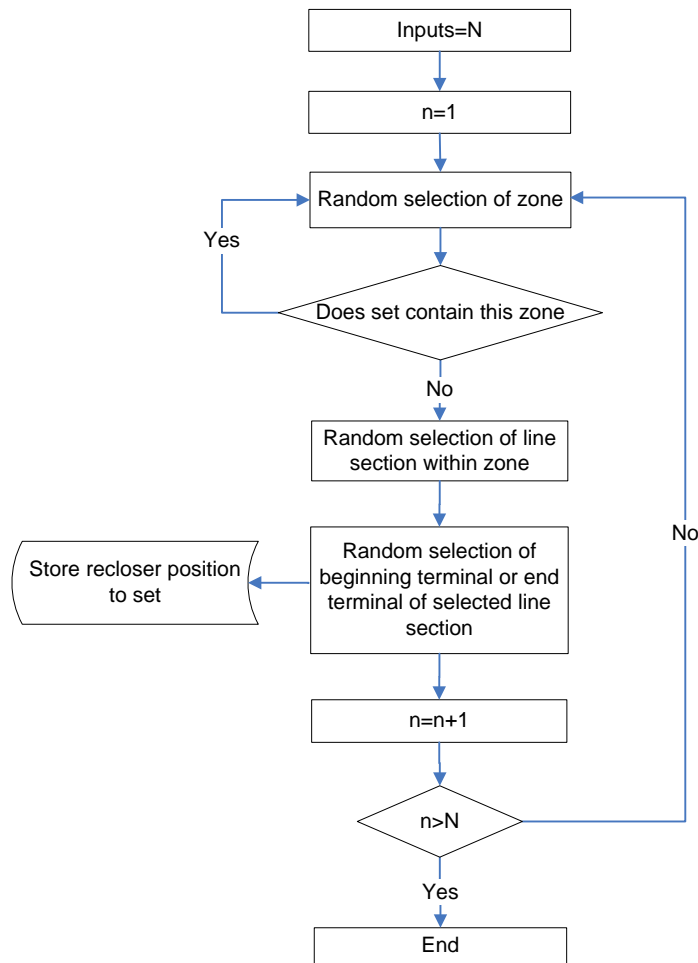


Figure 6.4. Flowchart of selection of random recloser positions

The random generation of a recloser set consists of the following processes:

- A zone is randomly selected. If the zone already exists in the set, another zone is randomly selected.
- A section of line within the zone is randomly selected.
- The beginning or end node of the selected section of line is randomly selected.

6.5 SIMULATION MODEL

The simulation model depicting each process that takes place in the optimisation of recloser placement is shown in Figure 6.5.

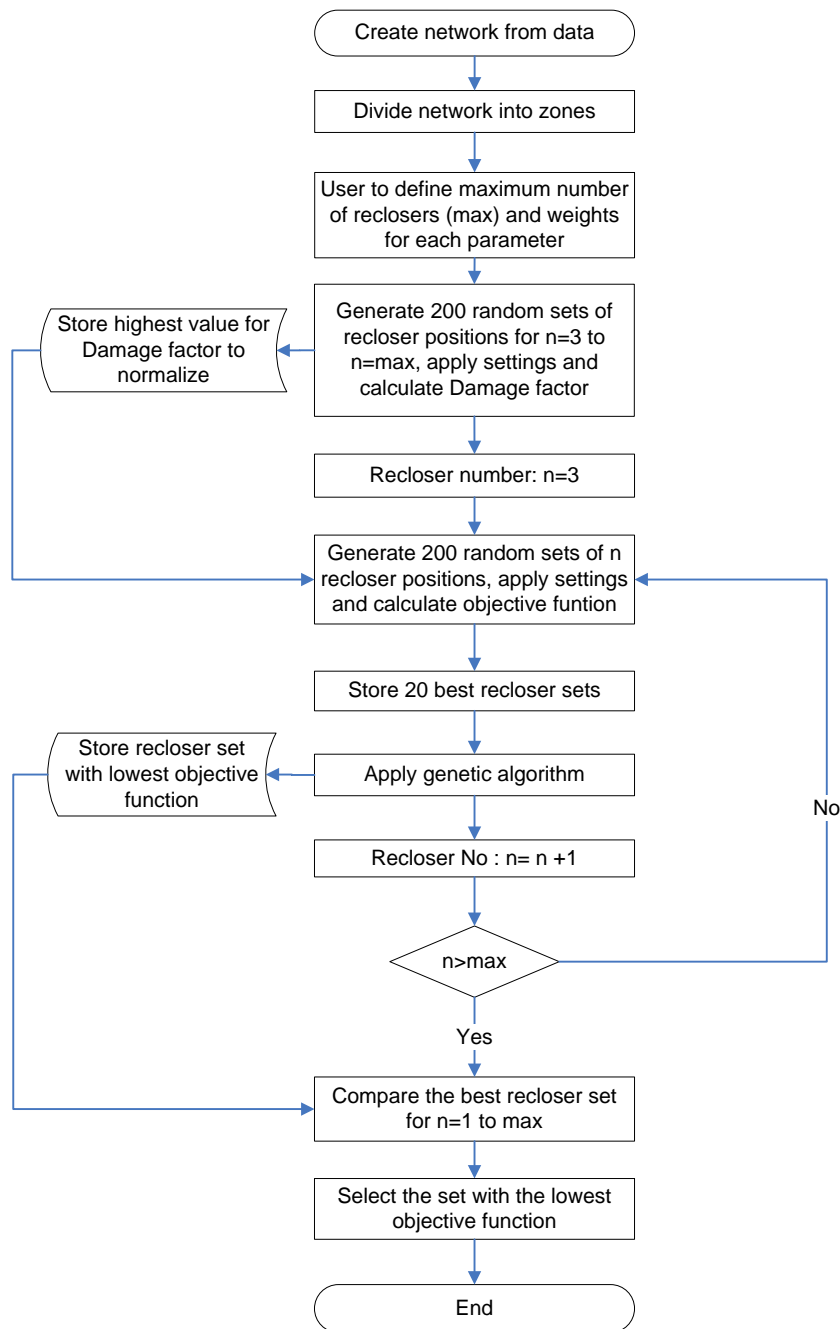


Figure 6.5. Flowchart of methodology used to obtain the optimal placement of reclosers

The tool created to optimise recloser placement implements the following steps for a given feeder:

1. The feeder is created from the data provided in the form of Addendum A and the user inputs that are stated in Section 6.1.

2. The network is divided into zones as per the criteria stated in Section 6.3.
3. The user will be prompted to enter the weightings for each factor in the objective function. These should be entered as per the priorities of the user.
4. 200 sets of recloser positions consisting of 3 reclosers each are created. Protection settings are allocated to each recloser in each set and the damage factor for each set is calculated and stored. The number of reclosers is incremented and the process is repeated until the recloser number is equal to the maximum number of reclosers specified by the user. The damage factors of all combinations of reclosers are assessed and the maximum damage factor is stored to use as the normalisation factor for the damage factor.
5. The number of reclosers, n , is initialised to 3 reclosers.
6. 200 sets of recloser positions consisting of n reclosers each are created. Protection settings are allocated to each recloser in each set and the objective function for each set is calculated and stored.
7. The top 20 recloser sets with the lowest value for the objective function are stored as the parent generation.
8. The genetic algorithm is applied to the parent generation identified in point 7. Refer to Figure 5.2 for details on the genetic algorithm.
9. After 10 generations, the best recloser set based on the set with the lowest objective function is stored as the best set of n reclosers for the priorities entered in point 3.
10. The number of reclosers, n , is incremented.
11. Processes 6-10 are repeated until the number of reclosers, n , exceeds the maximum number of reclosers specified by the user, max .
12. The best recloser sets stored for $n=3$ to $n=max$ are assessed and the set with the lowest objective function is deemed to be the overall best solution considering the weightings specified by the user in point 3.

6.6 CHAPTER IN PERSPECTIVE

The protection settings philosophy, the objective function and the genetic algorithm discussed in Chapters 3, 4 and 5 are integrated into the tool developed to optimise recloser placement. The tool is able to optimise recloser placement on any feeder that has the same

pole number naming convention as discussed in Section 6.1. The importance of the network model is emphasised to provide fault study results, which are required for the calculation of the protection settings applied to each recloser and for the calculation of the damage factor in the objective function. Chapter 7 validates the results of the tool and tests the tool on a real feeder.

CHAPTER 7 APPLICATION OF OPTIMISATION TOOL

The optimisation tool, discussed in Chapter 6, is validated in the first section of the present chapter to identify the individual impact of each factor of the objective function, discussed in Chapter 3, on the recloser placement. Thereafter, the tool is applied to a real feeder and the results are analysed and compared to the actual placement of reclosers on the network.

7.1 VALIDATION MODEL

The network model used for the validation of the tool is a hypothetical network. The algorithm is validated on a simple 11 kV network based on the following data.

Table 7.1. The positions of loads on a feeder

Loads	Pole number	kVA	Cust
1	5/1	500	50
2	6/2/75	1000	1
3	6/3/65	50	200
4	6/145	25	5
5	50/150	25	1
6	70/230	2000	300
7	90/1	25	1
Total		3625	558

The data in Table 7.1 can be visualised as in Figure 7.1. The conductor length between each pole is assumed to be 100 m. The fault level at the busbar is assumed to be 5 kA.

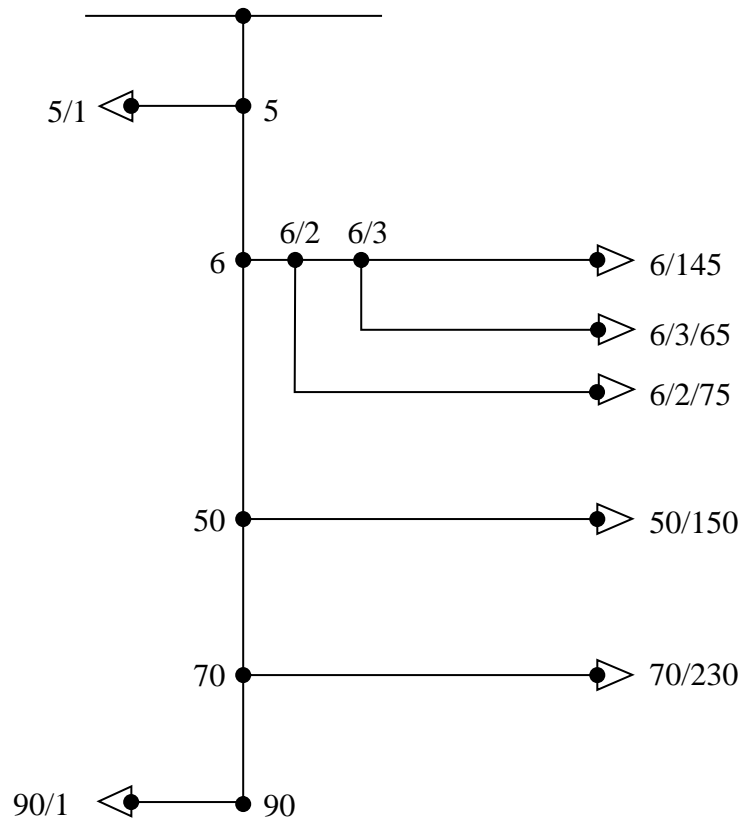


Figure 7.1. Hypothetical network

The backbone and branches of the feeder are considered as possible positions for reclosers, if the sum of all conductor lengths beyond the first node of the backbone or the branch is longer than 5 km. The maximum possible length for a zone is 10 km. If the branch is longer than 10 km, a new zone is created for every 10 km span of the branch. A zone can consist of several line segments. The starting point and end point of each line segment within a zone is considered as a possible position for a recloser. Ten zones are created from the network depicted in Figure 7.2. Branches from pole 5 and pole 90 are only 100 m and are therefore not defined as zones since placing a recloser at a position where the probability of a fault is low is ineffective.

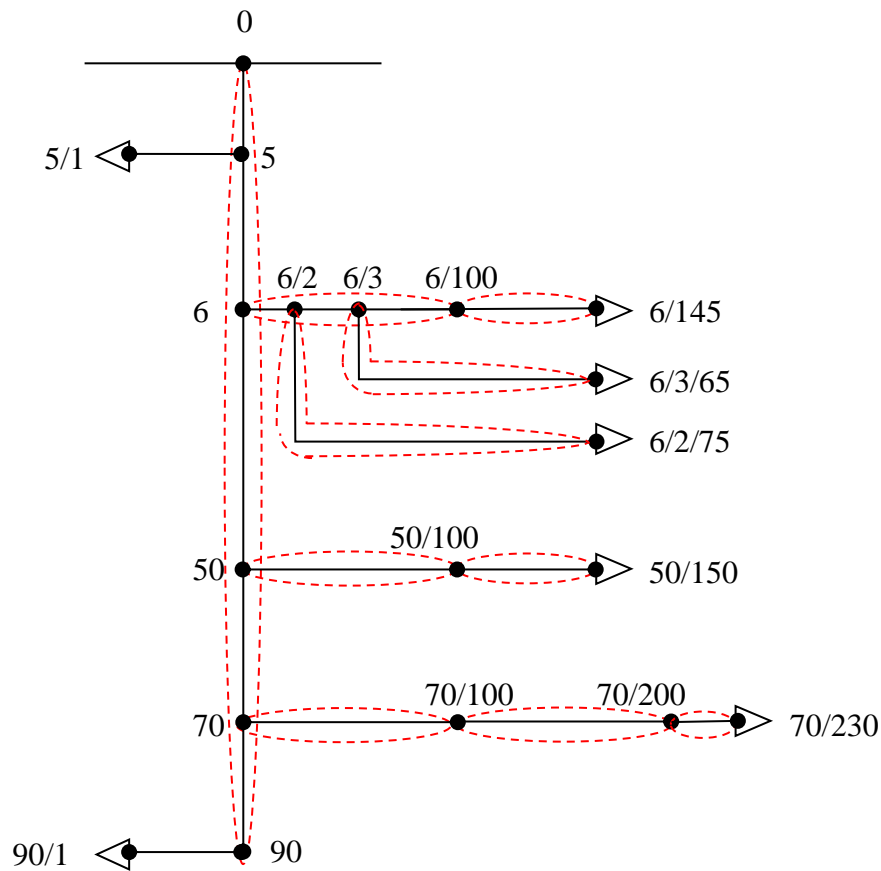


Figure 7.2. Division of network into zones

7.2 VALIDATION OF ALGORITHM

Each factor of the objective function is analysed in isolation from the other factors to validate that the tool reacts as expected. The results of the application of the tool to a hypothetical network can be analysed since it is simple, unlike the situation where the tool is applied to a real network where the solution space is vast.

7.2.1 Results of algorithm with high priority on cost

If cost is the only weighted parameter, the obvious solution would be to place the minimum number of reclosers. As the number of reclosers increases, the value of the objective function increases proportionally. The logical solution would thus be to place a single recloser at the feeder breaker.

This tool has not been designed to cater for obtaining the best recloser positioning or number for the case where cost is the only weighted parameter. The cost function is supposed to be used in conjunction with the other weighted parameters mentioned in this work. This is due to the fact that the algorithm cannot differentiate between different recloser placement options, since the objective function or the cost of all recloser combination sets with the same number of reclosers remains constant irrespective of where the reclosers are positioned.

7.2.2 Results of algorithm with high priority on load outages

High priority was given to minimise the risk of an outage scenario on loads connected to the network. The weight for the load outage was set to ten and all other weights were set to zero. The results of the tool suggested the following positions: Table 7.2. shows the overall best solution set of recloser positions.

Table 7.2. The solution set of recloser positions

Name	Recloser Positions	Load lost if recloser trips (kVA)	% Load lost	Length Coverage (km)	% Length Coverage
A	0-5 start	3625	100	0.7	0.92
B	6-50 start	2025	55.86	31.5	41.61
C	6-6/2 start	1075	29.66	0.2	0.26
D	6/2-6/3 start	75	2.07	28.3	37.38
E	50-50/100 start	25	0.69	15	19.82

Table 7.3. The optimal recloser positions for varied number of reclosers

No of Reclosers	Recloser Positions	Objective function value	Reduction in objective value
1	A	10	-
2	A,D	7.309	2.691
3	A,B,D	4.64	2.669
4	A,B,D,E	3.533	1.107
5	A,B,C,D,E	2.817	0.716

The results indicate that the maximum number of reclosers, prescribed by the user, will be selected to be the optimal number of reclosers. As the number of reclosers on the network increases, the risk of the loss of supply to customers reduces. The reduction in the value of the objective function, which represents the risk to the network, tends to become smaller as the number of reclosers increases.

From Table 7.3, it is evident that the addition of reclosers B, D and E has a significant impact on reducing the risk on the network. The percentage length coverage of the reclosers that have a significant impact is high. The percentage load that is dependant on reclosers D and E is very low, unlike recloser B, where it is high. Recloser C has a very small impact on the overall risk since it has a very low percentage length coverage and a high percentage load.

Reclosers should ideally be placed on spans that have a high probability of faults and where the percentage load connected to the recloser is low. This will ensure that a large percentage of the load will not be affected by a fault on the span of conductor whose probability of faults is high due to the large percentage length coverage of such a span. Placing a recloser at a position connected to 80 % of the load means that if there is a fault on the protected span of the feeder, only 20 % of the load remains unaffected which is not ideal. The impact of this recloser on the reduction of risk to the network would thus be low.

Prioritizing on the load factor would improve the Reticulation Supply Loss Index (RSLI) which is calculated using equation 7.1.

$$RSLI = \frac{\sum(\text{Load size} \times \text{Outage time})}{\sum \text{Load size}} \quad (7.1)$$

If reclosers are placed in positions where the affected load under fault conditions is minimal, RSLI can be improved.

7.2.3 Results of algorithm with high priority on customer outages

High priority was given to minimise the risk of the loss of supply in terms of the customer number connected to the network. The weight for the risk of customer outages was set to ten and all other weights were set to zero. Table 7.4 shows the overall best solution set of recloser positions.

Table 7.4. The solution set of recloser positions

Name	Recloser Positions	Customers lost if recloser trips	% Customers lost	Length Coverage (km)	% Length Coverage
A	0-5 start	558	100	0.7	0.10
B	6-50 start	301	53.94	31.5	41.61
C	6-6/2 start	1	0.18	14.3	19
D	6/3-6/100 start	5	0.90	14.2	19
E	50-50/100 start	1	0.18	15	19.82

Table 7.5. The optimal recloser positions for varied number of reclosers

No of Reclosers	Recloser Positions	Objective function value	Reduction in objective value
1	A	10	-
2	A,B	7.18	2.82
3	A,B,C	4.81	2.37
4	A,B,C,E	3.74	1.07
5	A,B,C,D,E	3.06	0.68

The results in Table 7.5 portray similar patterns to the case where the load size is prioritised. As the number of reclosers on the network increases, the risk of the loss of customers reduces. The impact of the added recloser on the value of the objective function is based on the percentage length coverage and the percentage of the customers connected to the recloser.

The choice of the recloser position at 6/2-6/3 in the case where high priority is given to the load size is replaced by 6/3-6/100 when the priority is given to the customer number. This is due to the fact that the number of customers connected to 6/2/-6/3 is 225 (40.32 %), whereas the number of customers connected to 6/3/-6/100 is 5 (0.9 %). Placing a recloser at 6/3/-6/100 would ensure that 99.1 % of customers are still connected for a fault on the protected span of the network, where there is a 19 % probability of fault occurrences, which is equivalent to the percentage length coverage of the recloser.

Reclosers should ideally be placed on spans that have a high probability of faults and where the percentage of customers connected to the recloser is low. In this way, a large percentage of the customers will not be affected by a fault on the span of conductor where the probability of having a fault is high.

Prioritizing the risk for customer outages would improve the SAIDI and SAIFI since reclosers are placed in positions where the affected number of customers under fault conditions is minimal.

7.2.4 Results of algorithm with high priority on damage factor

When damage is the only weighted parameter, the solution tends to consist of recloser positions where the most effective high-sets can be implemented. The algorithm suggests that installing one recloser at the feeder circuit-breaker is the best solution to minimise damage. One recloser at the substation with a high-set set to twice the fault level at the furthest reach is the most effective high-set application and is thus the best solution if the damage factor is the only consideration.

With each recloser addition to the network, the high-set applied to the feeder breaker increases, increasing the value of the objective function. Since the high-set of the feeder breaker is set to a multiple of the fault current at the downstream recloser, positions with the lowest close-up fault would be appropriate to enable the application of a lower high-set on the feeder breaker. Applying a lower high-set on the feeder breaker would minimise the

damage caused to the network, since most of the feeder's conductors would be protected by the instantaneous trip of the high-set on the feeder breaker.

Table 7.6 shows the best values of the objective function for various numbers of reclosers. It shows how the value of the objective function or the damage increases as the number of reclosers increase. The best recloser set with two reclosers consists of the feeder breaker and a recloser at pole 70/230, where the fault current level is the lowest at 232 A. Only positions with low fault current levels are selected as the number of reclosers increase. The high-set of the feeder circuit-breaker will be set to 1.5 times the maximum fault level at the positions of the downstream reclosers.

Table 7.6. The objective function values for varied number of reclosers

No of Reclosers	Objective function value	Increase in objective value
1	1.29	-
2	1.38	0.09
3	1.69	0.31
4	1.7	0.01
5	1.79	0.09

The algorithm tends to select potential recloser positions that are furthest away from the source and that are not in series with each other. The increase in the value of the objective function can be observed from Table 7.6 as the number of reclosers on the network increases. The increase in the value is not due to the time delay as a result of grading between reclosers, but rather the magnitude of the instantaneous high-set current pick up value on the feeder breaker.

The damage factor is dependent on the number of reclosers and the positions of reclosers, but its sensitivity to the position of reclosers is very high. The position of downstream reclosers has a huge impact on the possibility of applying a high-set to the upstream

recloser. Placing a recloser near the feeder breaker would highly reduce the chance of applying an instantaneous high-set on the feeder breaker due to the insignificant difference in the magnitude of the short-circuit current between the feeder circuit-breaker and the recloser location.

If the damage factor is given a very high weighting in comparison to the other factors, the solution will tend to have a lower number of reclosers and the selected locations for reclosers will tend to be at positions where the fault level is very low.

7.2.5 Results of algorithm with high priority on recloser pickup limits

High priority was given to minimise the difference between the current pickup of the recloser and the conductor rating of the feeder. This is to ensure that the feeder does not trip on load as a result of setting reclosers sensitive enough to detect faults at the furthest reach of the recloser. The positioning of reclosers on the network affects the furthest reach of reclosers. The weight for the recloser pickup was set to ten and all other weights were set to zero. Table 7.7. shows the overall best solution set of recloser positions.

Table 7.7. The best solution set of recloser positions

Name	Recloser Positions
A	0-5 start
B	50-50/100 end
C	50/100-50/150 end
D	70-70/100 start
E	70/100-70/200 start

The best recloser set is the one that ensures that majority of the reclosers on the feeder can be set as close as possible to the emergency rating of the conductor it is connected to. The pick-up should be sensitive enough to detect 80 % of phase-to-phase fault current at the end of the intended reach, allowing for the bypassing of one immediate downstream

recloser. Table 7.8 shows all the load points and the corresponding fault current that the installed protection on the feeder must detect.

Table 7.8. Fault levels at the load points on the network

Load points	80 % of phase-to-phase fault current at load point (kA)
6/2/75	0.50
70/230	0.16
90/1	0.77
6/3/65	0.55
5/1	2.84
6/145	0.28
50/150	0.24

The furthest reach of the feeder is at pole 70/230 and the protection on the feeder must be sensitive enough to detect a fault of 160 A. If the feeder circuit-breaker is the only protection on the feeder, the pick-up must be set to 160 A, although the backbone of the feeder consists of Hare conductor and has an emergency rating of 380 A. This would be detrimental to the operation of the feeder if the actual load is higher than 160 A, as the feeder would consistently trip on load. If the feeder circuit breaker is set lower than the conductor rating, all downstream reclosers will have to be set even lower than the feeder breaker for grading purposes. The current pick-up of the feeder circuit breaker is thus critical.

From the results displayed in Table 7.7, it is evident that the addition of two reclosers between the feeder breaker and the two load points with the lowest fault currents at poles 70/230 and 50/150, produces the best results. The addition of these reclosers enables the exclusion of the fault levels at poles 70/230 and 50/150 from the furthest reach of the feeder breaker. Reclosers B and C are required to pick up for a fault at pole 50/150 and reclosers D and E are required to pick up for a fault at pole 70/230. The feeder circuit-

breaker would only need to reach until reclosers C and E considering the allowance for the bypassing of one immediate downstream recloser. Since the maximum number of reclosers has been pre-defined to be 5, the results do not cater for the furthest reach at pole 6/145.

This factor would drive an increase in the number of reclosers on the network, based on the number of load points that would be a limiting factor on the pickup setting of reclosers.

7.2.6 Results of algorithm with mixed weighting factors

The analysis of each factor of the objective function in isolation from the others is now complete. The combined effect of each factor in the objective function is expected to produce results that are balanced. If unit weighting is given to each factor, the results are as shown in Table 7.9.

Table 7.9. Selected recloser positions for unit weighting on each factor

Name	Recloser Positions
A	0-5 start
B	6-6/2 start
C	50-50/100 start
D	70-70/100 start

Although all factors are given equal weights, the results tend to prioritise the cost, load and customer factors, rather than the damage factor and the pick-up limit factor. The results look similar to the solution when the customer and load factors are the only priorities, but the number of reclosers has reduced by one due to the cost factor. Due to the position of recloser B, the application of a high-set on the feeder circuit-breaker is not possible. Since there is no other recloser on the backbone of the feeder, the backbone would be protected by the NI element of the feeder circuit-breaker only, which is not ideal. With the placement suggested in Table 7.9, the issue of reclosers being set below the line rating of the conductor connected to it is not addressed.

If the weighting is changed such that the damage is given twice the priority of the other factors, the results are as displayed in Table 7.10.

Table 7.10. Selected recloser positions for damage having twice the weighting in comparison to all other factors in the objective function.

Name	Recloser Positions
A	0-5 start
B	6-6/2 end
C	50-50/100 start
D	70-70/100 start
E	6-50 start

An increased weighting on the damage factor results in the addition of a recloser on the backbone at E. In Section 7.2.4, the observation was that the damage increases as the number of reclosers increases. This generalisation cannot be made when other factors in the objective function are also allocated a certain priority. The addition of the recloser at E ensures instantaneous protection for most of the backbone from pole 6 to pole 90. At the same time, it excludes the loads beyond reclosers C and D from the feeder breaker's intended reach. The feeder breaker will thus not be limited by the low fault levels at poles 70/230 and 50/150.

The allocation of the recloser at 6-6/2 is driven by the priority given to loss of customers and loads. Having the feeder breaker with a recloser at 6-6/2 results in the application of a low high-set on the recloser at 6-6/2, but the application of a high-set on the feeder breaker would not be possible due to the insignificant difference in the magnitude of the short-circuit current between the feeder circuit-breaker and the recloser at 6-6/2. Adding a third recloser at 6-50 in this case would reduce the damage factor significantly, since an effective high-set can be applied to it. The section of conductors beyond this point was previously protected by the NI element of the feeder breaker, but with the addition of the recloser, it would be protected by the instantaneous element of the recloser at 6-50.

If the damage factor is given equal or greater priority than the other factors, the number of reclosers selected may increase based on the locations driven by the other factors.

7.3 APPLICATION OF TOOL ON REAL FEEDER

The tool was applied to the 11 kV Fairfield Moloto feeder, which has a fault level of 8.516 kA at the feeder breaker. The network diagram of the Fairfield Moloto feeder is shown in Figure 7.3. The feeder is constructed of Mink conductor, which has an emergency current rating of 272 A.

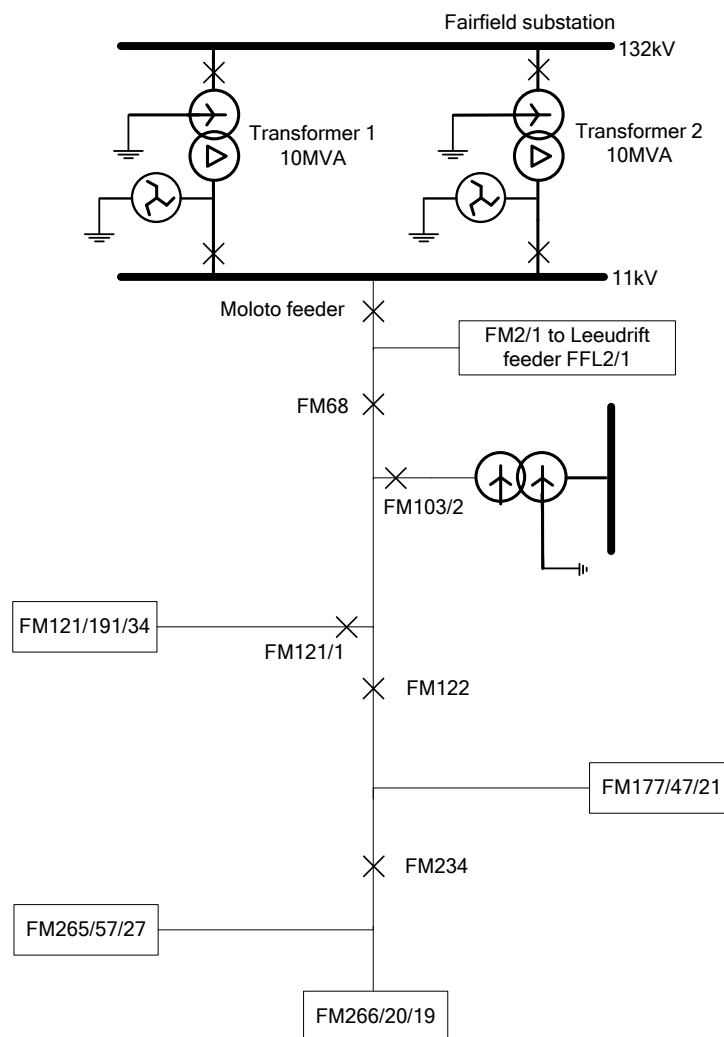


Figure 7.3. Network diagram of Fairfield Moloto Feeder

The reclosers positioned at FM68 and FM103/2 exist for reasons not covered by the tool. These reclosers will not be considered in the initial comparison between the actual

positioning on site and the tool's proposed positions. According to Figure 7.3, provision to feed an adjacent feeder is made at FM2/1. The purpose of the recloser at FM68 is thus to ensure that faults on the Fairfield Moloto feeder do not affect the adjacent feeder in the case of faults on Fairfield Moloto feeder. The recloser at FM103/2 is solely placed for the protection of the transformer.

The results of the tool with equal weightings for each factor in the objective function are as follows:

Table 7.11. Selected recloser positions for unit weighting on each factor

Name	Recloser positions
A	0-82 start
B	121-121/3 start
C	121-123 start
D	237-243 end

Table 7.12. Comparison of objective function values for various cases

Parameter	Selected recloser positions	Actual placement, without FM68 and FM103/2	Actual placement
Customer risk	0.370	0.417	0.415
Load risk	0.323	0.327	0.326
Damage	0.371	0.352	0.408
Cost	0.400	0.400	0.600
Pick-up limit	0.444	0.444	0.197
Total	1.908	1.940	2.143

The proposed recloser placement for unit weighting on each factor in the objective function shown in Table 7.11 is very similar to the actual recloser placement without the

reclosers at FM68 and FM103/2. A comparison of the factors within the objective function is shown in Table 7.12 for the proposed recloser placement and the actual recloser placement. The impact of the additional 2 reclosers at FM68 and FM103/2 is as follows:

- It has very little impact on the the risk of losing customers and loads as the critical positions for improvement are already in place.
- The damage factor deteriorates as the instantaneous high-set on the feeder is set higher than in the case when there was no recloser at FM68.
- The cost factor increases due to the addition of 2 reclosers.
- The pick-up limit factor improves due to the addition of the recloser at FM68. The feeder circuit-breaker is not required to detect a fault at FM121/114/42 where the three phase fault level is 379.7 A due to the presence of the recloser at FM68.

The tool provides a sound manner in which recloser combinations can be compared in terms of the risk of losing customers and load, the risk of false tripping, cost and damage. The magnitude of each factor of the objective function could give an indication to the user on areas that could be improved and thus indicate the need for an increased weighting factor on the specific factor that needs to be improved. The improvement of the pick-up limit in this case is possible by allocating a greater weighting to the factor.

7.4 CHAPTER IN PERSPECTIVE

The algorithm has been validated and tested and is a practical tool that can be applied to a real feeder. In the process of validating the solutions of the tool when each factor is considered in isolation, logical recloser placements were observed based on each factor. The addition of the protection related factors to the objective function, such as the damage factor and the limitations on the current pickup settings of reclosers, caters for recloser positions that would previously not have been considered on the basis of reliability. It is an improvement on the existing methods by way of its ability to realise the value of adding reclosers at positions that were previously not considered. The tool tends to converge to solutions where several factors of the objective function benefit from the placement of a recloser at a specific position. The tool also caters for the comparative analysis of various sets of recloser placement, based on each factor of the objective function.

CHAPTER 8 CONCLUSION

The evaluation of the main hypothesis was facilitated by investigating the answers to the research questions posed in Chapter 1. The first section of the present chapter summarises the answers to these questions which were developed over the course of the study. The hypothesis is thereafter assessed considering the research findings, and the scope for future research is identified.

8.1 RESEARCH QUESTIONS ANSWERED

The answers to the questions are summarised below.

How will recloser number and placement change based on the priority given to the various factors in the objective function?

The risk of the loss of customers and loads on the network will improve with the increase in recloser numbers, but the percentage improvement will reduce as the number of reclosers increases. The recloser positions with the highest impact on the percentage improvement are reclosers with high length coverages and low customer or load base.

The cost factor will always drive the reduction in the number of reclosers. It is the only factor that is not dependent on the placement of reclosers.

If the damage factor is prioritized in isolation from the other factors, the solution will tend to have a lower number of reclosers and the selected locations for reclosers will tend to be at positions where the fault level is very low. The practicality of applying an instantaneous high-set on the recloser is a crucial element in the behaviour of this factor as the application of a high-set improves the damage factor greatly.

High priority given to minimise the difference between the NI current pick-up of the recloser and the emergency rating of the conductor ensures that the feeder will not trip for load conditions. The pick-up limit factor would drive an increase in the number of

reclosers on the network based on the number of load points that would be a limiting factor on the pickup setting of reclosers. Increasing the number of reclosers between the feeder breaker and the load point would ensure that the pick-up of the feeder breaker is not limited to 80% of the phase-to-phase fault at the load point. Instead, a downstream recloser will cater to reach for the load point, which is an improvement as it would have a smaller load connected to it compared to the feeder breaker. This factor would not have an effect on the results if there are no load points where the fault current is below the emergency rating of the conductor.

If mixed priority is given to all factors of the objective function, the weightings of each factor defined by the user will drive the placement of reclosers. The behaviour of the damage factor changes when considered in isolation, in comparison to when all factors of the objective function are given a certain weighting. The damage factor may increase the number of reclosers based on the locations driven by the other factors. If the objective function is favourable, based on factors such as the risk to load and customers, the cost and the risk of false tripping, the genetic algorithm will select a recloser position where the damage can be minimised for positions that cater for the other factors. The best recloser combination for each factor prioritized in isolation of the other factors will not cater for the minimisation of the other factors. Recloser combinations that score well on various factors of the objective function will tend to converge as the solution set of the tool.

What is the suggested recloser number and placement with equal priority given to each factor in the objective function on a real network? For an actual distribution network, how do the actual device numbers and placements compare with those suggested by the algorithm?

The tool was applied to a real feeder and the results were compared to the actual placement of reclosers on the network where equal priority was allocated to each factor in the objective function. The magnitude of each factor in the objective function was used as the basis of comparison between the two cases. The results of the tool compared well with the actual placement of reclosers on the network, except for the reclosers that were placed on

the network for reasons not catered for in the algorithm. Excluding the reclosers that are on the network for special purposes, the number of reclosers in both scenarios was the same and the locations of reclosers in both scenarios were very similar. From the analysis, areas that need to be improved can be identified from the values of each factor of the objective function.

As a result of this research, recloser placement with a balanced priority given to each of the factors in the objective function can be attained.

8.2 ASSESSING THE HYPOTHESIS

Answers to the research questions above facilitated the evaluation of the main hypothesis that was proposed in Chapter 1. The hypothesis stated that:

Recloser placement studies with the additional consideration of protection-related factors such as equipment damage and the risk of false tripping will result in different recloser positions compared to when the priority is only on improving reliability indices and cost.

The addition of the protection-related factors to the objective function is unique in its ability to realise the value of recloser positions that cater for minimising the damage factor and the possibility of tripping for load conditions. In the absence of these factors, the value of certain recloser positions would not be identified as they would not improve reliability or cost factors.

The importance of reliability and cost are not overruled by the addition of the protection-related factors. In the study of mixed priorities on a hypothetical feeder, it could be seen that the recloser positions driven by reliability and cost factors are maintained, but the inclusion of a couple of additional reclosers at specific positions could greatly reduce the magnitude of the protection-related factors.

8.3 OPTIMISATION OF RECLOSER PLACEMENT

While it is standard practice for planners to consider reliability and cost as the only factors influencing recloser placement, this study has demonstrated the importance of protection as a consideration for deciding on recloser placement. This research has confirmed that the addition of protection related factors to the objective function can add value to the optimisation of recloser placement. The results of this study demonstrate the importance of considering the limitations that the placement of reclosers imposes on the protection settings applied to reclosers on the network. The compromises made on the protection of a feeder to cater for good reliability and reduced investment costs can be mitigated by including protection as a consideration in the process of deciding on recloser placement.

8.4 SCOPE FOR FURTHER RESEARCH

This research into the optimisation of recloser placement has identified a number of areas requiring further research. These include the following:

- In future, consideration should be given to recloser positions that cannot be compromised on, such as reclosers that cater for the protection a transformer on the distribution network. This is considered a special case and the recloser position could be included as a fixed point on the network.
- A study on how various protection philosophies affect the protection-related factors such as the damage factor and the risk of false tripping could be done. The impact of different protection philosophies on recloser placement can also be investigated.
- This study could be extended to addressing the impact of fuses and sectionalisers on reliability.
- The effect of distributed generation, such as rooftop photovoltaic installations, on the placement of reclosers in the distribution network needs to be investigated.

8.5 CONCLUSION

Considering that the majority of the overhead line network of any utility consists of MV distribution networks, importance must be given to the protection of the MV distribution network. The number and placement of reclosers has been identified as a limitation to the

application of effective protection settings on MV distribution networks. The standard practice of the protection settings engineer is to apply the best possible protection settings on the network, within the limitations of the network structure, the recloser number and placement. In doing this, engineering judgement is applied and certain aspects of protection are compromised to ensure the smooth operation of the feeder. The compromise of protection of the feeder will be avoided if protection-related factors are considered in the planning process of optimising recloser placement. This would ensure that the feeder is adequately protected, which would inherently have a positive effect on the lifespan of the equipment on the feeder.

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ADDENDUM A

The pole numbers of loads connected to a sample feeder are shown below. The size of the load and the number of customers connected to the specific pole number are specified in the table below.

Load	Pole number of loads					Size of Load (kVA)	Number of customers
1	112	7				50	98
2	114	1				25	50
3	121	10	9	2		25	34
4	121	114	42			100	165
5	121	114	5	3		25	1
6	121	124	18			25	47
7	121	13				25	2
8	121	136				25	50
9	121	140				200	44
10	121	143				25	1
11	121	146				100	72
12	121	149				100	5
13	121	3				50	130
14	121	40				16	15
15	121	4	11	1		25	2
16	121	4	12			25	2
17	121	41	3			25	85
18	121	4	13	1		25	1
19	121	4	2			25	33
20	121	4	22	3		25	1
21	121	4	29			25	1
22	121	4	3			25	50
23	121	44	6			32	62
24	121	46	2			50	93
25	121	4	9	1		50	34
26	121	4	9A	1		50	1
27	121	5				50	89
28	121	65	2			50	2
29	121	69	4			25	48
30	121	69	5	3		25	57
31	123	1				25	99

32	143	10	1			25	2
33	143	11				25	46
34	143	17	2			25	49
35	143	26				50	2
36	143	28				25	1
37	143	8	1			50	3
38	177	20	4			25	10
39	177	20	9			25	21
40	177	39				100	1
41	177	47	15	2		25	1
42	177	47	16			25	47
43	177	47	2			100	1
44	177	47	21			25	2
45	177	55	1			25	2
46	177	62				25	1
47	184	3				100	8
48	188	1				100	5
49	204	10	5	2		25	1
50	204	10	7			25	2
51	204	11				100	1
52	216	9				50	4
53	219	9				50	1
54	233	1				25	40
55	233	6				100	2
56	237	4				25	1
57	243	17	5			25	1
58	243	20	13			25	1
59	243	20	4	2		25	1
60	243	2	2			25	1
61	243	28	1			25	1
62	243	41	2			25	2
63	243	48	3			25	1
64	243	68				25	1
65	243	7	2			25	1
66	243	9	4	5		50	4
67	243	9	5			25	1
68	265	18	1			25	1
69	265	43	2			50	3
70	265	55	2			25	24
71	265	57	15	1		25	10
72	265	57	15	1A	26	16	4

73	265	57	27			25	12
74	265	58				25	1
75	266	12	3			25	1
76	266	15	2			50	46
77	266	17	3			25	1
78	266	20	19			100	1
79	266	20	6			25	1
80	266	2	2			25	4
81	266	5	1			50	1
82	82	1				100	1
83	83	2	2			25	43
84	83	3				25	2
85	83	32				25	1
86	83	38				315	5
87	84	2				25	38
88	84	2	2			50	4
89	84	5				16	1
90	92	2	6			25	1
91	93	11	2			25	30
92	93	14	2			25	48
93	93	14	2A			25	48
94	93	14	5			25	46
95	93	2	4			25	22
96	93	29	1			25	50
97	93	30	2			25	1
98	93	7				25	5
99	93	7	1			25	48
100	99	5				25	1
101	103	2				5000	1

ADDENDUM B

The program created to automatically determine the optimal number and placement of reclosers has the following functions.

- **Main:** This module calls each program module below.
- **CreateNetwork:** The network is created based on the data in the Excel spreadsheet in the format provided in Addendum A.
- **AllocLoadToTerm:** Each terminal in the created network is allocated the number of customers and the load size that are connected to the terminal.
- **FaultMatrix:** The three-phase fault current is simulated at every 100 m of the network and stored in the matrix to enable calculation of the damage factor of the objective function without repetitive fault calculation simulations.
- **ZoneCreation:** The assessments of each terminal of each line in the network are done to differentiate nodes that meet the criteria to be allocated to zones, which are the terminals that are considered as potential positions for reclosers. Each zone consists of a set of lines with a maximum length of lines.
- **randRecloserPosWeights:** The number of reclosers are varied from 2 reclosers to the maximum number of reclosers specified by the user and 200 random recloser placements are simulated for each case. This module has 2 sub-modules that calculate the relevant settings for reclosers and calculate the damage factor of the corresponding recloser placement. The largest damage factor obtained from this module is stored as the normalisation factor of the damage factor.
- **randRecloserPos:** The number of reclosers are varied from 2 reclosers to the maximum number of reclosers specified by the user and 200 random recloser placements are simulated for each case. This module has 3 sub-modules that

calculate the relevant settings for reclosers, calculate the objective function of the corresponding recloser placement and implement the genetic algorithm to the created sets of reclosers.