RELIABILITY-BASED OPTIMIZATION OF DISTRIBUTION SYSTEM PROTECTION

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ABSTRACT

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The power system is one of the most complex systems in existence. In any complex system, it is impossible to avoid abnormal operations. In order to reduce the impact of abnormal operations and to restore the system more quickly to normal states, many control and protection mechanisms are established. Protection systems consist of sensing and isolation devices that operate in the event of a fault to disconnect the part of the power system that is affected by the fault. However, malfunctions can also occur within the protection system. Therefore, one objective of this thesis is to develop approaches for analyzing and modeling the reliability of power systems when the malfunctions of protection systems are considered. A methodology of evaluating reliability of distribution systems are presented. This method uses matrices to represent the relationship of devices in distribution systems and loads. Reliability indices such as SAIFI and SAIDI of the distribution system of RBTS bus 2 are calculated using the proposed methodology. Since power utilities are aim to provide reliable electric power with low cost to customers, the investment of protective devices need to be taken into consideration. In this thesis, an optimization problem is presented. The objective in this optimization problem is the cost of disconnects and the constraint is the reliability indice, SAIDI. This reliability-based optimization problem is solved for RBTS distribution system by Genetic Algorithm (GA).

Dedicated to:
My parents, Lifeng Tian and Jing Huang

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CHAPTER 1
INTRODUCTION

1.1 Introduction

The primary objective of the power grid is to provide reliable and economic electrical energy to customers. However, the power system is one of the most complex systems in existence and it is impossible to avoid abnormal operations in any complex system. Abnormal operation is usually caused by system disturbances, which is defined as an undesired variable applied to a system that tends to affect adversely the value of a controlled variable [1].The most common disturbances in power systems are lightning, faults, large changes in load and failure of equipment due to weather, fatigue, etc. In order to reduce the impact of abnormal operation and to restore the system to normal status more quickly, many control and protection mechanisms are established. Protection of power system is an extremely important aspect as the quality and scheme of the protection decides system reliability, controllability and stability [2]. The performance of protection systems affects the whole power system in many ways, including electrical facilities and customers. Hence, there are always ongoing efforts toward improving the performance of protection systems and the links between protection systems and power systems.

The electric power system is one of the largest and most complicated systems in the world, and consists of a generation part, a transmission part and a distribution part. The research reported in this thesis deals with protection issues encountered in distribution systems. The distribution system is the portion of power systems which delivers electric energy from the transmission system to the customer. The distribution system extends downstream from the distribution substation to the customer meter. Often the initial overcurrent protection and voltage regulators are within the substation fence and are considered to be part of the distribution system [3].

1.2 Research Objectives

The reliability of an electric power system is defined as the probability that the power system will perform the function of delivering electric energy to customers on a continuous basis and with acceptable service quality [4]. This character shows how well a system is performing its intended function. There are several reliability indices that quantify different aspects of distribution service interruptions, and some of the most commonly used indices are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Customer Total Average Interruption Duration Index (CTAIADI), and Customer Average Interruption Frequency Index (CAIFI). These indices will be introduced in chapter two in detail. These indices help to evaluate the customer satisfaction by representing the number of momentary and sustained interruptions, duration of interruptions and number of customers interrupted. The significance of conducting research of system reliability also plays roles in improving system performance. Besides, they provide a basis for new or expanded system planning and maintenance scheduling, as well as resource allocation.

It has been observed that protection system hidden failures commonly lead to multiple or cascading outages, which consequently can cause large-scale power system blackouts [5]. The protection system contains many protection devices, such as relays, breakers, fuses and disconnects. Each component could fail to operate, which may lead to the failure of protection systems and this would endanger the power grid in step. Thus, it is necessary to take the the likelihood of protection failure into consideration when evaluating the reliability of the distribution system.

Assessment of system performance is a valuable procedure for three important reasons. First of all, it establishes the chronological changes in system performance and therefore helps to identify weak areas and the need for reinforcement. Secondly, it establishes existing indices which serve as a guide for acceptable values in future reliability assessments. Finally, it enables previous predictions to be compared with actual operating experiences [6]. Therefore, as operating conditions and technologies evolve in distribution systems, it is important to develop improved and more sophisticated models and methods for reliability evaluation of these systems. One of the objective of this thesis is to develop an improved model and method for distribution system reliability that takes into account the role of protective devices.

The fundamental goal of an electric utility has always been to serve its customers with a reliable and low cost power supply [7]. It is apparent that more the protective devices are installed in the system, less the interruption duration is of the customer. However, the investment cost of utility will be more with the increase of the number of protective devices. Therefore, an optimization problem need to be solved to find the optimum number and placement for protective devices.

This is the second objective of this thesis. The objective function is the total cost of protective devices, and reliability indice should be taken into consideration as a constraint. Genetic Algorithm is applied in this thesis to solve the optimization problem, the detail is presented in chapter four.

1.3 Outline of Thesis

The contents of this thesis are organized into five chapters. Following the chapter on introduction, chapter two gives a brief overview of the distribution system. Also, the main indices to be used in this research for assessing the reliability of the distribution system have been discussed.

Chapter three proposes a methodology based on relation matrix to evaluate the reliability indices of distribution systems. Six cases are used to illustrate the method in detail. The variables in these cases are fuse, disconnect, alternative supply and fuse failure. The system reliability and individual load point reliability for six cases of the RBTS bus 2 distribution system are evaluated by the methodology proposed in this thesis.

Chapter four presents a reliability-based optimization problem. This chapter proposes a methodology of using Genetic Algorithm to solve the reliability-related optimization problem. The optimum number and placement of disconnects are found for both the IEEE-RBTS bus 2 system and the whole RBTS system.

Chapter five is a summary of the whole thesis. It discusses the work that has been done and makes suggestions for future research.

CHAPTER 2
RELIABILITY EVALUATION OF DISTRIBUTION SYSTEM

2.1 Overview of Distribution System

Generally, an electric power system includes a generating, a transmission, and a distribution system. The distribution system is the portion of power systems which delivers electric energy from the transmission system to the customer. The distribution system extends downstream from the distribution substation to the customer meter. Distribution lines are different from transmission and subtransmission lines in that (1) they operate at lower voltages than transmission lines, (2) they are usually radial, and (3) they usually have loads tapped all along the line, not just at the terminals [8]. In the past, distribution system received less attention than the other part of electric power system when considering reliability. The main reason for this are that generating stations are individually very capital intensive and that generation inadequacy can have widespread catastrophic consequences for both society and its environment [6]. However, in 1977, [9] presented that analysis of the customer failure statistics of most utilities shows that the distribution system makes the greatest contribution to the unavailability of supply of customer. What's more, in book [10], the author states that the distribution systems account for up to 90% of all customer reliability problems. Therefore, it is essential to conduct research about reliability evaluation of distribution systems.

2.2 Previous Work

After decades of effort in study of reliability of distribution systems, several methods have been applied to this area. Basically, these methods can be divided into two parts, analytical methods and simulation methods. Analytical methods are those that use system topology along with mathematical expressions to calculate reliability indices, which include Markov modeling, network reduction, fault tree analysis and cut-set analysis. Network reduction is useful for systems consisting of series and parallel subsystems. This is a method that uses series-parallel combinations to reduce network and then to determine load point indices and aggregate them to calculate the system wide indices. When using fault tree analysis, the components that cause interruptions to load, for each one should be determined first. Then the load point indices need to be combined to get the system indices. As for the cut set method, it can be applied to systems with simple as well as complex configurations and it is a very suitable technique for the reliability analysis of power distribution system [11]. The first step is to determine the first and second order minimal cut-sets that cause outages at each load point, then we can evaluate the reliability indices.

When a system can be described by a set of discrete states, and the probability of moving to a new state is only dependent upon the current state, the system can be described by a Markov model [12]. Since protective devices and most components in power systems are repairable, Markov modeling shows its advantage in evaluating the reliability of protective systems. However, since distribution systems contain a large number of states, many simplifying assumptions must be made to limit the Markov model to a manageable size [12].

Monte Carlo simulation is a way of simulating the conditions on the system by generating system states of failure and repair randomly to compute the reliability indices. One advantage of the simulation method is that this method is not restricted by the large size of the power grid. Two types of simulation methods are often used: sequential Monte Carlo simulation and non-sequential Monte Carlo simulation. The former one simulates the system operation by generating an artificial history of failure and repair events in time sequence. The later type evaluates the system's response to a set of events and its order has no influence.

When evaluate the reliability of distribution system, the performance of protection system should be taken into consideration. Hidden failures in the protection system are a main issue that affects the reliability of the distribution system and decreases the satisfaction of customers. A large amount of studies on reliability evaluation considering protection failures are conducted by researchers [12-16].

2.3 Reliability Indices for Distribution System

System availability, estimated unsupplied energy, number of incidents and number of hours of interruption are aspects that should be taken into consideration when evaluating the reliability of the power grid. Reference [3] presents a set of terms and definitions which can be used to foster uniformity in the development of distribution systems and several reliability indices are defined, which are listed below.

The system average interruption frequency index (SAIFI) is defined as,

$$\text{SAIFI}=\frac{\sum \text{Total Number of Customers Interrupted}}{\text{Total Number of Customers Served}} \tag{2.8}$$

This index indicates the average frequency of a sustained interruption that the customer experiences. Sustained interruptions are those interruptions that last more than five minutes.

SAIDI refers to System Average Interruption Duration Index, which indicates the total duration of interruptions for the average customer, and it is defined as,

$$\text{SAIDI}=\frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Customers Served}} \tag{2.9}$$

CAIDI is Customer Average Interruption Duration Index, which indicates the average time required to restore service, which is determined by,

$$\text{CAIDI}=\frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Customers Interrupted}} \tag{2.10}$$

This index could also be calculated as below,

$$\text{CAIDI}=\frac{\text{SAIDI}}{\text{SAIFI}} \tag{2.11}$$

CAIFI is the Customer Average Interruption Frequency Index, which represents the average frequency of sustained interruptions for those customers experiencing sustained interruptions. The equation is given below,

$$\text{CAIFI}=\frac{\sum \text{Total Number of Customer Interruptions}}{\text{Total Number of Distinct Customers Interrupted}} \tag{2.12}$$

One thing that needs to be noticed is that the customer interrupted is counted once, regardless of the the number of interruptions for this customer.

CHAPTER 3
RELIABILITY EVALUATION OF DISTRIBUTION SYSTEM CONSIDERING PROTECTION FAILURES

3.1 Methodology for the Distribution System

Reliability Evaluation

Distribution lines are different from transmission and subtransmission lines. Distribution lines have characteristics such as lower voltage, radial and load tapped all along the line. If we assume there are l lines, m transformers and n loads in a distribution system. We can use a matrix R_L to represent the relationship between loads and lines, the size of R_L is $n \times l$, and use R_T to represent the relationship between loads and transformers, the size of R_T is $n \times m$. If load i will be affected by line j, then $R_L(ij) = 1$. If the fault on line j will not interrupt load i, $R_L(ij) = 0$. Similarly, if load i will be affected by transformer j, then $R_T(ij) = 1$, otherwise, $R_T(ij) = 0$. These could be represented as follows,

$$R_L(i, j) = \begin{cases} 1, & \text{if load } i \text{ will be affected by line } j \\ 0, & \text{otherwise} \end{cases}, \quad \begin{matrix} 1 \le i \le n \\ 1 \le j \le l \end{matrix} \tag{3.1}$$

$$R_T(i,j)=\begin{cases}1, \text{ if load } i \text{ will be affected by transformer } j \\ 0, \text{ otherwise}\end{cases}, \quad \begin{matrix}1\le i\le n \\ 1\le j\le m\end{matrix} \tag{3.2}$$

In this methodology, we use λ_L to represent the failure rate of distribution lines. λ_L is a $1\times l$ vector and $\lambda_L(i)$ is the failure rate of line i, $1\le i\le l$. I_L and U_L are used to represent the number of interruptions and interruption duration of each load caused by distribution lines, respectively. The size of I_L is $n\times 1$ and the size of U_L is $n\times l$. The element of I_L and U_L can be calculated as below,

$$I_L(i)=R_L(i)\lambda_L{}^T \tag{3.3}$$

$$U_L(i,j)=tR_L(i,j)\lambda_L(1,j) \tag{3.4}$$

where t is the recovery time of load, which could be the fault clearing time or the isolation and switching time. The value of t depends on situations, the detail will be illustrated later by six cases in section 3.2.

Similarly, we use λ_T to represent the failure rate of transformers. I_T and U_T represent the number of interruptions and interruption duration of each load caused by transformers, respectively. The size of I_T is $n\times 1$ and the size of U_T is $n\times m$. I_T and U_T are calculated as follows,

$$I_T(i)=R_T(i)\lambda_T{}^T \tag{3.5}$$

$$U_T(i,j)=tR_T(i,j)\lambda_T(1,j) \tag{3.6}$$

Finally, the number of interruptions and interruption duration of each load can be calculated. We use matrix I and U to represent the total number of interruptions and total interruption duration of loads. The total number of interruptions is equal to the sum of the number of interruptions caused by lines and the number of interruptions caused by transformers. Similarly, The total interruption duration equals to the sum of interruption duration caused by lines and interruption duration caused by transformers.

$$I(i) = I_L(i) + I_T(i) \tag{3.7}$$

$$U(i) = \sum_{j=1}^{l} U_L(i,j) + \sum_{j=1}^{m} U_T(i,j) \tag{3.8}$$

Then SAIFI and SAIDI can be calculated as

$$\text{SAIFI}=\frac{\sum N_i \lambda_i}{\sum N_i} = \frac{\sum N_i I(i)}{\sum N_i} \tag{3.9}$$

$$\text{SAIDI}=\frac{\sum N_i U_i}{\sum N_i} = \frac{\sum N_i U(i)}{\sum N_i} \tag{3.10}$$

3.2 Case Study

Part of the distribution system of IEEE-RBTS bus 2 will be used as an example. The procedure of evaluating reliability of this part by the methodology proposed in section 3.1 will be described. Table 3.1 and 3.2 contain the reliability-related data of transformers and lines. Table 3.3 shows the number of customer connected to each load. Six cases will be analyzed to show how to calculate the reliability of distribution system according to the methodology proposed in this thesis. Case 1 is the basic case, in this case the only protective device is a circuit breaker. In case 2, fuses are installed to protect the lateral lines. In case 3, disconnects are installed. In case 4, both fuses and disconnects are installed. In case 5, fuses, disconnects and alternative supply are all under consideration. Fuse failure is considered in case 6 based on case 5.

Table 3.1 Data of Transformer

Transformer	Failure rate (/yr)	Repair time (h)
1~7	0.015	200

Table 3.2 Data of Lines

Feeder type	Length (km)	Feeder section numbers	Failure rate (/yr)	Repair time (h)
1	0.60	2, 6, 10	0.039	5
2	0.75	1, 4, 7, 9	0.04875	5
3	0.80	3, 5, 8, 11	0.052	5

Table 3.3 Number of Customers Connected to Each Load

Load	1	2	3	4	5	6	7
Number	210	210	210	1	1	10	10

3.2.1 Case 1

In this case, the reliability of a small branch will be evaluated, which does not contain fuse or disconnect, only a circuit breaker is applied as protection in this basic case. The single line diagram is shown in Figure 3.1.

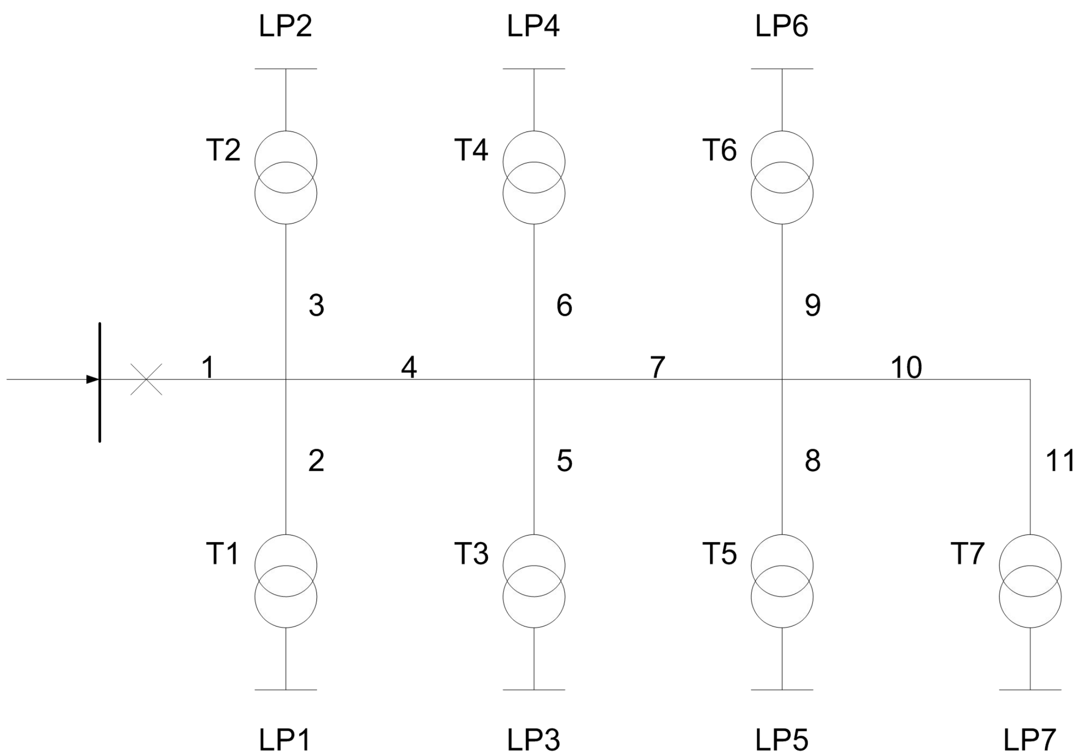

Figure 3.1 Diagram for Basic Case

The failure rate matrix of distribution lines is shown as below,

$$\lambda_L = [0.0488 \quad 0.0390 \quad 0.0520 \quad 0.0488 \quad 0.0520 \quad 0.0390 \quad 0.0488 \quad 0.0520 \quad 0.0488 \quad 0.0390 \quad 0.0520] \tag{3.11}$$

Since there is no protective equipment at lateral lines, fault occurs on every line and each transformer will trip the breaker and thus, interrupt all the customers. Hence, R_L and R_T should be all-ones matrices.

$$R_L = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \qquad R_T = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{3.12}$$

Then the number of interruptions and interruption duration can be calculated by the methodology proposed.

The number of interruptions and interruption duration caused by lines are as follows,

$$R_L(i) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{3.13}$$

$$I_L(i) = R_L(i)\lambda_L^{\ T} = 0.52 \tag{3.14}$$

Interruption duration of load i caused by distribution line j is

$$U_L(i,j) = r_L R_L(i,j)\lambda_L(1,j) \tag{3.15}$$

where, $r_L = 5h$.

In this case, the interruption duration for load i is

$$\sum_{j=1}^{n} U_L(i,j) = 2.6 \text{, for all } i \tag{3.16}$$

Then the number of interruption and duration caused by transformers can be obtained.

$$\lambda_T = [0.015 \quad 0.015 \quad 0.015 \quad 0.015 \quad 0.015 \quad 0.015 \quad 0.015] \tag{3.17}$$

$$R_T(i) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{3.18}$$

$$I_T(i) = R_T(i)\lambda_T{}^T = 0.105 \tag{3.19}$$

The interruption duration for load i caused by transformer j is,

$$U_T(i,j) = r_T R_T(i,j)\lambda_T(1,j) = 200 \times 1 \times 0.015 = 3, \text{ for all } i, j \tag{3.20}$$

In this case,

$$\sum_{j=1}^{7} U_T(i,j) = 21, \text{ for all } i \tag{3.21}$$

Then the total number of interruption and interruption duration for each load can be calculated.

$$I(i) = I_L(i) + I_T(i) = 0.52{+}0.105 = 0.625 \tag{3.22}$$

$$U(i) = \sum_{j=1}^{l} U_L(i,j) + \sum_{j=1}^{m} U_T(i,j) = 2.6 + 21 = 23.6 \tag{3.23}$$

Hence, all the load will experience 0.625 times interruption in a year and the duration is 23.6 hours.

Therefore,

$$\text{SAIFI}{=}\frac{\sum N_i\lambda_i}{\sum N_i} = \frac{\sum N_i I(i)}{\sum N_i} = 0.625 \tag{3.24}$$

$$\text{SAIDI}{=}\frac{\sum N_i U_i}{\sum N_i} = \frac{\sum N_i U(i)}{\sum N_i} = 23.6 \tag{3.25}$$

The units for SAIFI and SAIDI are interruption/customer.yr and hr/customer.yr, respectively.

3.2.2 Case 2

In this case, the transformer is assumed to be protected by a fuse in each lateral. When a short circuit fault occurs, the corresponding fuse will blow and will disconnect that lateral. Hence, the fault on that lateral will not affect loads on other laterals. The interruption duration for the corresponding load is the repair time of failure.

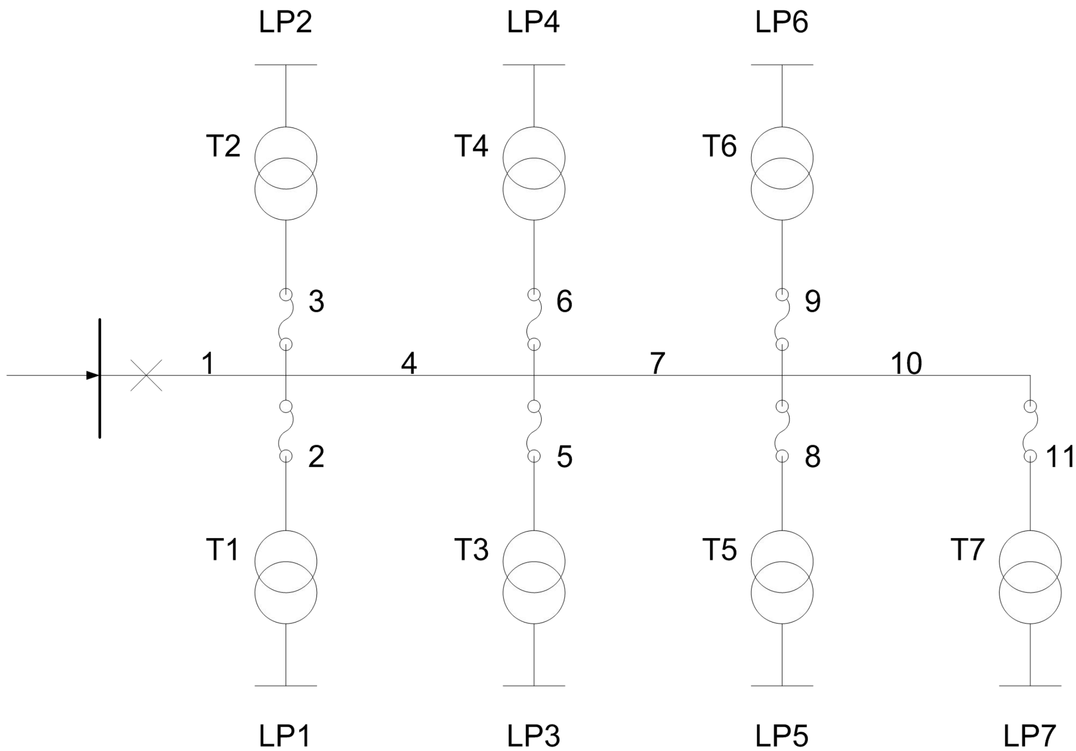

Figure 3.2 Diagram for Case 2

In this case the R_L and R_T matrix will not be all-ones matrix anymore. $R_L(i,j)=1$, if j=1,4, 7,10 and if load i is connected to line j.

$$R_L = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{3.26}$$

Now take load 1 as an example, the number of interruptions is,

$$I_L(1) = R_L(1)\lambda_L{}^T = 0.2244 \tag{3.27}$$

Interruption duration of load i caused by distribution line j is,

$$U_L(i,j) = r_L R_L(i,j)\lambda_L(1,j) \tag{3.28}$$

The interruption duration for load i is,

$$U_L(1) = \sum_{j=1}^{11} U_L(1,j) = 1.22 \tag{3.29}$$

Now, we can evaluate the interruption caused by transformers. Load i will only be affected by transformer j which connected directly to load i. Therefore,

$$R_T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{ 2.30}$$

For load 1,

$$R_T(1) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.31}$$

$$\lambda_T = [0.015 \cdots 0.015] \tag{3.32}$$

$$I_T(1) = R_T(1)\lambda_T{}^T = 0.015 \tag{3.33}$$

$$U_T(1,1) = r_T R_T(1,1)\lambda_T(1) = 3 \tag{3.34}$$

$$U_T(1,j) = r_T R_T(1,j)\lambda_T(1) = 0, \text{ for } 2 \le j \le 7 \tag{3.35}$$

Thus,

$$\sum_{j=1}^{7} U_T(i,j) = 3 \quad \text{for all } i \tag{3.36}$$

Then we can calculate the total number of interruptions and interruption duration for each load.

$$I(1) = I_L(1) + I_T(1) = 0.2244 + 0.015 = 0.2394 \quad (3.37)$$

$$U(1) = \sum_{j=1}^{11} U_L(1, j) + \sum_{j=1}^{7} U_T(1, j) = 1.122 + 3 = 4.122 \quad (3.38)$$

Finally SAIFI and SAIDI can be calculated as,

$$\text{SAIFI}=\frac{\sum N_i \lambda_i}{\sum N_i} = \frac{\sum N_i I(i)}{\sum N_i} = 0.248 \quad (3.39)$$

$$\text{SAIDI}=\frac{\sum N_i U_i}{\sum N_i} = \frac{\sum N_i U(i)}{\sum N_i} = 4.165 \quad (3.40)$$

The units for SAIFI and SAIDI are interruption/customer.yr and hr/customer.yr, respectively.

3.2.3 Case 3

In this case, disconnects are applied in the distribution system. When disconnect is added, faults on feeders will still cause circuit breaker operates. Thus, R_L and R_T are all-ones matrices, and the number of interruptions is the same as in case 1. However, loads between the circuit breaker and disconnects will be recovered before fault is cleared in this case. The interruption duration for those loads becomes the isolation and switching time, rather than the repair time.

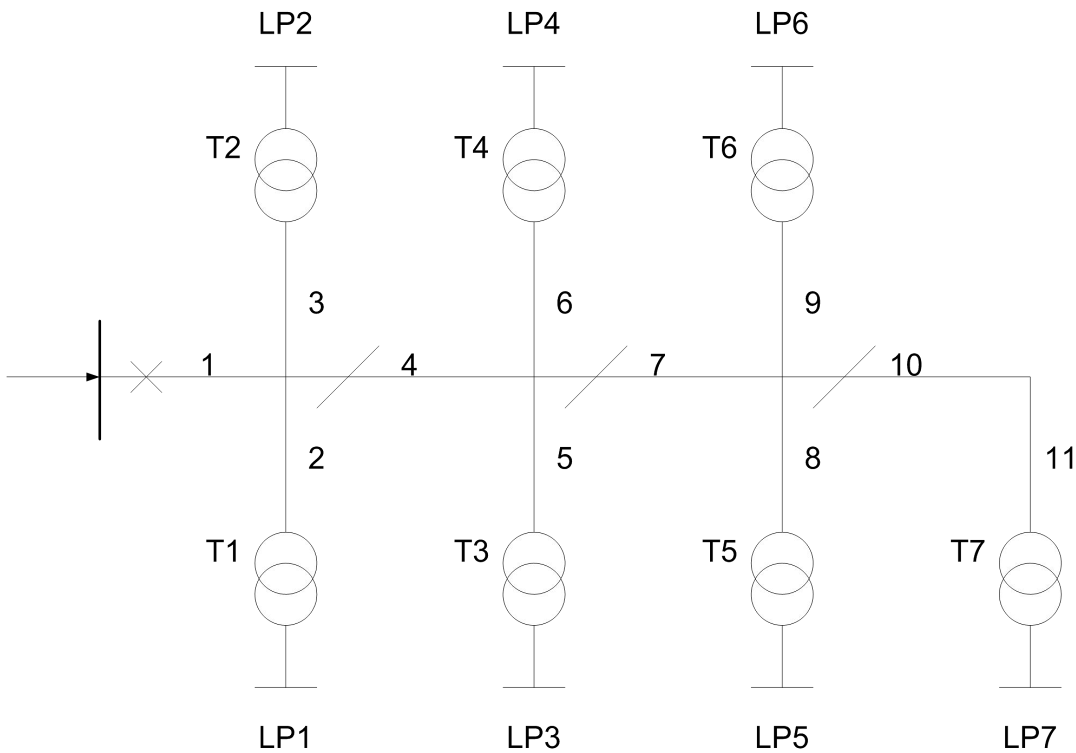

Figure 3.3 Diagram for Case 3

Let the isolation and switching time s equals 1 hour in this case. Let Z_i be the nearest line to load i which installed disconnect. For example $Z_1 = Z_2 = 4$, which means the nearest disconnect are installed on line 4 for load 1 and load 2. Then the interruption duration could be calculated as follows,

$$U_L(i,j) = \begin{cases} r_L R_L(i,j)\lambda_L(1,j), & j < Z_i \\ sR_L(i,j)\lambda_L(1,j), & \text{otherwise} \end{cases} \tag{3.41}$$

For example,

$$U_L(1,1) = r_L R_L(1,1)\lambda_L(1,1) = 5 \times 1 \times 0.0488 = 0.244 \tag{3.42}$$

$$U_L(1,5) = sR_L(1,5)\lambda_L(1,5) = 1 \times 1 \times 0.0520 = 0.0520 \tag{3.43}$$

After finding all the $U_L(1,j)$, then sum them up,

$$\sum_{j=1}^{11} U_L(1,j) = 0.871 \quad (3.44)$$

When calculating the duration caused by transformers, it is similar to the way of calculating duration caused by lines,

$$U_T(i,j) = \begin{cases} r_T R_T(i,j)\lambda_T(1,j), & j \in Y_i \\ sR_T(i,j)\lambda_T(1,j), & \text{otherwise} \end{cases} \quad (3.45)$$

Where, $Y(i)$ is a set of transformers which are in the same zone of load *i*.

For instance, $Y_1 = Y_2 = \{1,2\}, Y_7 = \{7\}$, then

$$U_T(1,1) = U_T(1,2) = r_T R_T(1,1)\lambda_T(1,1) = 200 \times 1 \times 0.015 = 3 \quad (3.46)$$

$$U_T(1,j) = sR_T(1,j)\lambda_T(1,j) = 1 \times 1 \times 0.015 = 0.015, \text{ for } 3 \le j \le 7 \quad (3.47)$$

After obtaining all the $U_T(1,j)$, we are able to calculate,

$$\sum_{j=1}^{7} U_T(1,j) = 6.075 \quad (3.48)$$

Thus,

$$U(1) = 0.871 + 6.075 = 6.946 \quad (3.49)$$

After finding all the $U(i)$, it is easy to obtain that SAIDI is equal to 9.740, and SAIFI is the same as in case 1, which is 0.625. The units for SAIFI and SAIDI are interruption/customer.yr and hr/customer.yr, respectively.

3.2.4 Case 4

In this case, both fuses and disconnects are applied to protect the power grid. The number of interruptions is the same as in case 2, since faults on line 1, 4, 7, 9 will still trip the circuit breaker, though disconnects are installed. The way to calculate the interruption duration is the same as in case 3. But the results are different, since R_L and R_T matrix are varied.

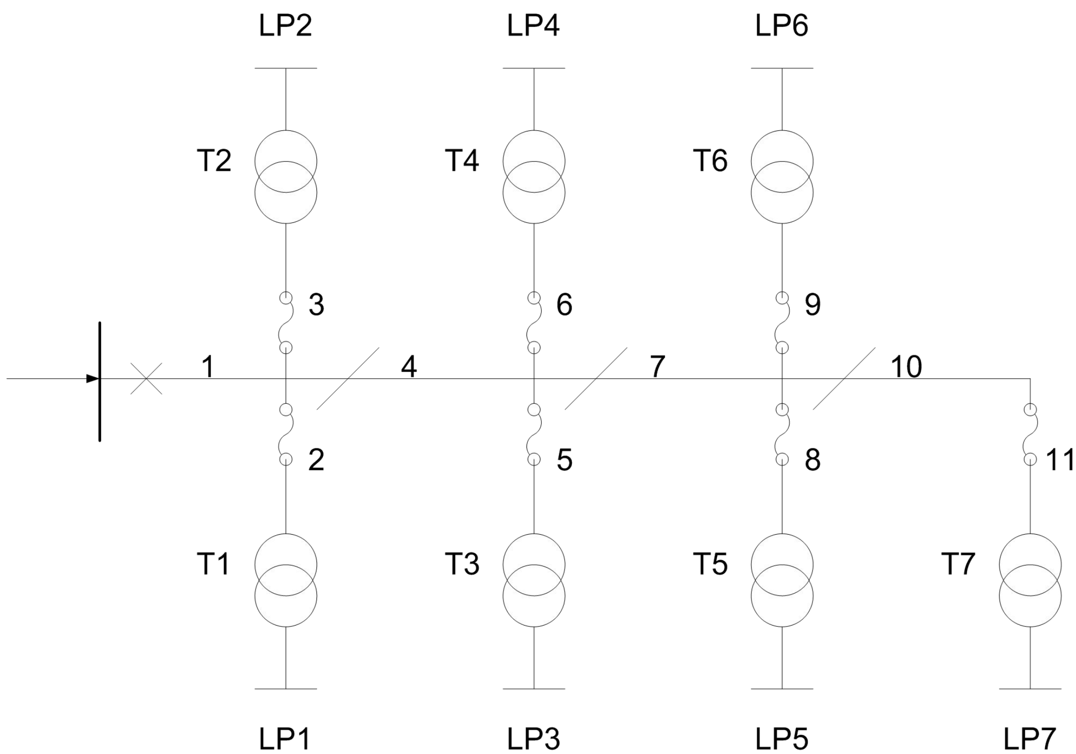

Figure 3.4 Diagram for Case 4

In this case,

$$R_L = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{3.50}$$

$$U_L(i,j) = \begin{cases} r_L R_L(i,j)\lambda_L(1,j), & j < Z_i \\ sR_L(i,j)\lambda_L(1,j), & \text{otherwise} \end{cases} \tag{3.51}$$

Take load 1 as an example,

$$U_L(1,1) = r_L R_L(1,1)\lambda_L(1,1) = 5 \times 1 \times 0.0488 = 0.244 \tag{3.52}$$

$$U_L(1,5) = sR_L(1,5)\lambda_L(1,5) = 1 \times 0 \times 0.0520 = 0 \tag{3.53}$$

Then,

$$\sum_{j=1}^{11} U_L(1,j) = \ 0.5753 \tag{3.54}$$

For transformers,

$$R_T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.55}$$

$$U_T(i,j) = \begin{cases} r_T R_T(i,j)\lambda_T(1,j), & j \in Y_i \\ sR_T(i,j)\lambda_T(1,j), & \text{otherwise} \end{cases} \tag{3.56}$$

$$U_T(1,1) = r_T R_T(1,1)\lambda_T(1,1) = 200 \times 1 \times 0.015 = 3 \tag{3.57}$$

$$U_T(1,j) = sR_T(1,j)\lambda_T(1,j) = 1 \times 0 \times 0.015 = 0, \text{for } 3 \le j \le 7 \tag{3.58}$$

$$\sum_{j=1}^{7} U_T(1,j) = \ 3 \tag{3.59}$$

Thus,

$$U(1) = 0.5753 + 3 = 3.5753 \tag{3.60}$$

Finally, it is found that SAIDI is 3.697 hr/customer.yr. SAIFI is 0.248 interruption/customer.yr, which is the same as in case 2.

3.2.5 Case 5

As shown in Figure 3.5 line 12 is connected to an alternative supply. In this case, the number of interruption is the same as in case 2, so as SAIFI. But the interruption duration will be shortened. For example, if there is a fault occurs on line 4, the breaker will trip and all the loads will be affected. Then the disconnects on line 4 and line 7 will open which isolates the fault, and then the breaker will reclosed. After this step, load 1 and load 2 are recovered. Later on, the normally open disconnect on line 12 will close, load 5, 6, 7 will be recovered. Therefore, the interruption duration for these loads, will change to the isolation and switching time, instead of the repair time of fault in line 4 as in case 3.

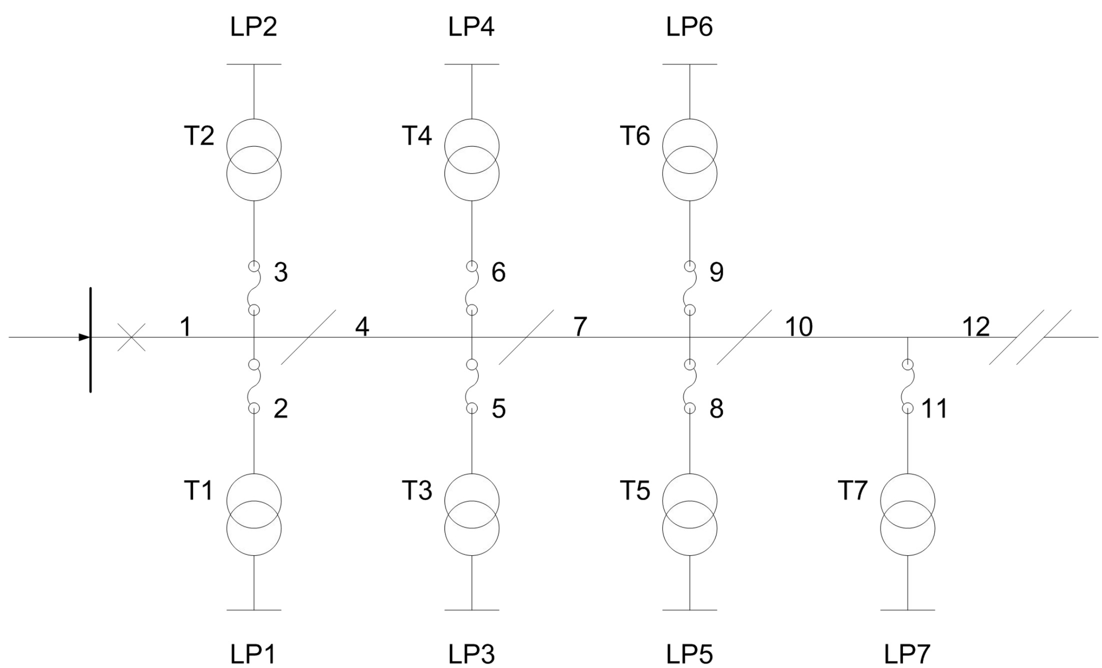

Figure 3.5 Diagram for Case 5

The procedure to value the interruption duration is described below.

Let's define a set *Z* to represent the protection zone sectioned by disconnects.

For example, $Z_1 = \{1,2,3\}, Z_3 = \{4,5,6\}$.

$$U_L(i,j) = \begin{cases} r_L R_L(i,j)\lambda_L(1,j), & j \in Z_i \\ sR_L(i,j)\lambda_L(1,j), & \text{otherwise} \end{cases} \quad (3.61)$$

Take load 1 as an example, since $Z_1 = \{1,2,3\}$,

$$U_L(1,1) = r_L R_L(1,1)\lambda_L(1,1) = 5 \times 1 \times 0.0488 = 0.244 \quad (3.62)$$

$$U_L(1,2) = r_L R_L(1,2)\lambda_L(1,2) = 5 \times 0 \times 0.0390 = 0 \quad (3.63)$$

$$U_L(1,3) = r_L R_L(1,3)\lambda_L(1,3) = 5 \times 1 \times 0.052 = 0.26 \quad (3.64)$$

The rest $U_L(i,j) = sR_L(i,j)\lambda_L(i,j)$,

For instance,

$$U_L(1,4) = sR_L(1,4)\lambda_L(1,4) = 1 \times 1 \times 0.0488 = 0.0488 \quad (3.65)$$

$$U_L(1,5) = sR_L(1,5)\lambda_L(1,5) = 1 \times 0 \times 0.052 = 0 \quad (3.66)$$

After calculating all the $U_L(1,j)$, we are able to find the interruption duration caused by lines of load 1, which is,

$$\sum_{j=1}^{11} U_L(1,j) = 0.5753 \quad (3.67)$$

The interruptions duration caused by transformers are the same as in case 4, which is 3h. Then,

$$U(1) = 0.5753 + 3 = 3.5753 \quad (3.68)$$

Finally, it is found that SAIFI is 0.248 interruption/customer.yr and SAIDI is 3.613 hr/customer.yr.

3.2.6 Case 6

Protective devices are not 100% reliable, so we need to consider protection failures. In this case, we assume that fuse could operate when it needed with probability 0.9 [6]. Then the number of interruptions and duration will be different to case 5. R_L and R_T in this case is as shown in 3.69 and 3.70.

$$R_L = \begin{bmatrix} 1 & 1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 \\ 1 & 0.1 & 1 & 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 \\ 1 & 0.1 & 0.1 & 1 & 1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 \\ 1 & 0.1 & 0.1 & 1 & 0.1 & 1 & 1 & 0.1 & 0.1 & 1 & 0.1 \\ 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 1 & 0.1 & 1 & 0.1 \\ 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 & 1 & 1 & 0.1 \\ 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 1 \end{bmatrix} \tag{3.69}$$

$$R_T = \begin{bmatrix} 1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \end{bmatrix} \tag{3.70}$$

Then the number of interruptions and duration caused by lines for load 1 are as below,

$$
\begin{aligned}
I_L(1) &= R_L(1)\lambda_L{}^T \\
&= \begin{bmatrix}1 & 1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 1 & 0.1\end{bmatrix}\lambda_L{}^T \\
&= 0.2538
\end{aligned} \tag{3.71}
$$

$$
U_L(i,j) = \begin{cases} r_L R_L(i,j)\lambda_L(1,j), & j \in Z_i \\ sR_L(i,j)\lambda_L(1,j), & \text{otherwise} \end{cases} \tag{3.72}
$$

For instance

$$U_L(1,1) = r_L R_L(1,1)\lambda_L(1,1) = 5 \times 1 \times 0.0488 = 0.244 \tag{3.73}$$

$$U_L(1,2) = r_L R_L(1,2)\lambda_L(1,2) = 5 \times 0.1 \times 0.0390 = 0.0195 \tag{3.74}$$

$$U_L(1,3) = r_L R_L(1,3)\lambda_L(1,3) = 5 \times 1 \times 0.052 = 0.26 \tag{3.75}$$

$$U_L(1,4) = sR_L(1,4)\lambda_L(1,4) = 1 \times 1 \times 0.0488 = 0.0488 \tag{3.76}$$

$$U_L(1,5) = sR_L(1,5)\lambda_L(1,5) = 1 \times 0.1 \times 0.052 = 0.0052 \tag{3.77}$$

Then,

$$\sum_{j=1}^{11} U_L(1,j) = 0.5803 \tag{3.78}$$

The analysis for transformer's affect is similar.

Then the number of interruptions caused by transformers is,

$$I_T(i) = R_T(i)\lambda_T{}^T = 0.024 \quad \text{for all } i \tag{3.84}$$

In this case,

$$
U_T(i,j) = \begin{cases} r_T R_T(i,j)\lambda_T(1,j), & j \in Y_i \\ sR_T(i,j)\lambda_T(1,j), & \text{otherwise} \end{cases} \tag{3.85}
$$

For load 1,

$$U_T(1,1) = r_T R_T(1,1)\lambda_T(1,1) = 200 \times 1 \times 0.015 = 3 \tag{3.86}$$

$$U_T(1,2) = r_T R_T(1,2)\lambda_T(1,2) = 200 \times 0.1 \times 0.015 = 0.3 \tag{3.87}$$

$$U_T(1,j) = sR_T(1,j)\lambda_T(1,j) = 1\times 0.1\times 0.015 = 0.0015, \text{for } 3\le j\le 7 \tag{3.88}$$

Therefore,

$$\sum_{j=1}^{7} U_T(1,j) = 3.3075 \tag{3.89}$$

Then we could calculate the total number of interruptions and duration for each load.

For example,

$$I(1) = I_L(1) + I_T(1) = 0.2538 + 0.024 = 0.2778 \tag{3.90}$$

$$U(1) = \sum_{j=1}^{11} U_L(1,j) + \sum_{j=1}^{7} U_T(1,j) = 0.5803 + 3.3075 = 3.8878 \tag{3.91}$$

Finally, SAIFI and SAIDI can be valued. In this case SAIFI is 0.284 interruption/customer.yr and SIDAI is 3.888 hr/customer.yr.

3.3 Reliability Evaluation for RBTS Busbar 2

In this section the reliability of RBTS busbar 2 [17] will be evaluated. This system contains 36 lines, 22 loads and 1908 customers. The single line diagram for RBTS Busbar 2 is shown in Figure 3.6. Customer data, feeder types and length, loading data, reliability and system data are listed in Table 3.4~3.7.

Table 3.4 Feeder Type and Length

Feeder type	Length/km	Feeder section numbers
1	0.60	2, 6, 10, 14, 17, 21, 25, 28, 30, 34
2	0.75	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35
3	0.80	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36

Table 3.5 Customer Data

Number of load points	Load points	Customer type	Load level per load point, MW		Number of customers
			Average	Peak	
5	1-3, 10, 11	Residential	0.535	0.8668	210
4	12, 17-19	Residential	0.450	0.7291	200
1	8	Small user	1.00	1.6279	1
1	9	Small user	1.15	1.8721	1
6	4, 5, 13, 14, 20, 21	Govt/inst	0.566	0.9167	1
5	6, 7, 15, 16, 22	Commercial	0.454	0.7500	10
Total			12.291	20.00	1908

Table 3.6 Loading Data

Feeder number	Load points	Feeder load, MW		Number of customers
		Average	Peak	
F1	1-7	3.645	5.934	652
F2	8-9	2.15	3.500	2
F3	10-15	3.106	5.057	632
F4	16-22	3.390	5.509	622
Total		12.291	20.00	1908

Table 3.7 Reliability and System Data

Component	λ_P	λ_T	λ''	r	r_P	r''	r_C	s
T 33/11	0.015	0.05	1		15	120	0.083	1
11/0.415	0.015			200	10			1
B33	0.002	0.02	0.5	4	96	8	0.083	1
B11	0.006	0.06	1.0	4	72	8	0.083	1
L33	0.046	0.06	0.5	8	8	8	0.083	2
L11	0.065			5				
Cable	0.040				30			3

Where,

λ_P : permanent(total) failure rate (f/yr) (for lines/cables (f/yr.km))

λ_T : temporary failure rate (f/yr) (for lines/cables (f/yr.km))

λ'' : maintenance outage rate (out/yr)

r : repair time (hr)

r_P : replace time by a spare (hr)

r'' : maintenance outage time (hr)

r_C : reclosure time (hr)

s: switching time (hr)

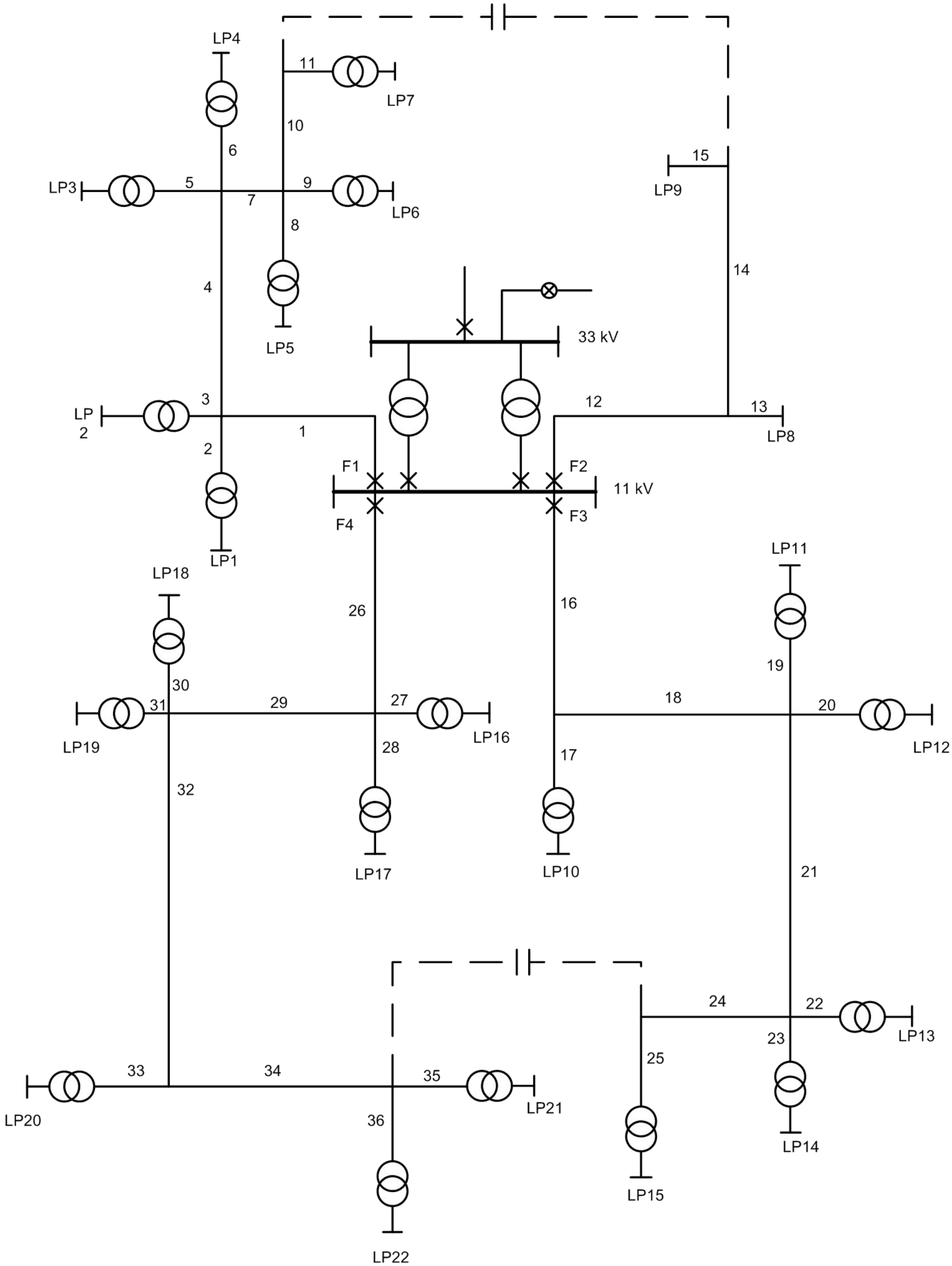

Figure 3.6 Distribution System of RBTS Busbar 2

Reliability of six cases will be calculated and their characteristics are shown in Table 3.8. The differences are the inclusion or not of disconnects in the main feeders, fuses in each lateral, an alternative supply and fuses failures.

Table 3.8 Summary of Six Cases

Case	Fuse	Disconnect	Alternative Supply	Repair of Transformer	Failure of Fuse
1					
2	√			√	
3		√		√	
4	√	√		√	
5	√	√	√	√	
6	√	√	√	√	√

Table 3.9 Result for Case 1

CASE 1		
	SAIFI	SAIDI
F1	0.625	23.6
F2	0.192	0.959
F3	0.558	20.34
F4	0.625	23.6
SYSTEM	0.602	22.496

Table 3.10 Result for Case 2

CASE 2		
	SAIFI	SAIDI
F1	0.248	4.165
F2	0.14	0.699
F3	0.25	4.174
F4	0.247	4.16
SYSTEM	0.248	4.163

Table 3.11 Result for Case 3

CASE 3		
	SAIFI	SAIDI
F1	0.625	9.740
F2	0.192	0.777
F3	0.558	8.465
F4	0.625	11.66
SYSTEM	0.602	9.934

Table 3.12 Result for Case 4

CASE 4		
	SAIFI	SAIDI
F1	0.248	3.697
F2	0.14	0.621
F3	0.25	3.76
F4	0.247	3.75
SYSTEM	0.248	3.732

Table 3.13 Result for Case 5

CASE 5		
	SAIFI	SAIDI
F1	0.248	3.618
F2	0.14	0.523
F3	0.25	3.624
F4	0.247	3.605
SYSTEM	0.248	3.613

Table 3.14 Result for Case 6

CASE 6		
	SAIFI	SAIDI
F1	0.286	3.926
F2	0.145	0.529
F3	0.282	3.83
F4	0.285	3.917
SYSTEM	0.284	3.888

Table 3.15 Comparison of Six Cases Results

CASE	SAIFI	SAIDI
1	0.602	22.496
2	0.248	4.163
3	0.602	9.894
4	0.248	3.732
5	0.248	3.613
6	0.284	3.888

3.4 Summary

In this chapter, a methodology is proposed to calculate the reliability indices of distribution system. This methodology is derived from R. Billiton's book [6]. Reference [31] introduced a methodology, zone branch reduction, which also uses matrix to calculate the reliability indices. The comparison between cases demonstrates the effect of protective devices. It is obvious that Case 5 is the most reliable one with lowest SAIFI and SAIDI, since it contains fuses, disconnects and alternative supply and all the protective devices are assumed perfectly reliable. SAIDI in case 1 is bigger than others, since it has no protection except the circuit breaker. The difference of SAIFI between case 2 and case 4 is because of the effect of disconnects. Since, disconnects are able to let the loads which are outside the fault zone recover more quickly. The interruption duration for such loads are decreased from repair time as 5 hours to switching and isolation time as 1 hour. Therefore, SAIDI in case 4 is smaller than case 2. SAIFI of case 2, 3 ,4 and 6 are the same, since fuses are installed in laterals in these four cases. The effects of faults will be reduced by fuses. Hence, SAIFI in these four cases are smaller than case 1 and case 5. Alternative supply is also a very effective way to improve the system reliability. SAIDI is decreased from 3.732 as in case 4 to 3.613 as in case 5.

CHAPTER 4
OPTIMIZATION OF ALLOCATION OF DISCONNECTS USING GENETIC ALGORITHM

4.1 Introduction

The fundamental goal of an electric utility has always been to serve its customers with a reliable and low cost power supply [7]. From the cases in chapter 5, we find that disconnects are helpful to reduce the interruption duration of customers, which is able to enhance the reliability of distribution systems. It is apparent that more the disconnects are installed in the distribution feeder, less the interruption duration is of the customer. However, the investment cost of utility will be more with the increase of the number of disconnects. In recent years, electric utility industry has confronted many challenges in the increasingly competitive market, which demands them to serve its customers with higher reliability and lower cost power supply [20]. The presence of inverse relation between economic constraint and reliability is obvious, as shown in Figure 4.1 [21], so this causes complexity in management decisions. Hence, a method is needed to find an optimum solution with lower investment cost and higher reliability. In this vein, this chapter proposes an optimization method for planning adequate number and location of disconnect in a distribution system with reliability consideration.

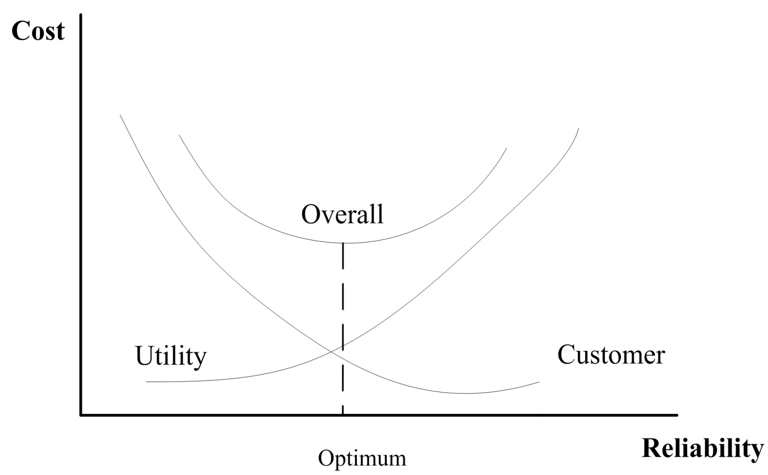

Figure 4.1 Cost as a Function of Reliability

The relationship between allocation of protective devices and SAIDI is complex and the constraint is non-differentiable. Thus, traditional analytical approaches such as linear and nonlinear programming have difficulty in dealing with this optimization problem. Previous work, such as [19][25-26], stated that the problem of location of protective devices naturally has binary specification in distribution networks. Each protective device has two states: connected or disconnected and can be model as 0 and 1, respectively. This specification causes using binary programming method for optimal location of protective devices [20]. However, as the size of the distribution system becomes larger, the possible position to install protective devices increases rapidly and this lead to slower speed when solving this problem by binary programming. Therefore, evolutionary methods are applied to solve this kind of problem [20][27-29]. In recent past, nontraditional search and optimization methods are becoming popular in electrical engineering, such as Genetic Algorithms (GA), Ant colony optimization (ACO) and Particle Swarm Optimization (PSO). The method proposed in this chapter uses GA to find the optimum solution. Genetic algorithms are computerized search and optimization algorithms based on the mechanic of natural genetics and natural selection [23]. This method was first used by J. H. Holland in mid-sixties [22]. The detail of this methodology is presented in the next section.

4.2 Methodology

The goal of system optimization is to minimize an objective function without violating any constrains [18]. The objective of this problem is to minimize the cost of investment, which is equal to the sum of the price of each disconnect.

$$\text{Minimize } F = X^T C$$

Where,

F is the total cost of investment;

C is a vector of the unit price of disconnect, C_i is the price of disconnect installed on possible position i;

X is a vector of decision of positions. x_i is the decision for position i, if $x_i = 1$, which means a disconnect is installed on position i. Otherwise, if $x_i = 0$, this means position i is not connected to a disconnect. The constraint is reliability. In this model, we use SAIDI to evaluated the reliability. Since the change of position and number of disconnects will also let the SAIDI varied. Therefore, SAIDI should be updated each time. This step can be realized by the methodology proposed in chapter 3. Using the methodology proposed in chapter 3, the interruption duration in each feeder and the whole system can be obtained.

Then the constraint is as shown below,

$$S < S_{\max} \tag{4.1}$$

Where S is the Sustained Average Interruption Duration Index (SAIDI), $S_{\max}$ is the maximum SAIDI allowed.

As shown before [3],

$$\text{SAIDI}=\frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Customers Served}} \tag{4.2}$$

Therefore, the mathematical model for this optimization problem can be stated as follows,

$$\begin{aligned} &\text{Minimize } F = X^T C \\ &\text{Subject to} \\ &S < S_{\max} \end{aligned} \tag{4.3}$$

This reliability-based optimization problem is solved by Genetic Algorithm (GA) and the steps of a typical genetic algorithm is as follows [23],

Step 1 Choose a coding to represent problem parameters, a selection operator a crossover operator, and a mutation operator. Choose population size *n*, crossover probability p_c, and mutation probability p_m. Initialize a random population of strings of size *l.* Choose a maximum allowable generation number $t_{\max}$. Set *t=0.*

Step 2 Evaluate each string in the population.

Step 3 If $t > t_{\max}$ or other termination criteria is satisfied, Terminate.

Step 4 Perform reproduction on the population.

Step 5 perform crossover on random pairs of strings.

Step 6 Perform mutation on every string.

Step 7 Evaluate strings in the new population. Set *t=t+1* and go to Step 3.

The detail of each step is presented below.

4.2.1 Coding

In order to solve the optimization problem by GAs, the variables are firstly coded in strings. GAs work with a population of binary string (0 and 1), and because of the characteristic of this problem, binary coding is used in this methodology. With the binary coding method, the decision of possible positions would be coded as a binary string with length *n*, where *n* is the total number of possible positions. The binary-coded string shows the decision for each possible position to connect to a disconnect or not. In the string, “1” represents “connected” and “0” represents “not-connected”. The string *X* can be shown as below,

$$X = \{x_1 \quad x_2 \quad \cdots \quad x_n\} \tag{4.4}$$

Where,

n Number of possible positions to install disconnect

x_i Decision for position *i*, $x_i = 0$ or 1 and $1 \le i \le n$.

4.2.2 Fitness

When dealing with constrained optimization problems, a penalty-parameter-less constraint handling approach is popular used, which is proposed by K. Deb in 2000 [24]. The concept is simple. In a tournament selection operator comparing two population members, three possibilities and corresponding selection strategy were suggested [23]:

(a) When one solution is feasible and the other is infeasible, the feasible solution is selected.

(b) When both solutions are feasible, the one with better function value is selected.

(c) When both solutions are infeasible, the one with smaller constraint violation is selected.

The definition of a Constraint Violation (CV) is determined in [24] . There are two steps to find CV. First, normalize all constraints using the constant term in the constraint function. For example, the constraint $g_j(x) - b_j \geq 0$ is normalized as $\overline{g}_j(x) = g_j(x)/b_j - 1 \geq 0$ [23]. Equality constraints can also be normalized to $\overline{h}_k(x)$. Second, the constraint violation can be determined as follows,

$$CV(x) = \sum_{j=1}^{J} \left\langle \overline{g}_j(x) \right\rangle + \sum_{k=1}^{K} \left| \overline{h}_j(x) \right| \quad (4.5)$$

A way to use the above penalty-parameter-less approach is to convert the problem into the following unconstrained fitness function [23].

$$fitness(x) = \begin{cases} f(x), & \text{if x is feasible} \\ f_{\max} + CV(x), & \text{if x is infeasible} \end{cases} \quad (4.6)$$

Where $f_{\max}$ is the maximum objective function value among the feasible solutions or zero when there is no feasible solution in a population. In this optimum allocation of disconnects problem, the only constraint is the reliability requirement, therefore, CV can be expressed as follows,

$$CV(x) = S(x)/S_{\max} - 1, \text{ if x is infeasible} \quad (4.7)$$

4.2.3 Reproduction

Reproduction, also known as selection operator. Reproduction selects good strings in a population and forms a mating pool [23]. Roulette-wheel selection and tournament selection are often used to form mating pool. In this work, tournament selection is applied. First, pick *s* individuals from the population, then choose the best among them to the mating pool. A binary tournament selection with *s=2* is used in this work. After forming the mating pool, stings in mating pool are going to the next step: crossover.

4.2.4 Crossover

In a crossover operator, new strings are created by exchanging information among strings of the mating pool [23]. This step is mainly responsible for the search of new strings. In order to create new strings, two strings are selected randomly from the mating pool, and these two strings are called parent strings, the newly created strings are known as children strings. After randomly selecting the parent strings from the mating pool, a single-point crossover is applied. First, a crossing point is randomly chosen. Then exchange all the bits on the right side of the crossing point, as shown below,

$$\begin{array}{cc|ccc} 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \end{array} \Rightarrow \begin{array}{cc|ccc} 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 \end{array} \qquad (4.8)$$

Not all the old strings are used in crossover, a crossover probability p_c is used in order to preserve some of the good strings. Only $100 p_c$ percent of old strings are used in crossover operation.

4.2.5 Mutation

Mutation of gene happens with low probability in nature. In GAs, a mutation operation is applied to mimic this change. The mutation operator changes 1 to 0 and vice versa for each bit of every string with a small mutation probability p_m. This step allows the algorithm to a local search around current solutions.

4.3 Case Study

In this section, two cases will be presented. One case is still the RBTS bus 2 [17], another is the whole RBTS system. The information of the whole RBTS system can be found in [17] and [30].

4.3.1 Case 1

There are ten possible locations to install disconnect in this distribution system, which are on line 4, 7, 10, 14, 18, 21, 24, 29, 32 and 34. So we have 10 variables for this system. we can use variables x_1 to x_{10} to represent these possible positions. Then x_1 represents the decision for position 1, which is on line 4 and x_{10} represents the decision for position 10, which is on line 34. For example, if the result shows that x_1 is 1, this means a disconnect is installed on line 4. Variables x_i in the objective function are calculated using MATLAB to obtain the optimum solution. X can be coded as below,

$$X = \{x_1 \quad x_2 \quad \cdots \quad x_{10}\} \qquad (4.9)$$

In this case, the mathematical model is as follows,

$$\text{Minimize } F = X^T C$$

$$\text{Subject to,} \qquad (4.10)$$

$$S < S_{\max}$$

In this case we assume the price for each disconnect is 3000$ [20], that is $C_i = 3000$ for all i. Several optimum solutions for different maximum SAIDI are obtained by MATLAB. The result is listed in Table 4.1. The flowchart for the methodology is as shown in Figure 4.1.

Table 4.1 Optimum Solution for Case 1

SAIDI_max	SAIDI	Position of disconnects	Number of disconnects	Investment cost ($)
3.66	3.6579	4, 18, 21, 29, 32	5	15000
3.63	3.6169	4, 7, 18, 21, 29, 32	6	18000
3.615	3.6150	4,7,10,18, 21, 29, 32	7	21000
3.614	3.6140	4, 7, 10, 18, 21, 24, 29, 32	8	24000
3.613	3.6128	4, 7, 10, 14, 18, 21, 24, 29, 32	9	27000

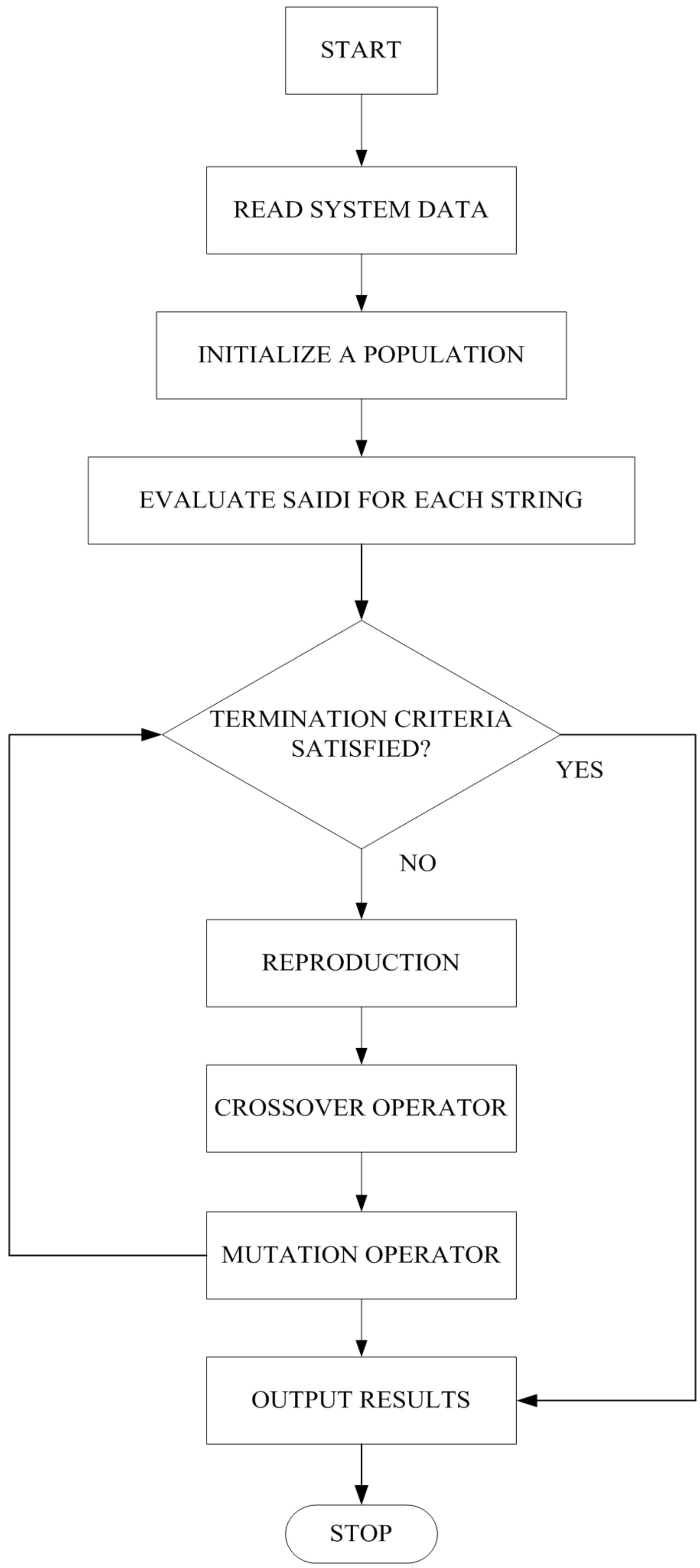

Figure 4.2 Flowchart

4.3.2 Case 2

In this case, the whole RBTS system is used. In this system, there are 287 lines, 170 loads and 18,289 customers in this test system, some of the system data are listed in Table 4.2 [17][30]. 69 possible places are chosen to install disconnects. The optimal solution is obtained by Genetic Algorithm and the result is shown in Table 4.3.

Table 4.2 System Data for RBTS

	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Total
Lines	36	77	67	43	64	287
Loads	22	44	38	26	40	170
Customers	1,908	5,806	4,779	2,858	2,938	18,289
Positions	10	19	16	13	11	69

Table 4.3 Optimum Solution for Case 2

SAIDI_max	SAIDI	Position of disconnects	Number of disconnects	Investment cost ($)
4.0	3.9959	Bus 3: 6, 23, 35, 45, 59 Bus 4: 5, 23, 36, 63 Bus 6: 7, 21	11	33,000
3.9	3.8897	Bus 2: 4 Bus 3: 3, 8, 23, 35, 38, 45, 59 Bus 4: 5, 23, 36, 60, 63 Bus 5: 7, 18, 39 Bus 6: 7, 21	18	54,000
3.8	3.7928	Bus 2: 4, 18, 21, 32 Bus 3: 3, 8, 21, 23, 35, 38, 45, 57, 59 Bus 4: 5, 7, 23, 26, 33, 36, 39, 60, 63 Bus 5: 4, 18, 36 Bus 6: 7, 17, 23	28	84,000
3.7	3.6969	Bus 2: 4, 7, 18, 21, 29, 32 Bus 3: 3, 6, 8, 10, 21, 23, 26, 33, 35, 38, 40, 45, 50, 57, 59, 62 Bus 4: 3, 5, 7, 10, 21, 23, 26, 33, 36, 39, 58, 60, 63, 65 Bus 5: 4, 16, 20, 28, 36, 41 Bus 6: 5, 9, 17, 21, 23	47	141,000

CHAPTER 5
CONCLUSION

5.1 Summary

Protection systems play significant roles in power systems, which help to improve the reliability of power grids. In this thesis, basic reliability indices, such as SAIFI and SAIDI are presented. What's more, this thesis proposes a methodology which is based on the methodology presented in the book "Reliability Evaluation of Power Systems" by R. Billiton, but the methodology in this thesis is easier to implement compared to the original one proposed by R. Billiton. To calculate the number of interruptions and interruption duration for each loads, this method uses matrices to represent the relationship of components, which is very straightforward and self-explanatory. SAIFI and SAIDI of IEEE-RBTS bus 2 system are calculated in six different cases. By comparing the results of the six cases, it is obvious to see the impact of protection systems and protection failures.

Further, based on the methodology of evaluating reliability indices, a reliability-based optimization problem is proposed and solved by Genetic Algorithm. This optimization problem is aim to find the minimum cost of investment of disconnects with reliability constraint. Optimum solutions have been found for RBTS bus 2 and the whole RBTS system. When I first try to solve the optimization problem, the binary programming method is used as applied in [25-26]. However, this method is slower compare to Genetic Algorithm, especially when the system becomes larger. Therefore, GA is chosen to solve the optimization problem. It is suitable for this allocation optimization problem and fast to find the optimum solution.

5.2 Future Work

A multi-objective reliability-based optimization model would be established. The pareto-optimum can be found by performing a multi-objective optimization model. In addition, disconnect is the only protective device taken into consideration in this work. Other protective devices, such as reclosers, relays and fuses would also be considered in an optimization problem in the future.

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