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Enhancing Distribution Network Reliability through Optimal Placement of Sectionalizing Switches and Tie Lines based on Fault Incidence Matrix

by

Arbind Kumar Jha

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE IN POWER SYSTEM ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING
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Thesis Supervisor

Assoc. Prof. Mahammad Badrudoza

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Lalitpur, Nepal
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CERTIFICATE OF APPROVAL

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ABSTRACT

Improving the reliability of electric power distribution networks has become a key priority for today's utility providers. Repeated power interruptions and extended recovery periods not only inconvenience customers but also disrupt economic activities and undermine confidence in the power system. Sectionalizing switches and tie lines are essential components in reducing the consequences of faults in power distribution systems, as they allow faulty sections to be quickly isolated and help restore service to unaffected areas. Despite their importance, deciding how many of these devices are needed and where they should be installed is a complex planning task. This difficulty arises from the interplay of network structure, fault behavior, varying customer loads, and financial constraints. To address this challenge, the present study introduces a structured approach to enhance both reliability and operational performance in distribution networks by optimally placing sectionalizing switches and tie lines using a Fault Incidence Matrix (FIM). FIM offers a clear and organized way to model how faults spread across the network and to assess the resulting customer interruptions under different fault conditions. When combined with standard reliability metrics such as Expected Energy Not Supplied (EENS), the proposed method directly connects fault characteristics with reliability outcomes and the associated costs of power outages. The optimization problem is formulated with the objective of minimizing the total system cost, which includes the cost of expected energy not supplied, installation and maintenance costs of sectionalizing switches, and construction costs of tie lines, while satisfying operational constraints such as radial network structure and unique load restoration paths. Two metaheuristic optimization techniques, Genetic Algorithm (GA) and Improved Grey Wolf Optimization (IGWO), are employed to solve the problem. The IGWO algorithm incorporates enhancement strategies to improve convergence speed, maintain population diversity, and balance exploration and exploitation, making it well suited for large-scale and discrete distribution planning problems. The methodology is applied to practical 11 kV feeders-Chyasal, Imadol-2, and Lubhu of the Nepal Electricity Authority to demonstrate real-world applicability. Simulation results show that the optimal allocation of sectionalizing switches and tie lines leads to significant reductions in EENS and overall optimization cost. While both algorithms improve system performance, IGWO consistently achieves better solutions with fewer devices and lower total cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

DE	:	Differential Evolution
EENS	:	Expected Energy Not Supplied.
FIM	:	Fault Incidence Matrix.
IGWO	:	Improved Grey Wolf Optimization.
MATLAB	:	Matrix Laboratory
NEA	:	Nepal Electricity Authority
PSO	:	Practical Swarm Optimization
QOBL	:	Quasi-Oppositional Based Learning
SAIDI	:	System Average Interruption Duration Index.
SAIFI	:	System Average Interruption Frequency Index.
SLM	:	Sectional Switch Location Method
TLM	:	Tie Line Location Method

CHAPTER 1. INTRODUCTION

1.1 Background

Electricity is a fundamental requirement of modern life, underpinning critical services, industrial operations, and everyday household activities. To keep these functions running smoothly, a dependable and uninterrupted power supply is essential. The distribution network is central to this task, as it carries electricity from transmission substations to consumers. It is made up of various elements such as feeders, transformers, switches, and tie line that work together to ensure the reliability of the power system.

Among these components, sectionalizing switches and tie lines are especially important for improving the reliability of the distribution network. Sectionalizing switches divide a feeder into smaller sections, making it easier to detect and isolate faults. When a fault occurs, these switches help disconnect only the affected section rather than the entire feeder. As a result, power outages are limited to a smaller area, reducing inconvenience to consumers. Tie lines, on the other hand, connect two or more feeders and allow power to be supplied from an alternative source when one feeder fails. This provides backup support and helps maintain continuous electricity supply during faults or maintenance activities.

The placement of sectionalizing switches and tie lines has a significant impact on the performance of the distribution network. Proper placement helps reduce the number of customers affected by faults and shortens the duration of outages. In addition, well-positioned tie lines improve system flexibility and ensure that power can be restored quickly. Therefore, optimal placement of these components is essential for minimizing outage costs and improving overall customer satisfaction.

However, determining the most effective positioning of sectionalizing switches and tie lines within the network is a challenging task. The process must consider various factors such as network structure, load distribution, fault occurrence, and installation costs. Since many possible placement combinations exist, the problem becomes a complex optimization task. The main objective is to find the best locations and number of switches and tie lines that can improve reliability while keeping costs as low as possible.

Several studies have proposed different optimization methods to solve this problem, including genetic algorithms, particle swarm optimization, and integer programming techniques. Although these methods can produce effective solutions, they often require high computational effort and may face scalability issues when applied to large distribution networks.

To overcome these limitations, a new approach based on the Fault Incidence Matrix (FIM) has been introduced [1]. The FIM represents the relationship between faults and different sections of the distribution network. By using this matrix, critical locations within the network can be identified more efficiently. The method uses a cost function that considers factors such as the number of sectionalizing switches and tie lines, their distances, and expected outage costs to determine optimal placement.

This FIM-based approach offers several advantages over traditional methods. It is computationally efficient and can handle large-scale distribution networks effectively. Its simplicity and lower computational requirements make it suitable for practical applications, including real-time decision-making. Simulation results have shown that this approach can significantly improve network reliability and reduce outage-related costs.

In conclusion, sectionalizing switches and tie lines are essential components of an efficient and reliable electricity distribution network. Their optimal placement plays a key role in minimizing power interruptions and improving service quality. The Fault Incidence Matrix-based method provides a simple, efficient, and scalable solution for optimal placement, helping improve distribution network performance while reducing outage costs.

1.2 Problem Statement

The distribution network is a crucial part of the electrical power system, as it performs the final task of delivering electricity from transmission substations to end consumers. It consists of various components such as feeders, transformers, sectionalizing switches, and tie lines. Among these elements, sectionalizing switches and tie lines play a key role in enhancing network reliability by limiting fault impacts and maintaining power continuity. Their proper placement directly affects the number of customers interrupted and the duration of outages.

When a fault occurs in a distribution feeder, the affected section must be isolated quickly to restore power to the healthy parts of the network. Sectionalizing switches enables this isolation by dividing the feeder into smaller sections, while tie lines allow power to be rerouted from neighboring feeders. However, the effectiveness of these devices depends largely on their location and quantity. Poor placement may lead to unnecessary outages, longer restoration times, and higher operational costs.

The most effective positioning of sectionalizing switches and tie lines within the network is a complex problem that depends on several factors, including network topology, load distribution, fault frequency, and economic constraints. This problem can be formulated as an optimization task where the objective is to minimize the expected outage cost while maintaining acceptable reliability levels.

The total outage cost C_{out}can be expressed as:

$$C_{out} = \sum_{i=1}^{N} \lambda_i \cdot t_i \cdot L_i \cdot C_e \tag{1.1}$$

where

λ_i= fault rate of section i,

t_i= outage duration of section i,

L_i= load connected to section i,

C_e= cost of energy not supplied,

N= number of network sections.

The placement of sectionalizing switches reduces t_i, while tie lines reduce the number of affected sections, thereby minimizing C_{out}.

Existing methods such as genetic algorithms, particle swarm optimization, and integer programming have been used to solve this optimization problem. Although effective, these methods often suffer from high computational burden and scalability limitations when applied to large-scale distribution systems.

To overcome these challenges, this thesis proposes an advanced methodology based on the Fault Incidence Matrix (FIM). The FIM represents the relationship between fault locations and network sections and can be defined as:

$$\mathrm{FIM}(i,j) = \begin{cases} 1, & \text{if fault at section } i \text{ affects section } j \\ 0, & \text{otherwise} \end{cases} \tag{1.2}$$

Using the FIM, critical sections that experience higher fault impact can be easily identified. This information is then incorporated into a cost function that considers the number of sectionalizing switches (S), tie lines (T), installation cost, and expected outage cost:

$$\min \quad J = C_{out} + \alpha S + \beta T \qquad (1.3)$$

where

$\alpha$and $\beta$are cost coefficients for switches and tie lines, respectively.

1.3 Objectives

The main objective of this thesis is to present an advanced approach for the optimal design and placement of sectionalizing switches and tie lines in a distribution network using the Fault Incidence Matrix (FIM). The proposed approach focuses on enhancing network reliability and minimizing outage-related costs by identifying the most suitable locations and the optimal number of sectionalizing switches and tie lines within the distribution system.

To accomplish this objective, the thesis sets out the following specific goals:

- To develop a systematic methodology that utilizes the Fault Incidence Matrix to identify critical sections of the distribution network, with particular emphasis on the placement of sectionalizing switches and tie lines.
- To formulate a comprehensive cost function that incorporates key factors such as the number of installed sectionalizing switches and tie lines, the distances between them, and the expected costs associated with power outages.
- To apply the proposed methodology in determining the optimal number and locations of sectionalizing switches and tie lines in the distribution network to achieve improved operational performance.
- To validate the effectiveness of the proposed approach through appropriate analysis, demonstrating its ability to enhance network reliability and reduce outage costs.
- To compare the proposed methodology with existing approaches to highlight its advantages and practical benefits.

Overall, this thesis aims to introduce an effective and practical methodology for optimizing the design of sectionalizing switches and tie lines in distribution networks. By offering a structured and data-driven approach, the proposed method seeks to improve reliability and reduce outage-related costs. The contribution of this work lies in providing utilities and system operators with a novel decision-support framework that can assist in making more informed and efficient planning decisions regarding the placement of sectionalizing switches and tie lines within modern distribution networks.

1.4 Scope

The scope of this thesis, titled "Enhancing Distribution Network Reliability through Optimal Placement of Sectionalizing Switches and Tie Lines Based on the Fault Incidence Matrix," is to introduce a systematic methodology for determining the strategic placement of sectionalizing switches and tie lines across the distribution network. The Fault Incidence Matrix is employed as a key analytical tool to identify critical network sections that significantly influence reliability performance.

The proposed methodology is primarily focused on enhancing the reliability of the distribution network while reducing outage-related costs. This is achieved by identifying the most suitable number and locations of sectionalizing switches and tie lines, ensuring that faults can be isolated efficiently and power can be restored with minimal disruption to consumers.

In developing the methodology, several important factors are taken into account, including the spacing between sectionalizing switches and tie lines, the total number of devices required to maintain acceptable reliability levels, and the expected costs associated with power outages. These factors are incorporated to ensure that the proposed solution is both technically effective and economically practical.

The methodology presented in this thesis is designed to be applicable to different types of distribution networks. As such, it can serve as a useful decision-support tool for utilities and system operators, helping them make informed and efficient planning decisions regarding the placement of sectionalizing switches and tie lines while accounting for different and changing network conditions.

It is important to note that this thesis does not address the detailed electrical or mechanical design of sectionalizing switches and tie lines. Instead, the focus is strictly on determining their optimal placement within the distribution network to achieve improved reliability performance.

Overall, the scope of this work is to present a novel and practical approach for optimizing the placement of sectionalizing switches and tie lines in distribution networks. The findings of this study aim to contribute to the field of power system engineering and provide tangible benefits to utilities and system operators by supporting efforts to improve the reliability of the network and reduce the frequency and impact of power outages.

1.5 Thesis Organization

The thesis contains total of six chapters, and each chapter contains the following:

Chapter 1 gives the highlight of the distribution system and the importance of reliability in power systems. The statement of the problem, various objectives and scope are also highlighted.

Chapter 2 focuses on the literature that this thesis has gone through. Also provide brief introduction of Fault Incidence Matrix, power distribution system and optimization.

Chapter 3 detailly explains the methodology to achieve the proposed objectives. It discusses reliability indices and cost functions to be calculated for the optimization of the sectional switch and Tie Lines. And discuss about Improved Grey Wolf Optimization of the algorithm.

Chapter 4 presented the systems consideration.

Chapter 5 presented the results and discussions of the proposed mechanism in various case scenarios.

Chapter 6 concludes the works and suggests the recommendations for future.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Introduction

The design and placement of sectionalizing switches and tie lines are essential for maintaining the reliability of electricity distribution networks. Over the past several years, a wide range of studies have explored different approaches to optimizing these components to improve fault isolation and service restoration. This literature review provides an overview of important research contributions in this area and identifies key limitations in existing approaches. It also outlines the research gaps that motivate and justify the methodology proposed in the present thesis.

2.1.1 Methods for Optimal Design of Sectional Switch and Tie Lines.

Several approaches have been proposed in the literature for the most effective design and arrangement of sectionalizing switches and tie lines in distribution networks. These methods differ in terms of complexity, accuracy, and computational requirements. The most commonly used approaches include scheme comparison methods, heuristic methods, intelligent algorithmic methods, and mathematical programming techniques.

a. Scheme Comparison Method

The scheme comparison method involves developing multiple design alternatives based on predefined criteria and evaluating their performance. In this approach, different configurations of sectionalizing switches and tie lines are created and analyzed using simulation tools or mathematical models. Each configuration is assessed in terms of fault isolation capability, system restoration time, reliability, and cost. The results of these evaluations are then compared, and the most suitable design is selected based on the specified criteria.

Advantages:

- Simple and straightforward to apply.
- Capable of providing quick insights into different design options.
- Allows both qualitative and quantitative comparison of alternative configurations.

Limitations:

- Does not always guarantee a globally optimal solution.
- It can become time-consuming when a large number of design options are evaluated.
- Strongly depends on predefined criteria, which may not fully capture all influencing factors.

b. Heuristic Method

Heuristic methods rely on practical experience, engineering judgment, and rule-based decision-making to address complex design problems. In the case of sectionalizing switches and tie lines, heuristics may be developed based on factors such as load density, feeder length, distance from the substation, or proximity to critical loads. These rules of thumb help guide the placement of devices without requiring detailed mathematical modeling.

Advantages:

- Easy to understand and implement.
- Requires limited computational effort.
- Produces practical solutions grounded in real-world experience.

Limitations:

- Does not ensure optimal solutions.
- Results may vary depending on the expertise of the individual applying the method.
- Less effective for large or highly complex distribution networks.

c. Intelligent Algorithmic Method

Intelligent algorithmic approaches use advanced optimization techniques inspired by artificial intelligence to solve the optimal design problem. Algorithms such as genetic algorithms, particle swarm optimization, and ant colony optimization are commonly applied to search for near-optimal configurations of sectionalizing switches and tie lines. These methods can explore a large solution space and adapt their search strategies based on feedback from previous iterations.

Advantages:

- Suitable for solving complex and large-scale problems.
- Capable of identifying global or near-optimal solutions.
- Flexible and adaptable to different objective functions and constraints.

Limitations:

- Often computationally intensive.
- May require significant data for calibration and validation.
- Implementation and tuning can be technically demanding.

d. Mathematical Programming Method

Mathematical programming techniques formulate the design problem as an optimization model with clearly defined objective functions and constraints. Methods such as linear programming, integer programming, and mixed-integer programming are used to determine optimal switch and tie-line placement. These approaches provide a structured and rigorous framework for decision-making.

Advantages:

- Offers a systematic and theoretically sound optimization approach.
- Can guarantee optimal solutions under specific conditions.
- Effectively incorporates multiple objectives and constraints.

Limitations:

- Requires strong expertise in mathematical modeling.
- Computational complexity increases with network size.
- May be less suitable for dynamic or real-time applications.

In summary, the most effective design and arrangement of sectionalizing switches and tie lines can be achieved using various methods, each with its own strengths and limitations. The choice of an appropriate approach depends on the complexity of the distribution network, available computational resources, and the level of expertise of the engineers or researchers involved. A careful selection of methodology is therefore essential to achieving a reliable and cost-effective distribution network design.

2.1.2 Past Paper Reviews: Literature Review and Research Summary

Early research on the optimal design of sectionalizing switches in distribution networks was carried out by Soliman and El-Saadany (2003). In their work, the authors introduced a probabilistic approach to identify optimal switch locations with the objective of minimizing outage costs. Their methodology combined genetic algorithms with Monte Carlo simulations to account for uncertainty in fault occurrences. While the study demonstrated promising results in improving reliability, it focused solely on sectionalizing switches and did not consider the role of tie lines. The authors themselves recognized this limitation and highlighted the need for future research to incorporate tie lines into the design framework.

Subsequent studies expanded on this foundation by considering both sectionalizing switches and tie lines, recognizing their combined importance in improving distribution network reliability. A major challenge identified in this area is the balance between enhancing reliability and controlling investment and operational costs. To address this issue, many researchers have developed cost-based optimization models that account for factors such as the number of switches and tie lines, their placement, and the expected cost of power outages.

Teng and Chang (2006) introduced a genetic algorithm–based approach to identify the most effective locations for installing sectionalizing switches and tie lines. Their approach employed a cost function that included switch installation costs, tie-line installation costs, and expected outage costs. The proposed method was tested on a benchmark distribution network, and the results showed noticeable improvements in system reliability along with a reduction in outage-related costs, demonstrating the effectiveness of evolutionary optimization techniques for this problem.

Similarly, Zeng and Lu (2012) developed a mathematical optimization model that considered fault occurrence probabilities and outage costs when determining the optimal locations of sectionalizing switches and tie lines. Their model integrated reliability performance and economic factors into a unified framework. Application of the model to a real distribution network confirmed its ability to identify effective placement strategies that enhance reliability while maintaining reasonable costs.

Despite these advancements, several challenges remain unresolved. One of the most significant issues is scalability, particularly when applying existing methodologies to large and complex distribution networks. In addition, many optimization-based approaches involve high computational complexity, which can limit their practical implementation by utilities and system operators.

To overcome these limitations, researchers have proposed hybrid and more computationally efficient methods. Kulkarni et al. (2015) introduced a hybrid approach that combined genetic algorithms with a rule-based expert system. This method leveraged both optimization capabilities and practical engineering knowledge, resulting in improved scalability and reduced computational burden. The study demonstrated that the proposed technique could effectively enhance network reliability and lower outage costs.

Yang et al. (2017) presented another optimization-based approach using particle swarm optimization. Their methodology incorporated factors such as switch costs, inter-device distances, and expected outage costs into the objective function. Testing on a practical distribution network showed that the method successfully improved reliability performance while maintaining economic efficiency.

Although existing studies have contributed valuable insights, most of them rely on deterministic models that do not fully capture the uncertainty associated with fault occurrences. Moreover, challenges related to scalability and computational efficiency persist. These limitations highlight the need for new methodologies that can efficiently handle large networks while incorporating fault uncertainty into the design process.

In response to these research gaps, this thesis proposes an optimal design methodology for sectionalizing switches and tie lines based on the Fault Incidence Matrix. The proposed approach aims to improve scalability, reduce computational complexity, and better account for fault-related uncertainties in distribution network planning.

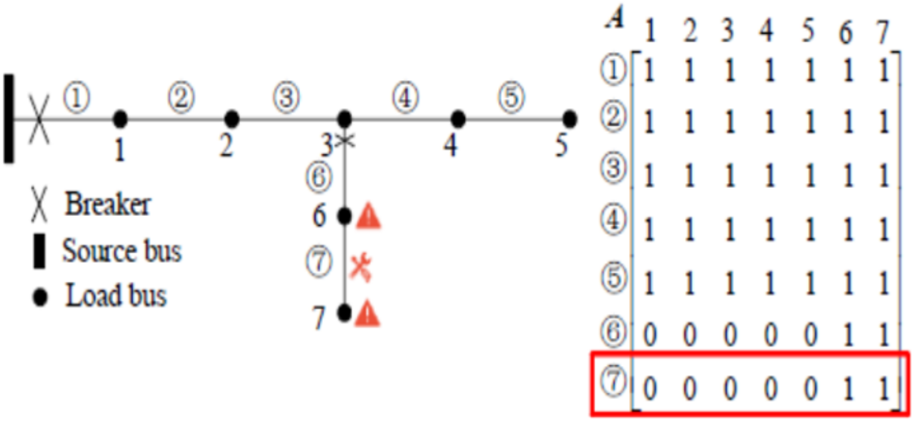
2.2 Fault Incidence Matrix:

The Fault Incidence Matrix (FIM) is a mathematical tool used to describe the relationship between faults and the components of a system or network. It is generally expressed as a binary matrix, where each element indicates whether a specific fault has an impact on a particular component. A value of 1 signifies that the component is affected by the fault, while 0 indicates no influence. Due to its ability to clearly represent fault–component relationships, the Fault Incidence Matrix is widely used in fault diagnosis, reliability assessment, and system optimization studies.

In power distribution systems, sectionalizing switches play an essential role in maintaining system reliability. These switches are installed at selected points along distribution feeders to divide the network into smaller sections. When a fault occurs, sectionalizing switches allow the faulty section to be isolated quickly, enabling faster fault localization and restoration of supply to unaffected areas. This sectionalization significantly reduces outage duration and improves overall system performance.

2.2.1 Formation of Fault Incidence Matrix

To explain the construction of a Fault Incidence Matrix, consider a distribution network that includes seven node and seven branches, also there is circuit breaker installed at branch one and six.



$$
A \quad \begin{array}{c} \\ ① \\ ② \\ ③ \\ ④ \\ ⑤ \\ ⑥ \\ ⑦ \end{array}
\begin{array}{c} \begin{array}{ccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 \\
\boxed{0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1}
\end{bmatrix} \end{array}
$$

Fig 2.1 Formation of FIM with breaker only.

In Fig. 2.1, branches ①–⑦ are considered potential fault locations. The impact of a fault occurring on each branch on the connected loads is represented using the Fault Incidence Matrix (FIM) A. In this matrix, each row corresponds to a faulted branch, while each column corresponds to a load point. The elements of matrix A are binary, taking values of either 0 or 1.

A matrix element equal to 0 indicates that a fault on the corresponding branch does not affect the associated load. In contrast, an element equal to 1 signifies that a fault on that branch will result in an outage of the corresponding load. For example, the highlighted elements $a_{76}$and a_{77} in Fig. 2.1 are both equal to 1, which implies that loads 6 and 7 are affected when branch ⑦ experiences a fault. These loads remain without supply until branch ⑦ is repaired.

Thus, the Fault Incidence Matrix provides a clear and systematic representation of the fault-to-load relationship in the distribution network, enabling efficient reliability assessment.

2.2.2 Effect of Sectionalizing Switch on FIM

Sectionalizing switches are installed to isolate faulty sections of the feeder and restore supply to the upstream loads. As a result, the installation of these switches directly modifies the binary elements of the Fault Incidence Matrix (FIM). When a sectionalizing switch is placed on a branch, it prevents fault propagation beyond that point, thereby changing the fault–load relationship represented in the FIM.

For example, if sectionalizing switches are installed on branches ②–⑤ and ⑦ in Fig. 2.1, the corresponding Fault Incidence Matrices are updated accordingly, as illustrated in Fig. 2.2. These changes reflect the improved fault isolation capability introduced by the switches, which reduces the number of loads affected by downstream faults.

After the installation of sectionalizing switches, load outages in the distribution system can be categorized into two distinct types, which are represented by Fault Incidence Matrices A and B.

Matrix A describes the scenario in which a branch fault causes a load interruption that persists until the faulty branch is repaired. In this case, restoration is not possible through switching actions, and the load remains out of service for the entire repair duration.

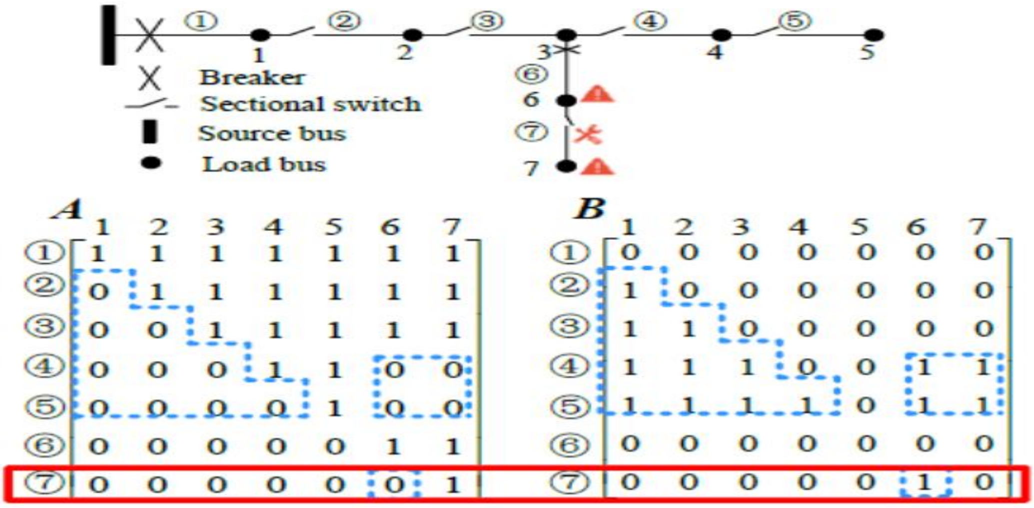


Fig.2.2 Formation of FIM with the effect of sectionalizing switch.

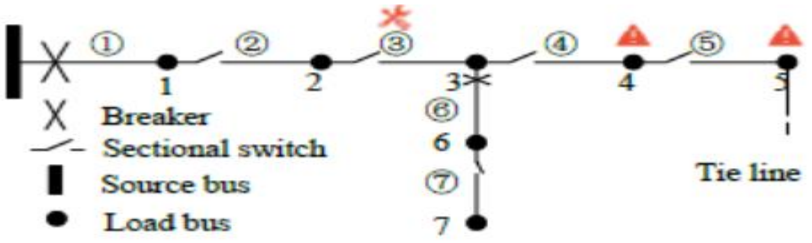
Matrix B, on the other hand, represents outages that occur immediately after a fault but can be resolved through fault isolation using sectionalizing switches, allowing the affected load to be restored from the source bus.

Taking the fault on branch ⑦ as an example, the element a_{77} in matrix A remains equal to 1, indicating that load 7 cannot be restored until the fault is repaired. However, the element a_{76}changes from 1 to 0, while b_{76} becomes 1, which indicates that load 6 can be restored after the fault is isolated by the sectionalizing switch installed on branch ⑦.

2.2.3 Effect of Tie line and Sectional switch combined on FIM.

When tie lines are introduced into the feeder, a third type of load outage arises, which is represented by the Fault Incidence Matrix C. The elements with a value of 1 in matrix C indicate that a fault initially causes a load interruption; however, after the faulty section is isolated, the affected load can be restored by transferring supply through the tie line from an adjacent feeder.

As illustrated in Fig. 2.3, a distribution network is considered where a tie line is added at bus 5. The resulting Fault Incidence Matrices A and C are presented in the same figure. These matrices demonstrate how the presence of the tie line enables additional restoration possibilities, further reducing the number of loads that remain interrupted after a fault.



$$A = \begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline ① & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ ② & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ ③ & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ ④ & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ ⑤ & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ ⑥ & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ ⑦ & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array} \qquad C = \begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline ① & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ ② & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ ③ & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ ④ & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ ⑤ & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ ⑥ & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ ⑦ & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

Fig. 2.3 Formation of FIM with the effect of combined sectionalizing switch and tie line.

With the introduction of a tie line, some of the elements that were originally classified as type-A outages are reassigned to Fault Incidence Matrix C. This reclassification reflects the additional restoration capability provided by the tie line.

For instance, considering the fault on branch ③, loads 4 and 5 are interrupted and must remain out of service until the fault is repaired when no tie line is available. However, after a tie line is installed, these loads can be supplied from an adjacent feeder once the faulty section is isolated. As a result, the outage types of loads 4 and 5 are transferred from FIM A to FIM C.

2.2.4 Reliability Indexes based on Fault Incidence Matrix:

Performance of power distribution networks is commonly assessed using reliability measures such as the System Average Interruption Frequency Index (SAIFI), the System Average Interruption Duration Index (SAIDI), and the Equivalent Energy Not Supplied (EENS). These indices provide quantitative measures of how often power interruptions occur, how long they last, and how much energy is not delivered to customers. The Fault Incidence Matrix (FIM) can be effectively used to estimate these indices by analyzing fault behavior and its impact on customers.

SAIFI represents the average number of service interruptions experienced by a customer over a given period, typically one year. It is calculated as the ratio of the total number of customer interruptions to the total number of customers served by the network. Using the Fault Incidence Matrix, SAIFI can be estimated by examining the number of fault events occurring in different sections of the network and identifying how many customers are affected by each fault. The FIM provides valuable information regarding faulty locations and the associated customer interruptions, enabling an accurate estimation of interruption frequency.

SAIDI reflects the typical amount of time a customer is without electricity over a given period. It is calculated by taking the total time of all customer power interruptions and dividing it by the number of customers supplied by the system. Unlike SAIFI, SAIDI accounts for both how often interruptions occur and how long they last. The Fault Incidence Matrix supports the calculation of SAIDI by providing insights into fault duration and restoration times. Information related to sectionalizing switches and tie lines within the FIM helps determine how quickly power can be restored after a fault, allowing the total interruption duration to be accurately estimated.

EENS quantifies the amount of energy not supplied to customers due to interruptions over a given period. It reflects both the duration of outages and the load demand affected by those outages. EENS can be estimated by combining information from SAIDI with customer demand data. Using the Fault Incidence Matrix, the duration of faults and the demand of the affected customers can be identified, allowing the total unsupplied energy to be calculated more effectively.

The Fault Incidence Matrix plays an important role in assessing how sectionalizing switches and tie lines influence the frequency and duration of faults within the distribution network. By analyzing fault patterns using FIM, planners can evaluate how different switching configurations affect reliability performance. Optimizing the placement and number of sectionalizing switches and tie lines based on the FIM can significantly reduce interruption frequency, shorten outage duration, and minimize the energy not supplied to customers.

As a result, improvements in network design guided by the Fault Incidence Matrix leads to better reliability outcomes, which are clearly reflected through reduced values of SAIFI, SAIDI, and EENS. This demonstrates the effectiveness of FIM as a practical tool for reliability assessment and optimization in power distribution systems.

2.3 Genetic Algorithm

A Genetic Algorithm (GA) is an optimization and search technique inspired by the principles of natural evolution. It is particularly effective for solving complex problems where conventional analytical or deterministic methods may be inefficient or impractical. The fundamental concept behind a GA is the idea of "survival of the fittest," where better solutions gradually evolved through an iterative process.

In a genetic algorithm, each possible solution to the problem is represented in a structured form known as a chromosome. These chromosomes may consist of binary values, real numbers, or symbolic representations, depending on the nature of the problem. A group of such chromosomes forms a population, which is usually generated randomly at the start to ensure diversity among candidate solutions.

The algorithm progresses through a sequence of generations. In each generation, the quality of every chromosome is assessed using a fitness function that reflects how well the solution satisfies the objective of the problem, such as minimizing cost or maximizing reliability. Chromosomes with higher fitness values are more likely to be selected as parents for the next generation.

Selected parent chromosomes are then combined through genetic operations. One of the main operations is crossover, where segments of two parent chromosomes are exchanged to produce new offspring solutions. This process allows beneficial characteristics from different solutions to be combined. Another important operation is mutation, which introduces small random changes in a chromosome. Mutation helps maintain genetic diversity within the population and reduces the risk of the algorithm becoming trapped in a local optimum.

After these operations, a new population of chromosomes is formed, replacing the previous generation. As this evolutionary process continues, the overall quality of the population generally improves, with better solutions becoming more prevalent over time. The algorithm continues to iterate until a stopping condition is met, such as reaching a predefined number of generations or achieving an acceptable solution quality.

Through this evolutionary process, a genetic algorithm can identify highly optimized or near-optimal solutions. Its ability to explore a wide solution space and adaptively improve solutions makes it a powerful tool for solving complex optimization problems in engineering and other fields.

2.4 Improved Grey Wolf Optimization (IGWO)

Grey Wolf Optimization (GWO) is a well-known metaheuristic optimization algorithm inspired by the social hierarchy and cooperative hunting behavior of grey wolves in nature. Due to its simple structure, fast convergence, and limited number of control parameters, GWO has been successfully applied to a wide range of optimization problems. However, despite these advantages, the standard GWO algorithm has certain limitations. In particular, it may suffer from premature convergence and an imbalance between exploration, which focuses on global search, and exploitation, which emphasizes local refinement of solutions.

To address these weaknesses, several improved variants of GWO have been proposed, collectively referred to as Improved Grey Wolf Optimization (IGWO) methods. These enhanced versions aim to strengthen the search capability of the original algorithm by improving diversity, maintaining a better balance between exploration and exploitation, and avoiding stagnation in local optima. IGWO techniques often incorporate additional strategies such as adaptive parameter control, hybridization with other optimization methods, or modified position-updating mechanisms.

This report presents an overview of the fundamental principles of the original GWO algorithm and discusses its inherent limitations that motivate the need for improvement. It further provides a comprehensive discussion of the key strategies employed in IGWO to enhance optimization performance. The overall process of the improved algorithm is also explained through a structured flowchart to clearly illustrate its working mechanism.

2.4.1 Introduction to Grey Wolf Optimization (GWO)

The Grey Wolf Optimization (GWO) algorithm, introduced by Mirjalili et al. in 2014, is a nature-inspired metaheuristic optimization technique that mimics the leadership hierarchy and cooperative hunting behavior of grey wolves. The algorithm models how wolves organize themselves socially and coordinate during hunting to locate and capture prey, which corresponds to finding the optimal solution in an optimization problem.

Social Hierarchy in GWO

Grey wolves follow a strict leadership hierarchy, which is mathematically mapped to candidate solutions in the optimization process. The population is divided into four distinct groups:

1. Alpha(α):
   The alpha wolf symbolizes the leader of the pack and represents the best solution identified up to that point. It guides the search process and has the greatest influence on the movement of other wolves.

2. Beta(β):
   The beta wolf is the second-best solution. It supports alpha by providing alternative guidance and helps maintain balance within the search process.

3. Delta(δ):
   The delta wolf represents the third-best solution. It follows the alpha and beta wolves while dominating the remaining wolves in the hierarchy.

4. Omega(ω):
   The omega wolves represent the rest of the candidate solutions. These wolves follow the guidance of the alpha, beta, and delta wolves during the optimization process.

Hunting Mechanism (Optimization Process)

The hunting behavior of grey wolves is modeled through two main phases: encircling the prey and hunting. These phases drive the optimization process by guiding candidate solutions toward the global optimum.

Encircling the Prey

Grey wolves gradually surround the prey, which represents the optimal solution. This behavior is mathematically modeled as:

$$D = | C \cdot X_p(t) - X(t) | \tag{2.1}$$

$$X(t+1) = X_p(t) - A \cdot D \tag{2.2}$$

where:

- $t$is the current iteration,
- $X_p(t)$is the position vector of the prey (best solution),
- $X(t)$is the current position vector of a grey wolf,
- $A$and $C$are coefficient vectors that control exploration and exploitation.

The coefficient vectors are defined as:

$$A = 2a \cdot r_1 - a \tag{2.3}$$

$$C = 2 \cdot r_2 \tag{2.4}$$

Here, $a$is a control parameter that decreases linearly from 2 to 0 as the iterations progress, while $r_1$and $r_2$are random vectors uniformly distributed in the range $[0, 1]$. The decreasing value of a helps the algorithm transition from exploration to exploitation.

Hunting (Position Updating)

During the hunting phase, the alpha, beta, and delta wolves collaboratively estimate the position of the prey. The omega wolves then update their positions based on the influence of these three dominant wolves. The position update rule is given by:

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \tag{2.5}$$

where X_1, X_2, and X_3represent the updated positions relative to the alpha, beta, and delta wolves, respectively. This averaging mechanism allows the algorithm to balance guidance from multiple high-quality solutions, improving convergence toward the optimal solution.

Overall, the Grey Wolf Optimization algorithm combines social hierarchy and cooperative hunting behavior to efficiently explore the search space and refine candidate solutions. Its simple structure and effective convergence behavior make it a powerful optimization tool, while also providing a strong foundation for further improvements such as the Improved Grey Wolf Optimization (IGWO) variants.

2.4.2. Limitations of the Standard GWO

Premature Convergence:
In the standard GWO algorithm, the control parameter a decreases linearly throughout the iterations. This causes the algorithm to shift too quickly from global exploration to local exploitation. As a result, the search process may become trapped in local optima, particularly when dealing with complex or high-dimensional optimization problems.

Imbalanced Exploration and Exploitation:

The fixed linear reduction of the parameter a does not adequately capture the dynamic and non-linear characteristics of many real-world optimization landscapes. Consequently, the algorithm may fail to maintain an effective balance between exploration and exploitation during different stages of the search process.

Stagnation in Later Iterations:

As the algorithm progresses, the population of candidate solutions tends to converge, leading to a significant reduction in diversity. Without additional mechanisms to reintroduce diversity or guide the search away from local optima, the algorithm may stagnate during the later stages and fail to reach the global optimum.

Sensitivity to Initial Population:

The performance of the GWO algorithm can be strongly influenced by the initial randomly generated population. Poor initial solutions may limit the search capability of the algorithm and reduce the likelihood of obtaining high-quality solutions.

2.4.3. Strategies for Improved Grey Wolf Optimization (IGWO)

IGWO methods integrate various strategies to address the above limitations. Common improvements include:

2.4.3.1. Non-Linear Control Parameter Adjustment

Instead of a linear decrease, the parameter `a` is decreased using a non-linear function (e.g., exponential, sinusoidal, or chaotic map). This allows for a more prolonged exploration phase and a more refined exploitation phase near the end.

Example: `a = a_initial - (a_initial - a_final) * (t / max_iter)^n` where `n` is a non-linear constant.

2.4.3.2. Hybridization with Other Algorithms

GWO is combined with the operators of other algorithms to enhance its search capability.

With Differential Evolution (DE): Incorporates DE's mutation and crossover operations to increase population diversity.

With Particle Swarm Optimization (PSO): Uses PSO's velocity and personal best concepts to improve the movement of wolves.

2.4.3.3 Quasi-Oppositional Based Learning (QOBL)

This technique generates quasi-opposite solutions for the initial population and during the search process. It provides a better starting point and a higher chance of being closer to the global optimum, accelerating convergence.

2.4.3.4. Adaptive Position Update Strategies

The weight of the alpha, beta, and delta wolves in the position update equation is made adaptive based on their fitness, rather than a simple average. A fitter wolf (e.g., alpha) guides the search more strongly.

Example: `X(t+1) = (w_α * X_1 + w_β * X_2 + w_δ * X_3) / (w_α + w_β + w_δ)` (2.6)

2.4.3.5. Lévy Flight Motion

Incorporating Lévy flight, a random walk with occasional long jumps, helps the wolves to escape local optima and explore the search space more effectively.

2.5. Flowchart of a Generic IGWO Algorithm

The following flowchart visualizes the typical structure of an IGWO algorithm, incorporating the improvement strategies mentioned above.

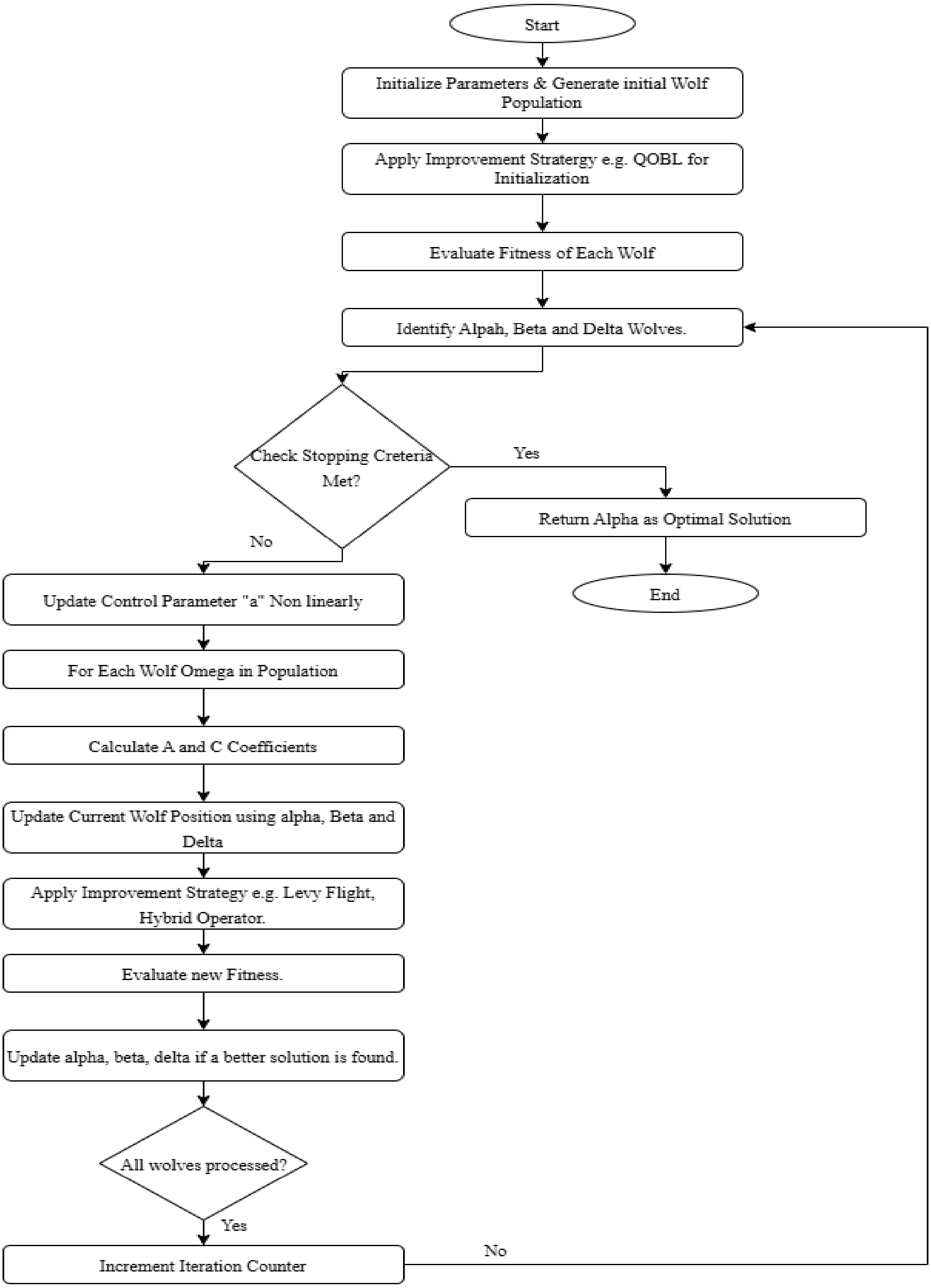


Fig 2.4: Flowchart of IGWO

CHAPTER 3: METHODOLOGY

This chapter explains the complete process used to determine the most effective locations for installing sectionalizing switches and tie lines.

3.1 Introduction

The paper "Enhancing Distribution Network Reliability through the most effective positioning of sectionalizing switches and tie lines within the network based on Fault Incidence Matrix" proposes a methodology for determining the most effective positioning of sectionalizing switches and tie lines in the distribution network. The proposed methodology consists of the following steps:

Step 1: Network Modeling: The first step in the proposed methodology is to model the distribution network. The distribution network is modeled using a one-line diagram, which represents the various components of the network such as transformers, feeders, sectionalizing switches, and tie lines.

Step 2: Fault Incidence Matrix Calculation: The second step is to calculate the fault incidence matrix. The fault incidence matrix is a tool used to identify the location and frequency of faults in the distribution network. The fault incidence matrix is calculated based on the fault data collected from the network operation center or through simulations. The fault incidence matrix is used to identify the critical components in the distribution network, including the sectionalizing switches and tie lines.

Step 3: Optimal Placement of Sectionalizing Switches: The third step is to determine the optimal placement of sectionalizing switches in the distribution network. The optimal placement of sectionalizing switches is determined by using a cost function, which considers the following parameters:

- The number of sectionalizing switches to be installed.
- The expected outage cost, which includes the cost of repair, cost of lost revenue, and cost of inconvenience to the customers.
- The distance between the sectionalizing switches and the fault location.
- The reliability index of the network.

Step 4: Optimal Placement of Tie Lines: The fourth step is to determine the optimal placement of tie lines in the distribution network. The optimal placement of tie lines is determined by using a cost function, which considers the following parameters:

- The number of tie lines to be installed.
- The expected outage cost, which includes the cost of repair, cost of lost revenue, and cost of inconvenience to the customers.
- The voltage profile of the network.
- The network losses.

The cost function is optimized using a metaheuristic algorithm, such as the Improved Grey Wolf Optimization (IGWO), to determine the optimal placement of tie lines.

Step 5: Validation: The final step in the proposed methodology is to validate the results through simulation studies. The proposed methodology is compared with the result of the previous paper and will be implemented on a Nepal Electricity Authority (NEA) distribution network model, and the results are compared with the existing network design. The validation studies include the evaluation of the effectiveness of the proposed methodology in improving network reliability and efficiency.

In summary, the proposed methodology for determining the most effective positioning of sectionalizing switches and tie lines in the distribution network is based on the fault incidence matrix. The proposed methodology uses a cost function and a metaheuristic algorithm to determine the most effective positioning of sectionalizing switches and tie lines within the network. The proposed methodology can be used by network planners and operators to improve network reliability and efficiency.

3.2 BIBC and BCBV load flow

Load flow analysis is performed to assess the steady-state operating conditions of the radial distribution network, both prior to and throughout the reliability assessment and optimization process. The load flow solution provides essential electrical parameters such as bus voltages, branch currents, and power losses, which are later used for reliability assessment and cost evaluation. The Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV) based load flow methods are well suited for radial distribution systems.

The load flow process begins after the network data, including line data and bus load data are defined. These data specify the physical topology of the network, electrical parameters of each branch, and the load demand at every bus. Since the system is radial, the number of branches is one less than the number of buses, which simplifies the formulation of current and voltage relationships.

The Load Flow function is first executed to establish the network configuration. This function identifies the sending and receiving buses of each branch and constructs the BIBC and BCBV matrices. The BIBC matrix captures how current injections at buses flow through different branches based on network topology, while the BCBV matrix relates branch currents to voltage drops using branch impedances. These matrices remain constant as long as the network topology does not change, which makes the load flow computation efficient.

Once the network configuration is established, the load flow function performs the actual load flow analysis. Initially, all bus voltages are assumed to be equal to the rated value (1.0 per unit) with zero phase angle, except for the slack bus which serves as the reference. Using these initial voltages, the load demands specified in the bus data are converted into equivalent current injections at each bus. This conversion is based on the complex power relationship, where the injected current is calculated from the ratio of the load power to the conjugate of the bus voltage.

After computing the bus current injections, branch currents are obtained by multiplying the BIBC matrix with the bus current vector. This step efficiently determines how much current flows through each branch without explicitly tracing each path in the network. Using the calculated branch currents, voltage drops across each branch are then computed using the BCBV matrix, which incorporates branch resistance and reactance. The updated bus voltages are obtained by subtracting these voltage drops from the slack bus voltage.

This process is iterative. The newly calculated bus voltages are used again to recompute bus current injections, branch currents, and voltage drops. The iteration continues until the maximum difference between bus voltages in two successive iterations becomes smaller than a predefined tolerance value. This tolerance ensures numerical accuracy and stable convergence of the solution. The number of iterations required for convergence is recorded, along with the maximum voltage mismatch error.

After convergence is achieved, the final bus voltages represent the steady-state voltage profile of the distribution system. Branch currents obtained at convergence are then used to calculate active and reactive power losses in each branch. These losses are determined using the square of branch current magnitude multiplied by the branch resistance and reactance, respectively. Summing up, the individual branch losses give the total system real and reactive power losses.

The load flow results generated by this process form the electrical foundation of the study. Voltage profiles are used to verify operational feasibility, while branch currents and losses support reliability modeling and economic analysis. By using the BIBC BCBV method, the code achieves a computationally efficient and numerically stable load flow solution, which is particularly suitable for repeated evaluations within the IGWO-based optimization framework.

3.3 Optimization Problem Formulation

3.3.1 Based on FIM the reliability index of the distribution network is calculated as:

$$SAIFI = \lambda \times A \times \frac{n^t}{N} \tag{3.1}$$

$$SAIDI = \lambda \circ \mu \times A \times \frac{n^t}{N} \tag{3.2}$$

$$EENS = \lambda \circ \mu \times A \times P^t \tag{3.3}$$

Here, λ and μ denote vectors that contain the failure rates and repair times of individual branches, arranged according to their respective branch indices. The vectors n and P represent the number of customers and the load demand associated with each load point in the system. N refers to the total number of customers served by the entire network. The symbol ∘ indicates the Hadamard (elementwise) product, meaning that corresponding elements of two vectors or matrices are multiplied together to obtain the result.

3.3.2 The reliability index of the distribution network with the influence of sectional switch is:

$$EENS = (\lambda \circ \mu \times A + \lambda \times t_{sw} \times B) \times P^t \tag{3.5}$$

where, t_{sw} represents the operation time of the sectional switch.

3.3.3 The optimization model of the sectional switch and tie lines are:

a) Sectional switch optimization model for the radial feeder without tie line.

Objective Function:

Minimize:

$$C = C_{EENS} + C_{SW} \tag{3.6}$$

$where,$

$$C_{EENS} = K_{EENS} \cdot EENS \cdot T \tag{3.7}$$

$$C_{SW} = C_{inv} \cdot \sum_{k=1}^{N_x} x_k + C_{mai} \cdot T \cdot \sum_{k=1}^{N_x} x_k \tag{3.8}$$

Where, T represents the switching life duration. C_{EENS} indicates the system outage penalty, which is related to the system outage EENS and the unit outage penalty coefficient K_{EENS}. C_{SW} indicates the investment cost and operation maintenance cost of the sectional switch. C_{inv} and C_{mai} are the unit price and the maintenance cost of the sectional switch. x_k is the sectional switch decision variable, and the value is '1' or '0'. '1' represents the installation of sectional switch on branch k, and '0' represents the no switch on branch k. N_x represents the total number of the network branches.

Constraints:

i. Unique load outage type

$$a_{ij} + b_{ij} \leq 1 \tag{3.9}$$

ii. Constraints between the switch decision variables x_k and the element variables in B.

$$\begin{cases} b_{ij} \geq x_k & x_k \epsilon \boldsymbol{S}_{ij} \\ b_{ij} \leq \sum x_k & x_k \epsilon \boldsymbol{S}_{ij} \end{cases} \tag{3.10}$$

Where, $\boldsymbol{S}_{ij}$ indicates the failure transfer path from the fault branch i to the load j. $x_k \epsilon \boldsymbol{S}_{ij}$ represents that switch x_k is on failure transfer path.

In summary the model of sectional switch optimal allocation for the radial feeder without tie line is expressed as:

Obj.

Minimization

$$C = C_{EENS} + C_{SW} \tag{3.11}$$

$where,$

$$EENS = (\lambda \circ \mu \times A + \lambda \times t_{sw} \times B) \times P^t$$

$$C_{EENS} = K_{EENS} \cdot EENS \cdot T$$

$$C_{SW} = C_{inv} \cdot \sum_{k=1}^{N_x} x_k + C_{mai} \cdot T \cdot \sum_{k=1}^{N_x} x_k$$

s.t.

$$\begin{cases} a_{ij} + b_{ij} \leq 1 \\ b_{ij} \geq x_k \qquad x_k \epsilon \boldsymbol{S}_{ij} \\ b_{ij} \leq \sum x_k \quad x_k \epsilon \boldsymbol{S}_{ij} \end{cases} \tag{3.12}$$

b) Sectional switch optimization model for the radial feeder with tie line.

Objective Function (Minimization)

$$C = C_{EENS} + C_{SW} + C_{\text{Tie Line}} \tag{3.13}$$

Constraints:

i. Unique load outage type

$$a_{ij} + c_{ij} \leq 1 \tag{3.14}$$

ii. Radial structure constraint within the scope of the tie line restoration.

$$c_{ij} \leq c_{ik} \quad k \epsilon \boldsymbol{S}_{tie \cdot j} \tag{3.15}$$

Where, $\boldsymbol{S}_{tie \cdot j}$ indicates the power supply path from the tie line to load j.

iii. For multiple tie lines for one feeder, load must be restored only by one tie line.

$$\sum_{l=1}^{N_{tie}} c_{ij}^{l} \leq 1 \tag{3.16}$$

In summary the model of sectional switch optimal allocation for the radial feeder without tie line is expressed as:

Obj.

Minimization

$$C = C_{EENS} + C_{SW} + \mathrm{C}_{\mathrm{Tie\ Line}} \tag{3.17}$$

$where,$

$$EENS = (\lambda \circ \mu \times A + \lambda \times t_{sw} \times B) \times P^t$$

$$C_{EENS} = K_{EENS} \cdot EENS \cdot T$$

$$C_{SW} = C_{inv} \cdot \sum_{k=1}^{N_x} x_k + C_{mai} \cdot T \cdot \sum_{k=1}^{N_x} x_k$$

s.t.

$$\begin{cases} a_{ij} + b_{ij} + \sum_{l=1}^{N_{tie}} c_{ij}^l \leq 1 \\ b_{ij} \geq x_k \qquad x_k \epsilon \boldsymbol{S}_{ij} \\ b_{ij} \leq \sum x_k \quad x_k \epsilon \boldsymbol{S}_{ij} \\ a_{ij} + \sum_{l=1}^{N_{tie}} c_{ij}^l \leq 1 \\ c_{ij}^l \leq c_{ik}^l \quad k \epsilon \boldsymbol{S}_{tie \cdot j} \\ \sum_{l=1}^{N_{tie}} c_{ij}^l \leq 1 \end{cases} \tag{3.18}$$

3.4 Method of implementation of GA and IGWO for optimal placement of the sectionalizing switch and Tie line

The procedures for the proposed optimal placement of the sectionalizing switch and Tie line using GA are summarized as follows.

3.4.1 Implementation steps using GA.

1. Objective of the Genetic Algorithm

The primary objective of applying the Genetic Algorithm (GA) in this study is to minimize the total real power loss in the distribution network. In addition to loss minimization, the optimization process also considers secondary objectives, including maintaining acceptable voltage levels at all buses and ensuring that the network operates under a radial topology throughout the reconfiguration process.

2. Decision Variables:

The main decision variables in the GA-based optimization are the switch positions within the distribution network. These include both sectionalizing switches, which are normally closed, and tie-line switches, which are normally open. Each candidate solution in the GA is represented as a chromosome, where each gene corresponds to the status of a switch. A binary encoding scheme is adopted, with a value of 0 indicating an open switch and 1 indicating a closed switch.

3. Population Initialization

The GA begins by generating an initial population of candidate solutions, each representing a possible switch configuration of the network. Every chromosome corresponds to a unique network reconfiguration. The initial population may be generated randomly to ensure diversity or guided by heuristic rules to improve convergence speed. For example, a chromosome such as [1 0 0 1 1 ….] represents a specific combination of open and closed switches.

4. Fitness Function Evaluation

The fitness of each chromosome is evaluated using load flow analysis. For a given switch configuration, the following steps are carried out:

The switch states are applied to the network model.

Branch currents, bus voltages, and total real power losses are calculated using the BIBC–BCBV load flow method.

The fitness value is computed based on the total real power loss of the network.

Since the objective is loss minimization, chromosomes with lower power losses are considered to have higher fitness.

5. Selection Process

During the selection phase, the GA chooses the better-performing chromosomes from the current population to serve as parents for the next generation. Common selection techniques such as roulette wheel selection and tournament selection are employed to ensure that fitter solutions have a higher probability of contributing to offspring while still maintaining population diversity.

6. Crossover Operation

Crossover is used to generate new solutions by combining information from two parent chromosomes. In this process, a crossover point is selected, and genetic material is exchanged between the parents to produce offspring. For example, if a single-point crossover occurs at the third gene, two parent chromosomes may generate a child that inherits part of its structure from each parent.

7. Mutation Operation

Mutation introduces random changes in selected genes of a chromosome to maintain genetic diversity and avoid premature convergence. This is typically achieved by flipping the value of a gene, such as changing a switch state from open to closed or vice versa. Mutation helps the algorithm explore new regions of the solution space.

8. Constraint Handling

GA incorporates constraints to ensure feasible network operation. These include maintaining a radial network structure without loops and keeping bus voltages within permissible limits, typically between 0.95 and 1.05 p.u. Constraint violations are handled using penalty functions, where infeasible solutions are assigned higher fitness values by adding penalty terms to the objective function.

9. Iterative Optimization Process

The GA iteratively performs selection, crossover, and mutation over a predefined number of generations. At each iteration, the fitness of all chromosomes is evaluated, and the best solution obtained so far is recorded. This iterative process continues until convergence criteria are satisfied.

10. Final Output of GA

At the end of the optimization process, the GA produces the best chromosome representing the optimal switch configuration. This solution achieves minimum power loss while maintaining a radial network structure and acceptable voltage levels. The final configuration is then applied to the load flow model to confirm the improved performance of the distribution network.

3.4.2 Implementation steps for IGWO

Implementation Procedure of IGWO for Power System Optimization

The implementation of the Improved Grey Wolf Optimization (IGWO) algorithm for power system optimization follows a systematic, step-by-step process that integrates power system modeling with evolutionary optimization.

Step 1: Preparation of the Power System Model

The process begins with the development of a detailed power system model. Line and bus data are loaded, and phantom lines are introduced where necessary to represent alternative switching paths. Switching time patterns are generated, and all bus and line data are organized in a format suitable for simulation. This prepared model serves as the foundation for power-flow analysis and is later used by the IGWO algorithm to evaluate the fitness of candidate solutions.

Step 2: Initialization of the IGWO Population

IGWO starts by generating an initial population of grey wolves, where each wolf represents a potential solution to the optimization problem. In the context of a power system, a wolf may represent a specific configuration such as the ON/OFF status of sectionalizing switches, feeder reconfiguration options, capacitor sizes, or tap settings. Each wolf therefore corresponds to a complete and feasible operating state of the power system.

Step 3: Fitness Evaluation Using Power-Flow Analysis

For each wolf in the population, the power system model is executed through a power-flow analysis. Using the prepared system data, the algorithm evaluates key performance parameters such as bus voltages, power losses, line loading levels, and any operational constraint violations. These results are combined into a fitness value, which represents the quality of the solution and serves as the objective to be minimized or maximized.

Step 4: Ranking of Wolves

After fitness evaluation, the wolves are ranked based on their performance. The best-performing solution is designated as the alpha (α) wolf, the second-best as beta (β), and the third best as delta (δ). The remaining solutions are classified as omega (ω) wolves. The alpha, beta, and delta wolves guide the search process by influencing the movement of the remaining population.

Step 5: Position Update Using IGWO Strategy

The positions of the wolves are updated using the IGWO position-update equations, which are enhancements of the standard GWO formulas. While the basic update follows the structure

$$X_{\text{new}} = X_{\text{leader}} - A \cdot | \, C \cdot X_{\text{leader}} - X \, | \qquad (3.19)$$

IGWO introduces additional mechanisms such as adaptive control parameters, nonlinear convergence control, random mutation, and improved exploration–exploitation balancing. These enhancements help prevent premature convergence, improve diversity, and increase the likelihood of escaping local optima.

Step 6: Generation of New Candidate Solutions

The updated positions of the wolves result in new candidate solutions, such as revised switching plans or modified network topologies. Each new solution is again evaluated through the power system model, and its fitness is recalculated using power-flow results.

Step 7: Iterative Optimization Process

Steps involving fitness evaluation, ranking, and position updating are repeated iteratively. The optimization process continues until a predefined stopping criterion is satisfied, such as reaching the maximum number of iterations, achieving a desired error tolerance, or observing no further improvement in fitness values.

Step 8: Final Output of IGWO

At the end of the optimization process, IGWO outputs the best solution represented by the alpha wolf. This includes the optimal system configuration, such as the best switching scheme, feeder arrangement, or component placement, along with corresponding performance improvements like reduced power losses or enhanced reliability.

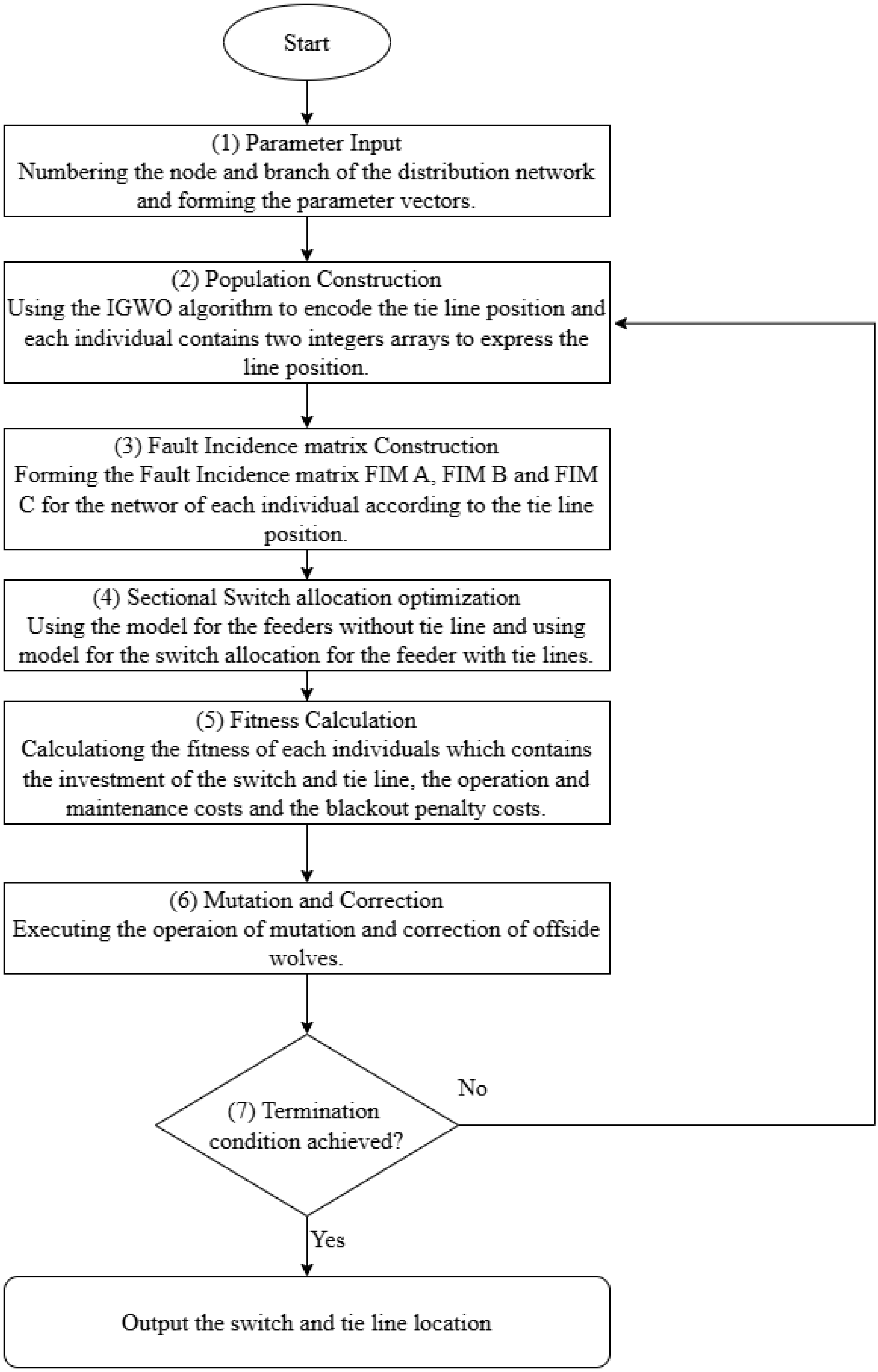


Fig 3.1: Flowchart for joint optimization of sectional switch and tie line.

CHAPTER 4: SYSTEM UNDER CONSIDERATION, SOFTWARE AND TOOLS

4.1 Systems under consideration

The thesis first examines a distribution network of the Taiwan Power Company. To further verify the effectiveness of the proposed methodology, the study is then applied to 11 kV feeder systems of the Nepal Electricity Authority (NEA). The single line diagram along with bus and branches data of the cases are shown below

Case I : Taiwan Power Company Network System

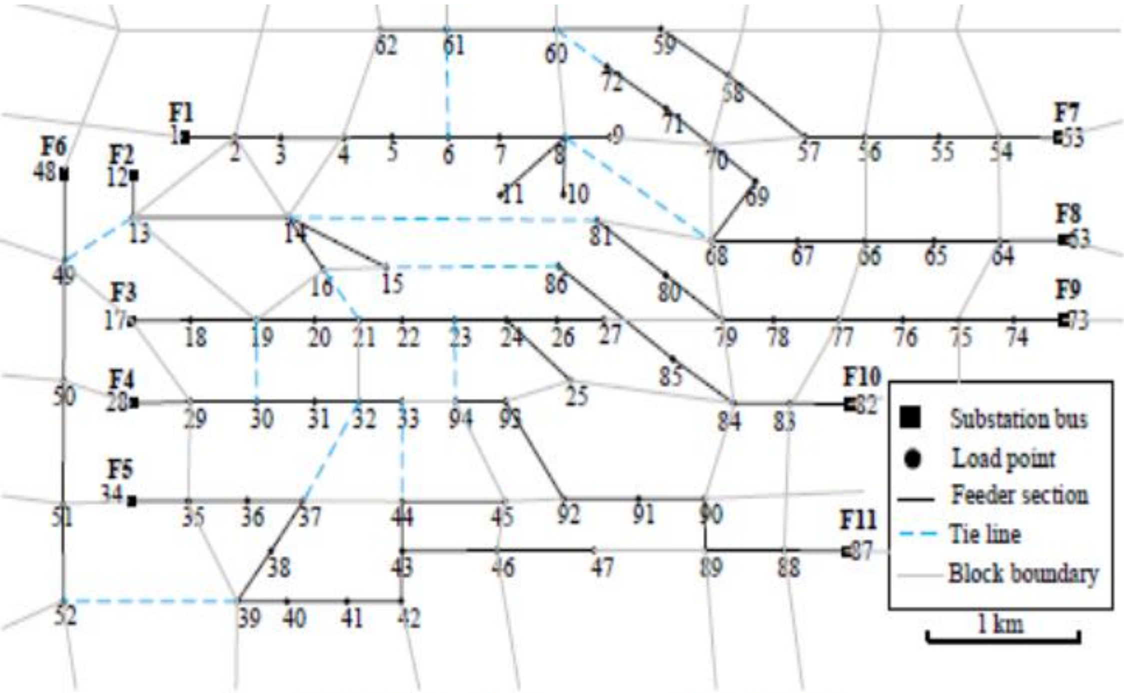


Figure 4.1: Single Line Diagram of TPC network System

Case II: Chyasal, Imadol-2 and Lubhu Feeder (Practical Feeders)

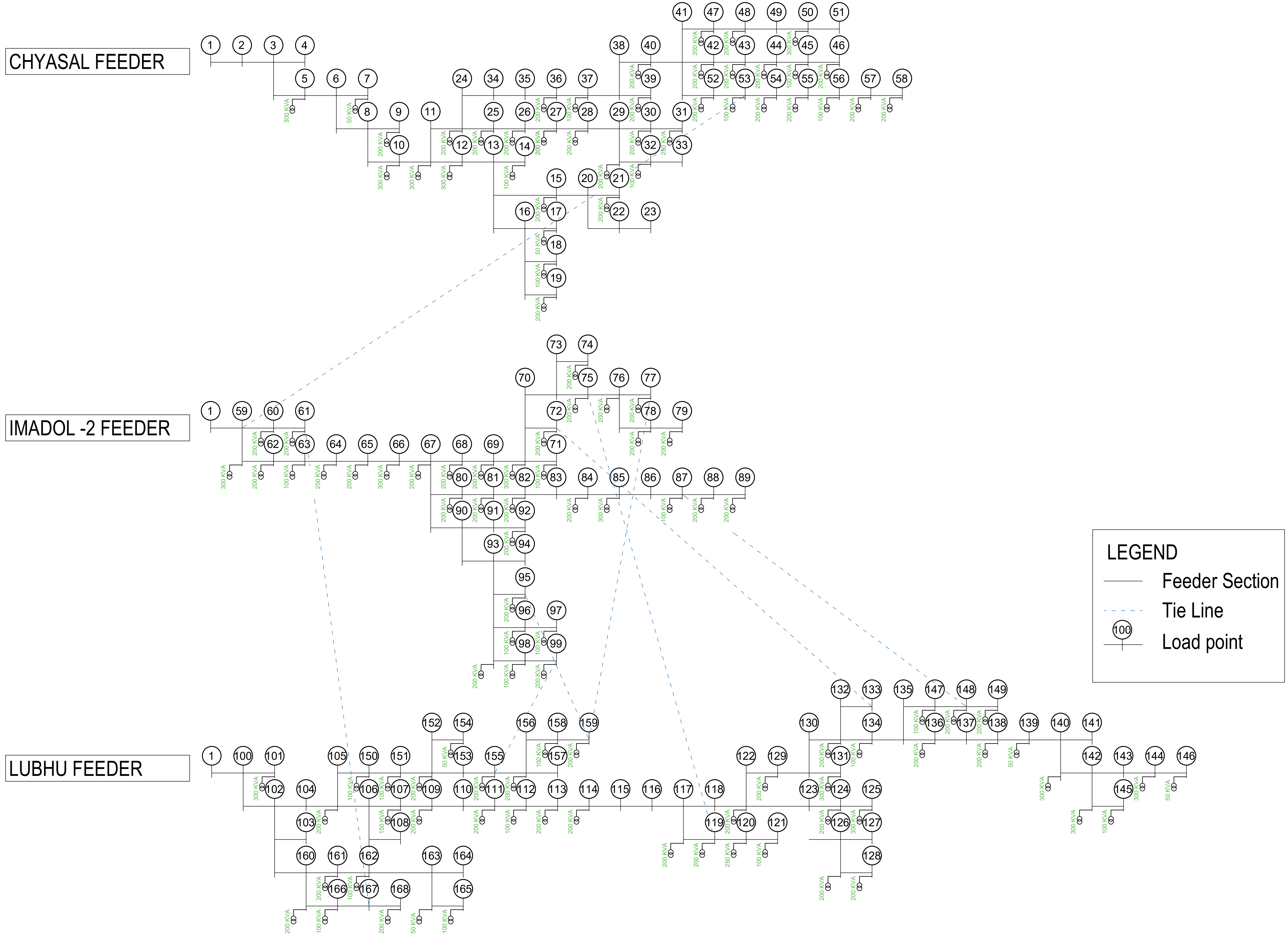


Fig 4.2: Single Line Diagram of Chyasal, Imadol-2 and Lubhu Feeders

4.2 Software and Tools Used

MATLAB was used as the primary computational environment for the work presented in this thesis. MATLAB, which stands for *Matrix Laboratory*, is a proprietary numerical computing platform developed by MathWorks. It offers a versatile framework for matrix operations, data visualization, algorithm implementation, user interface development, and integration with programs written in other programming languages. Typically, MATLAB is operated through the Command Window for interactive computations or by executing script and function files containing predefined code.

This thesis involves multiple power flow calculations within a single iteration, making computational efficiency a critical requirement. To address this, the MATPOWER toolbox was utilized. MATPOWER is a collection of MATLAB-based files designed for solving power flow and optimal power flow problems. It is widely adopted in research and educational applications due to its ease of use, flexibility, and computational performance. The toolbox is structured to achieve high efficiency while maintaining code readability and ease of modification. MATPOWER was originally developed at Cornell University by R. D. Zimmerman, C. E. Murillo-Sánchez, and D. Gan under the supervision of R. J. Thomas.

CHAPTER 5: RESULTS AND DISCUSSIONS

This chapter presents and analyzes the results produced by the proposed Fault Incidence Matrix (FIM) based optimization approach for determining the most effective placement of sectionalizing switches and tie lines. The effectiveness of the methodology is first evaluated on a standard benchmark distribution network of the Taiwan Power Company (TPC) and subsequently validated using practical 11 kV feeders-Chyasal, Imadol-2, and Lubhu of the Nepal Electricity Authority (NEA). For all simulation scenarios, a population size of 30 search agents and a maximum of 100 iterations were adopted to ensure a fair comparison between optimization techniques and consistent convergence behavior.

5.1 For Taiwan Power Company Distribution Network

The Taiwan Power Company distribution network consists of 11 radial feeders with a total of 84 buses. The aggregated active and reactive power demands of the system are 28.35 MW and 20.63 MVar, respectively. The network was modeled in MATLAB, and steady-state load flow analysis was carried out using the MATPOWER toolbox. Under base operating conditions, the system exhibited a real power loss of 531.954 kW, which reflects the inherent inefficiencies of a radial network without adequate sectionalizing and backup paths.

To analyze the impact of different protection and restoration strategies, three planning cases were investigated using both Genetic Algorithm (GA) and Improved Grey Wolf Optimization (IGWO).

Optimization with Genetic Algorithm

Case I: Base Case (Only Circuit Breaker)

In the base configuration, only the circuit breaker located at the substation was considered. This configuration represents a conventional radial feeder with limited fault isolation capability. As a result, any fault occurring along a feeder leads to interruptions for many downstream customers. The Expected Energy Not Supplied (EENS) of 38.2039 MWh/year and a corresponding Cost of Expected Energy Not Supplied (CEENS) of 887 x10^3 \$. These values serve as reference benchmarks for evaluating the effectiveness of subsequent enhancement strategies. The Fault

Incidence Matrix formed for the branch 30 to 42 and load node from 31 to 42 for this case is tabulated below.

Load No. Branch No.	1	…	31	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮		⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
31	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
33	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
34	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
35	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
36	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
37	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
38	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
39	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
40	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
41	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
83	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	1

Table 5.1 FIM A of Base case for TPC Network Using GA.

Case II: Circuit Breaker with Sectionalizing Switches

In this case, sectionalizing switches were allowed on each branch of the network, while tie lines were not considered. The presence of sectionalizing switches significantly improves fault isolation by limiting the outage to a smaller network section. After GA optimization, the EENS was reduced to 24.0357 MWh/year, representing a substantial improvement over the base case. The CEENS also decreased to 538.0748 x10^3 \$, indicating a considerable reduction in outage-related economic losses. A total of 34 switches were optimally placed, with an associated investment and maintenance cost of 19.754 x10^3 \$. When this cost is combined with the outage cost, the total optimization cost amounted to 557.8288 x10^3 \$. These results demonstrate that sectionalizing switches alone can effectively enhance system reliability, although the absence of alternative supply paths still limits restoration capability. The Fault Incidence Matrix (FIM A and FIM B) formed for this case is tabulated below.

Load No. Branch No.	1	…	31	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0		0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
31	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	0	0	1	1	1	1	1	1	1	1	1	1	…	0
33	0	…	0	0	1	1	1	1	1	1	1	1	1	1	…	0
34	0	…	0	0	0	0	1	1	1	1	1	1	1	1	…	0
35	0	…	0	0	0	0	0	1	1	1	1	1	1	1	…	0
36	0	…	0	0	0	0	0	0	1	1	1	1	1	1	…	0
37	0	…	0	0	0	0	0	0	0	1	1	1	1	1	…	0
38	0	…	0	0	0	0	0	0	0	1	1	1	1	1	…	0
39	0	…	0	0	0	0	0	0	0	0	0	1	1	0	…	0
40	0	…	0	0	0	0	0	0	0	0	0	1	1	0	…	0
41	0	…	0	0	0	0	0	0	0	1	1	1	1	1	…	0
42	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
83	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	1

Table 5.2 FIM A of Case II for TPC Network Using GA.

Load No. Branch No.	1	…	31	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	0	…	1	1	0	0	0	0	0	0	0	0	0	0	…	0
33	0	…	1	1	0	0	0	0	0	0	0	0	0	0	…	0
34	0	…	1	1	1	1	0	0	0	0	0	0	0	0	…	0
35	0	…	1	1	1	1	1	0	0	0	0	0	0	0	…	0
36	0	…	1	1	1	1	1	1	0	0	0	0	0	0	…	0
37	0	…	1	1	1	1	1	1	1	0	0	0	0	0	…	0
38	0	…	1	1	1	1	1	1	1	0	0	0	0	0	…	0
39	0	…	1	1	1	1	1	1	1	1	1	0	0	1	…	0
40	0	…	1	1	1	1	1	1	1	1	1	0	0	1	…	0
41	0	…	1	1	1	1	1	1	1	0	0	0	0	0	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
83	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.3 FIM B of Case II for TPC Network Using GA.

Case III: Circuit Breaker, Sectionalizing Switches, and Tie Lines

This scenario represents the most comprehensive reliability enhancement strategy, incorporating sectionalizing switches as well as tie lines that provide alternative power supply routes during contingencies. Initially, nine candidate tie lines were assumed based on network feasibility. GA optimization further reduced the EENS to 11.1687 MWh/year, highlighting the significant role of tie lines in enabling load restoration after fault isolation. The CEENS dropped to 252.0982 x10^3 \$, confirming a major reduction in outage costs. In this case, 73 sectionalizing switches were installed at a cost of 42.413 x10^3 \$, while 9 tie lines were constructed with a cost of 77.947 x10^3 \$. The total optimization cost was 374.179 x10^3 \$, which is notably lower than in previous cases despite the additional infrastructure investment. This outcome clearly indicates that coordinated placement of switches and tie lines provides the best trade-off between reliability improvement and overall system cost. The Fault Incidence Matrix (FIM A, FIM B and FIM C) formed for this case is tabulated below.

Load No. Branch No.	1	...	31	32	33	34	35	36	37	38	39	40	41	42	...	84
1	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
31	0	...	0	1	0	0	0	0	0	0	0	0	0	0	...	0
32	0	...	0	0	1	0	0	0	0	0	0	0	0	0	...	0
33	0	...	0	0	0	1	0	0	0	0	0	0	0	0	...	0
34	0	...	0	0	0	0	1	0	0	0	0	0	0	0	...	0
35	0	...	0	0	0	0	0	1	0	0	0	0	0	0	...	0
36	0	...	0	0	0	0	0	0	1	0	0	0	0	0	...	0
37	0	...	0	0	0	0	0	0	0	1	0	0	0	0	...	0
38	0	...	0	0	0	0	0	0	0	0	1	1	1	1	...	0
39	0	...	0	0	0	0	0	0	0	0	1	1	1	1	...	0
40	0	...	0	0	0	0	0	0	0	0	0	0	1	0	...	0
41	0	...	0	0	0	0	0	0	0	0	0	0	0	1	...	0
42	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	0
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
83	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	1

Table 5.4 FIM A of Case III for TPC Network Using GA.

Load No. Branch No.	1	…	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
31	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
32	0	…	1	0	0	0	0	0	0	0	0	0	0	…	0
33	0	…	1	1	0	0	0	0	0	0	0	0	0	…	0
34	0	…	1	1	1	0	0	0	0	0	0	0	0	…	0
35	0	…	1	1	1	1	0	0	0	0	0	0	0	…	0
36	0	…	1	1	1	1	1	0	0	0	0	0	0	…	0
37	0	…	1	1	1	1	1	1	0	0	0	0	0	…	0
38	0	…	1	1	1	1	1	1	1	0	0	0	0	…	0
39	0	…	1	1	1	1	1	1	1	0	0	0	0	…	0
40	0	…	1	1	1	1	1	1	1	1	1	0	1	…	0
41	0	…	1	1	1	1	1	1	1	1	1	1	0	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
83	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.5 FIM B of Case III for TPC Network Using GA.

Load No. Branch No.	1	…	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
31	0	…	0	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	0	0	1	1	1	1	1	1	1	1	1	…	0
33	0	…	0	0	0	1	1	1	1	1	1	1	1	…	0
34	0	…	0	0	0	0	1	1	1	1	1	1	1	…	0
35	0	…	0	0	0	0	0	1	1	1	1	1	1	…	0
36	0	…	0	0	0	0	0	0	1	1	1	1	1	…	0
37	0	…	0	0	0	0	0	0	0	1	1	1	1	…	0
38	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
39	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
40	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
41	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
42	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
83	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.6 FIM C of Case III for TPC Network Using GA.

Optimization with IGWO

Case I: Base Case (Only Circuit Breaker)

When IGWO was applied to the base case, the resulting EENS and CEENS remained identical to those obtained using GA. This confirms that, in the absence of additional decision variables, both algorithms converge to the same baseline reliability performance. The Fault Incidence Matrix (FIM A) formed for this case is tabulated below.

Load No. Branch No.	1	…	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
31	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
33	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
34	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
35	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
36	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
37	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
38	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
39	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
40	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
41	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
83	0	…	0	0	0	0	0	0	0	0	0	0	0	…	1

Table 5.7: FIM A of Base Case for TPC Network Using IGWO.

Case II: Circuit Breaker with Sectionalizing Switches

With sectionalizing switches enabled, IGWO achieved an EENS of 24.351 MWh/year and a CEENS of 541.184 x10^3 \$. Although the reliability indices are slightly higher than those obtained using GA, IGWO required only 31 switches compared to 34 in GA. Consequently, the switch installation cost was reduced to 18.011 x10^3 \$. The total optimization cost was 559.195 x10^3 \$, which is comparable to GA but achieved with fewer devices. This demonstrates the ability of IGWO to identify more cost-efficient solutions with a reduced number of assets. After the optimization of network the nodes were sectionalizing switch is placed to enhance the reliability are: 5,7,13,14,18,19,20,21,22,23,27,29,32,34,35,36,38,39,42,46,52,53,54,55,60,63,72,79, 80,81 and 82. The Fault Incidence Matrix (FIM A and FIM B) Formed for this case is tabulated below.

Load No. Branch No.	1	…	31	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
31	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	0	0	1	1	1	1	1	1	1	1	1	1	…	0
33	0	…	0	0	1	1	1	1	1	1	1	1	1	1	…	0
34	0	…	0	0	0	0	1	1	1	1	1	1	1	1	…	0
35	0	…	0	0	0	0	0	1	1	1	1	1	1	1	…	0
36	0	…	0	0	0	0	0	0	1	1	1	1	1	1	…	0
37	0	…	0	0	0	0	0	0	1	1	1	1	1	1	…	0
38	0	…	0	0	0	0	0	0	1	1	1	1	1	1	…	0
39	0	…	0	0	0	0	0	0	0	0	0	1	1	0	…	0
40	0	…	0	0	0	0	0	0	0	0	0	1	1	0	…	0
41	0	…	0	0	0	0	0	0	1	1	1	1	1	1	…	0
42	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
83	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	1

Table 5.8: FIM A of Case II for TPC Network Using IGWO.

Load No. Branch No.	1	…	31	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
31	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0
32	0	…	1	1	0	0	0	0	0	0	0	0	0	0	…	0
33	0	…	1	1	0	0	0	0	0	0	0	0	0	0	…	0
34	0	…	1	1	1	1	0	0	0	0	0	0	0	0	…	0
35	0	…	1	1	1	1	1	0	0	0	0	0	0	0	…	0
36	0	…	1	1	1	1	1	1	0	0	0	0	0	0	…	0
37	0	…	1	1	1	1	1	1	0	0	0	0	0	0	…	0
38	0	…	1	1	1	1	1	1	0	0	0	0	0	0	…	0
39	0	…	1	1	1	1	1	1	1	1	1	0	0	1	…	0
40	0	…	1	1	1	1	1	1	1	1	1	0	0	1	…	0
41	0	…	1	1	1	1	1	1	0	0	0	0	0	0	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	1	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
83	0	…	0	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.9: FIM B of Case II for TPC Network Using IGWO.

Case III: Circuit Breaker, Sectionalizing Switches, and Tie Lines

In the final case, twelve candidate tie lines were initially considered. IGWO optimization resulted in an EENS of 14.5476 MWh/year and a CEENS of 322.2683 x10^3 \$. Although the EENS is marginally higher than that obtained with GA, IGWO required only 35 sectionalizing switches and four tie lines. The corresponding costs for switches and tie lines were 20.335 x10^3 \$ and 27.0993 x10^3 \$, respectively, leading to a total optimization cost of 452.356 x10^3 \$, which is significantly lower than the GA-based solution. This confirms that IGWO provides a more economical configuration by balancing reliability improvement with infrastructure cost. The nodes were sectionalizing switch and Tie lines are placed after optimization:

Sectionalizing Switch: 6,7,13,14,17,18,19,20,21,22,23,28,29,31,32,34,36,37,40,42,50, 52,53,54,55,58,61,72,76,78,79,80,81,and 83.

Tie Line: 85 91 93 and 95.

The Fault Incidence Matrix (FIM A FIM B and FIM C) Formed for this case is tabulated below.

Load No. Branch No.	1	...	31	32	33	34	35	36	37	38	39	40	41	42	...	84
1	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
31	0	...	1	1	0	0	0	0	0	0	0	0	0	0	...	0
32	0	...	0	0	1	1	1	1	1	1	1	1	1	1	...	0
33	0	...	0	0	0	1	1	1	1	1	1	1	1	1	...	0
34	0	...	0	0	0	0	1	1	1	1	1	1	1	1	...	0
35	0	...	0	0	0	0	1	1	1	1	1	1	1	1	...	0
36	0	...	0	0	0	0	0	0	1	1	1	1	1	1	...	0
37	0	...	0	0	0	0	0	0	1	1	1	1	1	1	...	0
38	0	...	0	0	0	0	0	0	0	0	1	1	1	1	...	0
39	0	...	0	0	0	0	0	0	0	0	1	1	1	1	...	0
40	0	...	0	0	0	0	0	0	0	0	0	0	1	0	...	0
41	0	...	0	0	0	0	0	0	0	0	0	0	0	1	...	0
42	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
83	0	...	0	0	0	0	0	0	0	0	0	0	0	0	...	1

Table 5.10: FIM A of Case III for TPC Network Using IGWO.

Load No. Branch No.	1	…	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
31	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
32	0	…	1	0	0	0	0	0	0	0	0	0	0	…	0
33	0	…	1	1	0	0	0	0	0	0	0	0	0	…	0
34	0	…	1	1	1	0	0	0	0	0	0	0	0	…	0
35	0	…	1	1	1	0	0	0	0	0	0	0	0	…	0
36	0	…	1	1	1	1	1	0	0	0	0	0	0	…	0
37	0	…	1	1	1	1	1	0	0	0	0	0	0	…	0
38	0	…	1	1	1	1	1	1	1	0	0	0	0	…	0
39	0	…	1	1	1	1	1	1	1	0	0	0	0	…	0
40	0	…	1	1	1	1	1	1	1	1	1	0	1	…	0
41	0	…	1	1	1	1	1	1	1	1	1	1	0	…	0
42	0	…	1	1	1	1	1	1	1	1	1	1	1	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
83	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.11: FIM B of Case III for TPC Network Using IGWO.

Load No. Branch No.	1	…	32	33	34	35	36	37	38	39	40	41	42	…	84
1	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
31	0	…	0	1	1	1	1	1	1	1	1	1	1	…	0
32	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
33	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
34	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
35	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
36	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
37	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
38	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
39	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
40	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
41	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
42	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
83	0	…	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 5.12: FIM C of Case III for TPC Network Using IGWO.

Overall, the comparison summarized in Table 5.13 shows that IGWO consistently achieves lower total optimization costs, especially when tie lines are included. The convergence curves presented in Figures 5.3 and 5.4 further illustrate the stable and rapid convergence characteristics of IGWO.

Following table summarizes and compares the results for Taiwan Power Company Distribution Network:

Table 5.13: Comparison of GA and IGWO algorithm done for TPC Network

Description	**GA**	**IGWO**
a) Only with Breaker		
i) EENS (MWh/year)	38.204	38.2039
ii) CEENS (\$x10^3)	887.001	887
b) With Breaker and Sectionalizing Switch		
i) EENS (MWh/year)	24.0877	24.3512
ii) CEENS (\$x10^3)	538.217	541.184
iii) Number of switches optimized (Nos.)	34	31
iv) Cost of Switches (\$x10^3)	19.754	18.011
v) Total Cost for optimization (\$x10^3)	557.9717	559.195
c) With Breaker, Sectional Switches and Tie Lines.		
i) EENS (MWh/year)	11.1825	14.5476
ii) CEENS (\$x10^3)	253.819	322.268
iii) Number of switches optimized (Nos.)	73	35
iv) Cost of Switches (\$x10^3)	42.413	20.335
v) Number of Tie Lines (Nos.)	9	4
v) Cost of Tie Lines (\$x10^3)	77.947	27.0993
vi) Total Cost for optimization (\$x10^3)	374.179	369.702

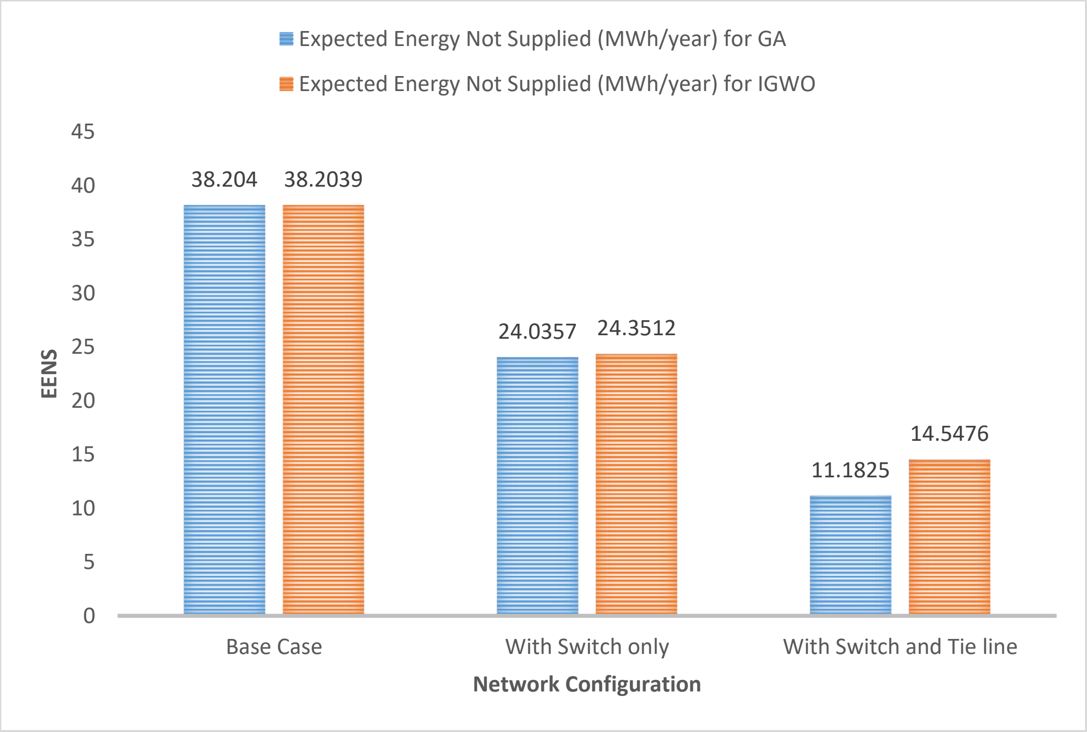


Figure 5.1 : Loss comparison for different cases for TPC Distribution Network

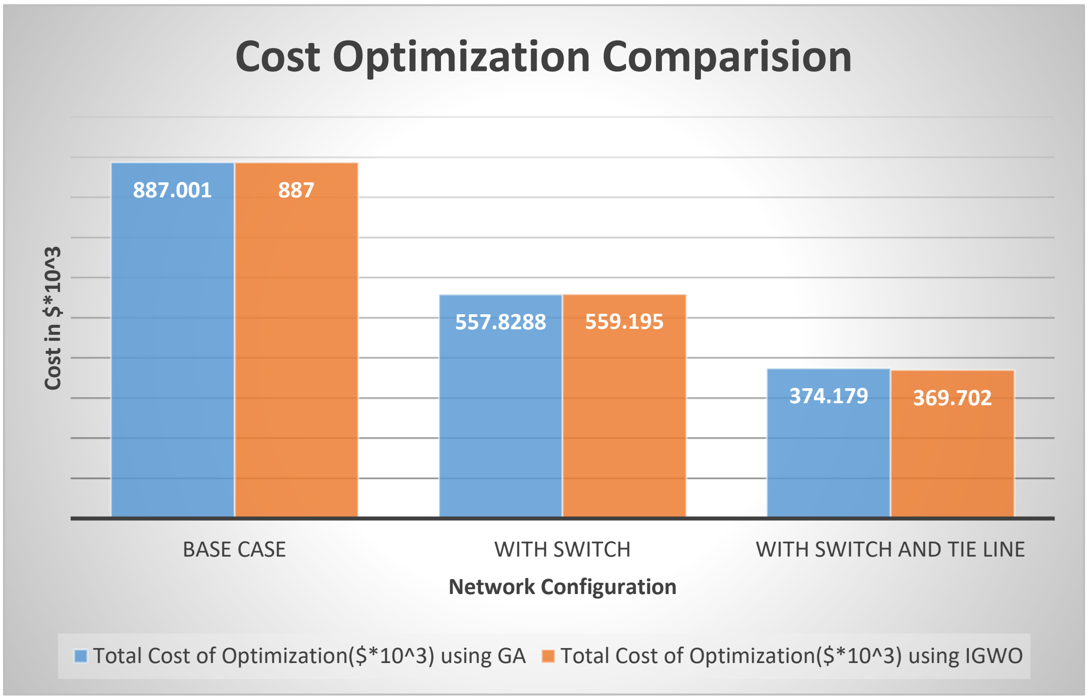


Figure 5.2 : Optimization Cost for different cases of TPC Distribution Network

Although both GA and IGWO achieve substantial reliability improvements, the total cost comparison charts indicate a clear distinction in their optimization behavior.

- Genetic Algorithm (GA) tends to minimize EENS more aggressively, but this comes at the expense of installing a larger number of sectionalizing switches and tie lines.
- Improved Grey Wolf Optimization (IGWO) achieves slightly higher EENS values in some cases; however, it requires significantly fewer devices, leading to a lower total optimization cost.

For the case including both switches and tie lines, the charts demonstrate that IGWO yields the minimum overall cost, even though the difference in EENS between GA and IGWO is relatively small. This indicates that IGWO provides a better cost–reliability trade-off, which is the primary objective of distribution system planning.

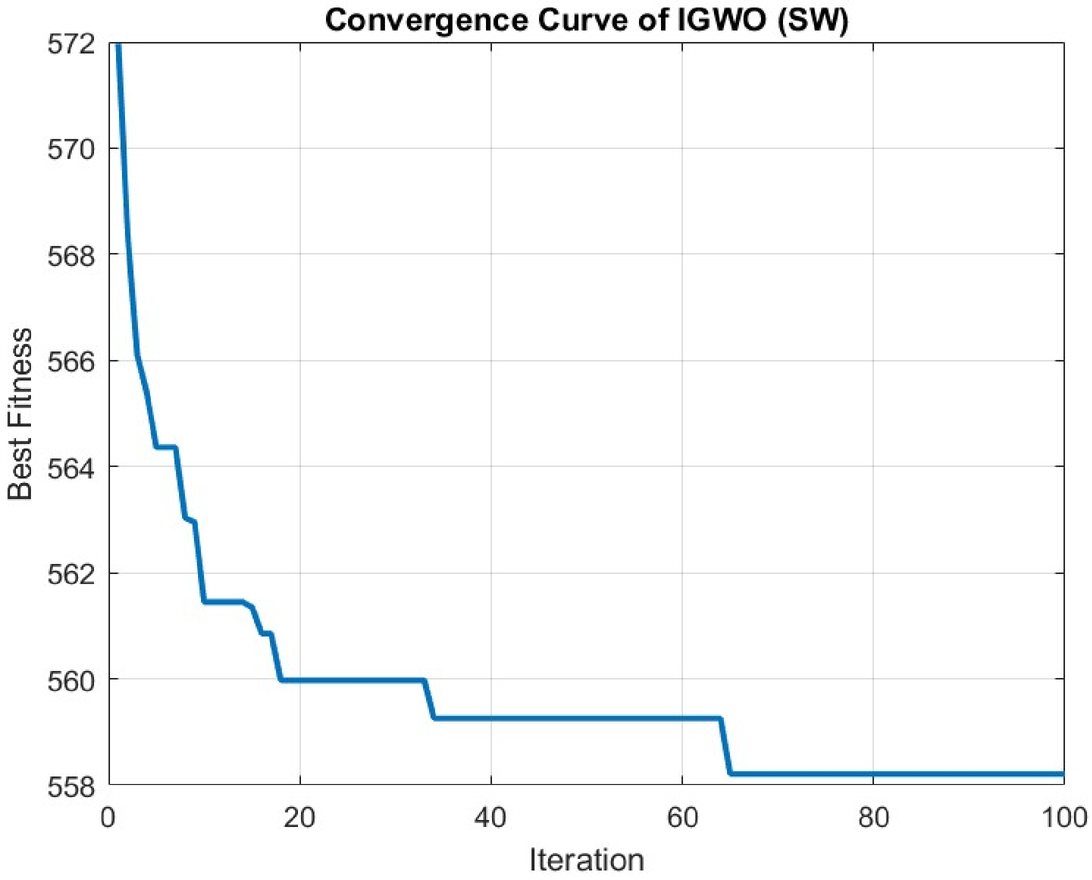


Figure 5.3 : Convergence curve for switch using IGWO in TPC Distribution Network.

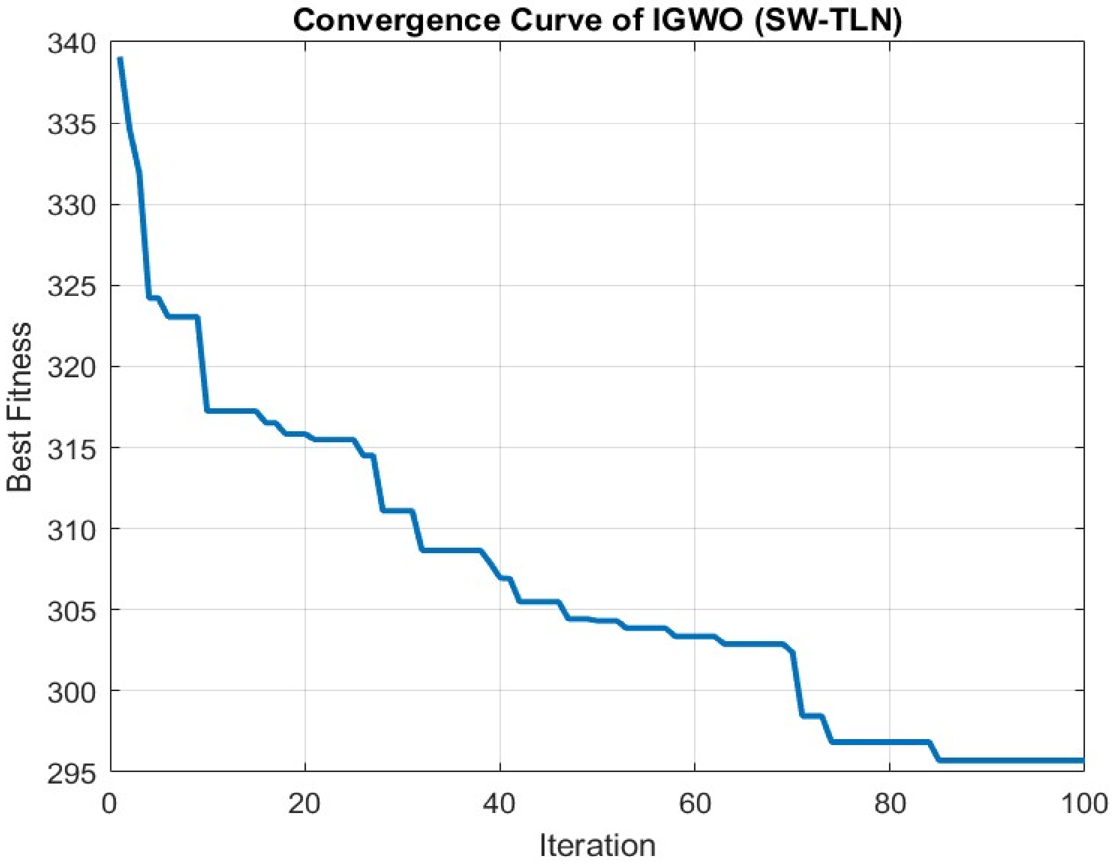


Figure 5.4 : Convergence curve for switch and tie line both using IGWO in TPC Distribution Network

The convergence curves reveal that IGWO exhibits:

- Rapid reduction in fitness value during early iterations.
- Smooth and stable convergence without oscillations.
- No evidence of premature convergence.

This behavior indicates that IGWO maintains a good balance between exploration and exploitation, enabling it to escape local optima while converging reliably toward cost-effective solutions. Such characteristics are especially important in large, constrained optimization problems such as sectionalizing switch and tie-line placement.

5.2 For Practical Feeders (Chyasal, Imadol-2 and Lubhu) using IGWO.

The practical feeders, namely Chyasal, Imadol-2 and Lubhu has 167 buses in the system with total active and reactive load of 19.08 MW and 11.82 MVar respectively. The given system was modeled in the MATLAB and with loadflow analysis done in MATPOWER the system real power loss was found to be 1435.21 kW and reactive power loss was found to be 1081.27 kVar.

Tripping information for this thesis was gathered from Minbhawan Grid substation operational records covering the previous three fiscal years. The dataset includes details such as the time and date of each tripping event, the feeders involved, the duration of outages, and the corresponding restoration actions. These records were obtained from routine substation logs and protection system reports maintained by the NEA. To ensure data reliability, the collected information was reviewed to exclude planned interruptions and repeated entries. The finalized dataset provided a realistic basis for estimating fault frequencies and outage durations used in the reliability assessment and optimization process. After the calculations fault outage rate for Chyasal was found to be 0.06 times/year/km, Imadol-2 was found to be 0.065 times/year/km and Lubhu was found to be 0.065 times/year/km. The details of tripping record is tabulated in the appendix section.

Optimization with IGWO

To validate the practical applicability of the proposed methodology, the IGWO algorithm was applied to real distribution feeders of NEA. The combined network consists of 167 buses with total active and reactive loads of 19.08 MW and 11.82 MVar, respectively. Load flow analysis revealed a base-case real power loss of 1435.21 kW, indicating a stressed radial system with limited fault management capability. The number of tie line that can be constructed among the feeders considering the physical feasibility and other constraints are 9.

Case I: Base Case (Only Circuit Breaker)

Under base conditions, the EENS was found to be 246.7255 MWh/year, with a CEENS of 5055.12 x10^3 \$. These high values reflect the severe impact of faults in large practical networks without sectionalizing and restoration facilities. The Fault incidence matrix (FIM A) formed in this case is on the next page.

Load No. Branch No.	1	……	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	……	168
1	0	…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
59	0	……	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	……	0
60	0	……	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	……	0
61	0	……	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	……	0
62	0	……	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	……	0
63	0	……	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	……	0
64	0	……	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	……	0
65	0	……	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	……	0
66	0	……	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	……	0
67	0	……	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	……	0
68	0	……	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	……	0
69	0	……	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	……	0
70	0	……	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	……	0
71	0	……	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	……	0
72	0	……	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	……	0
73	0	……	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	……	0
74	0	……	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	……	0
75	0	……	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	……	0
76	0	……	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	……	0
77	0	……	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	……	0
78	0	……	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	……	0
79	0	……	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	……	0
80	0	……	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	……	0
81	0	……	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	……	0
82	0	……	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	……	0
83	0	……	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	……	0
84	0	……	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	……	0
85	0	……	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	……	0
86	0	……	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	……	0
87	0	……	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	……	0
88	0	……	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	……	0
89	0	……	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	……	0
90	0	……	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	……	0
91	0	……	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	……	0
92	0	……	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	……	0
93	0	……	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	……	0
94	0	……	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	……	0
95	0	……	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	……	0
96	0	……	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	……	0
97	0	……	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	……	0
98	0	……	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	……	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
167	0	……	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	1

Table 5.14: FIM A of Base Case for NEA Network.

Case II: Circuit Breaker with Sectionalizing Switches

When sectionalizing switches were introduced, IGWO optimization reduced the EENS to 99.7475 MWh/year, representing a reliability improvement of more than 60%. The CEENS was reduced to 2031.5516 x10^3 \$. A total of 79 switches were optimally placed, incurring a cost of 45.899 x10^3 \$. The resulting total optimization cost was 2077.4506 x10^3 \$, demonstrating that sectionalizing switches are highly effective in practical networks with dense load distribution. The nodes were sectionalizing switch are placed after optimization:

Sectionalizing Switch: 3,6,8,10,11,12,19,23,24,26,27,28,33,37,38,39,41,43,44,46,47, 52,53,57,60,62,64,66,68,70,71,72,73,76,77,79,80,82,84,86,87,89,90,92,94,95,97,100, 102,104,105,107,112,113,114,116,117,118,122,123,124,126,127,128,130,131,132,135,139,143,144,148,149,150,152,156,157,159,and,162.

The Fault incidence Matrix (FIM A and FIM B) formed in this case is tabulated in next page:

Load No. Branch No.	1	......	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	......	168
1	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
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59	0	......	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	......	0
60	0	......	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
61	0	......	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	......	0
62	0	......	0	0	0	0	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	......	0
63	0	......	0	0	0	0	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	......	0
64	0	......	0	0	0	0	0	0	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	......	0
65	0	......	0	0	0	0	0	0	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	......	0
66	0	......	0	0	0	0	0	0	0	0	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	......	0
67	0	......	0	0	0	0	0	0	0	0	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	......	0
68	0	......	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
69	0	......	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
70	0	......	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
71	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
72	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
73	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
74	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
75	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
76	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
77	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
78	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
79	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
80	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
81	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
82	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
83	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
84	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
85	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
86	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	......	0
87	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	......	0
88	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	......	0
89	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
90	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	......	0
91	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	......	0
92	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	......	0
93	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	......	0
94	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	......	0
95	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	......	0
96	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	......	0
97	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	......	0
98	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	......	0
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167	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	1

Table 5.15: FIM A of Case II for NEA Network.

Load No. Branch No.	1	……	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	……	168
1	0	……	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
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59	0	……	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
60	0	……	1	1	0	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	……	0
61	0	……	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
62	0	……	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
63	0	……	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
64	0	……	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
65	0	……	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
66	0	……	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
67	0	……	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0
68	0	……	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
69	0	……	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
70	0	……	1	1	1	1	1	1	1	1	1	1	1	1	0	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	……	0
71	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	0	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	……	0
72	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
73	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
74	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
75	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
76	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
77	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
78	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	……	0
79	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
80	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
81	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
82	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
83	0	……	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
84	0	……	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	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
85	0	……	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	0	0	0	0	0	1	1	1	1	1	1	1	1	1	……	0
86	0	……	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	0	1	1	1	1	1	1	1	1	1	1	1	……	0
87	0	……	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	0	0	1	1	1	1	1	1	1	1	1	……	0
88	0	……	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	0	0	1	1	1	1	1	1	1	1	1	……	0
89	0	……	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	0	0	0	0	0	0	0	0	0	……	0
90	0	……	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	0	0	1	1	1	1	1	1	……	0
91	0	……	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	0	0	1	1	1	1	1	1	……	0
92	0	……	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	0	0	0	0	0	0	……	0
93	0	……	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	0	0	0	0	0	0	……	0
94	0	……	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	0	1	1	1	……	0
95	0	……	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	0	0	1	……	0
96	0	……	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	0	0	1	……	0
97	0	……	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	0	……	0
98	0	……	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	0	……	0
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167	0	……	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	……	0

Table 5.16: FIM B of Case II for NEA Network.

Case III: Circuit Breaker, Sectionalizing Switches, and Tie Lines

In the final case, nine feasible tie line candidates were initially considered. IGWO optimization further reduced the EENS to 62.7798 MWh/year and the CEENS to 1267.619 x10^3 \$. The optimized configuration included 79 sectionalizing switches and four tie lines, with respective costs of 45.899 x10^3 \$ and 74.8 x10^3 \$. The total optimization cost was reduced to 1388.318 x10^3 \$. These results clearly demonstrate that the coordinated use of sectionalizing switches and tie lines provides the highest reliability improvement and the lowest economic impact of outages in real-world distribution systems. The nodes were sectionalizing switch and Tie lines are placed after optimization:

Sectionalizing Switch: 42,46,47,51,52,53,54,56,59,61,62,64,65,66,68,69,71,72,74,75,76,77,79,81,84,86,88,89,90,93,94,95,97,103,105,108,112,113,116,120,121,122,123,124,125,128,131,134,138,143,144,145,146,147,151,152,155,156,157,159,160,161,and, 167.

Tie Lines: 169,170,172 and 176.

The Fault Incidence Matrix (FIM A, FIM B and FIM C) formed for this case is tabulated in next page:

Load No. Branch No.	1	......	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	......	168
1	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
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59	0	......	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
60	0	......	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
61	0	......	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
62	0	......	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
63	0	......	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
64	0	......	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
65	0	......	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
66	0	......	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
67	0	......	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
68	0	......	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
69	0	......	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
70	0	......	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
71	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
72	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
73	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
74	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
75	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
76	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
77	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
78	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
79	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
80	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
81	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
82	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
83	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
84	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	......	0
85	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	......	0
86	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	......	0
87	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	......	0
88	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	......	0
89	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
90	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	......	0
91	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	......	0
92	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
93	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	......	0
94	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	......	0
95	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	......	0
96	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	......	0
97	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	......	0
98	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	......	0
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167	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	1

Table 5.16: FIM A of Case III for NEA Network.

Load No. Branch No.	1	......	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	......	168
1	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
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59	0	......	1	0	0	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	......	0
60	0	......	1	0	0	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	......	0
61	0	......	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
62	0	......	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
63	0	......	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
64	0	......	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
65	0	......	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
66	0	......	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
67	0	......	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
68	0	......	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
69	0	......	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
70	0	......	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
71	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	0	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	......	0
72	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
73	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
74	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
75	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
76	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
77	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
78	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	......	0
79	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
80	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
81	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
82	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
83	0	......	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
84	0	......	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	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
85	0	......	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	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
86	0	......	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	0	1	1	1	1	1	1	1	1	1	1	1	......	0
87	0	......	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	0	0	0	0	0	1	1	1	1	1	1	1	1	1	......	0
88	0	......	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	0	1	1	1	1	1	1	1	1	1	......	0
89	0	......	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	0	0	0	0	0	0	0	0	0	......	0
90	0	......	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	0	0	1	1	1	1	1	1	......	0
91	0	......	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	0	0	1	1	1	1	1	1	......	0
92	0	......	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	0	0	0	0	0	0	0	0	0	......	0
93	0	......	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	0	1	1	1	1	......	0
94	0	......	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	0	1	1	1	......	0
95	0	......	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	0	0	1	......	0
96	0	......	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	0	0	1	......	0
97	0	......	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	0	......	0
98	0	......	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	0	......	0
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167	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0

Table 5.18: FIM B of Case III for NEA Network.

Load No. Branch No.	1	......	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	......	168
1	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
59	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
60	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
61	0	......	0	0	0	0	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	......	0
62	0	......	0	0	0	0	0	0	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	......	0
63	0	......	0	0	0	0	0	0	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	......	0
64	0	......	0	0	0	0	0	0	0	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	......	0
65	0	......	0	0	0	0	0	0	0	0	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	......	0
66	0	......	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
67	0	......	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
68	0	......	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
69	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
70	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
71	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
72	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
73	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
74	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
75	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
76	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
77	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
78	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
79	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
80	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
81	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
82	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
83	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	......	0
84	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	......	0
85	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	......	0
86	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
87	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	......	0
88	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
89	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
90	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
91	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
92	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
93	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
94	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
95	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
96	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
97	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
98	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0
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167	0	......	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	......	0

Table 5.19: FIM C of Case III for NEA Network.

Following table summarizes the results for practical Feeders on NEA Distribution Network:

Table 5.20: Summary of the results for Chyasal, Imadol-2 and Lubhu Feeders (NEA) Distribution Network.

Description	**NEA Feeders**
a) Only with Breaker	
i) EENS (MWh/year)	246.7255
ii) CEENS (x10^3 $)	5055.1235
b) With Breaker and Sectionalizing Switch	
i) EENS (MWh/year)	99.7475
ii) CEENS (x10^3 $)	2031.551
iii) Number of switches optimized (Nos.)	79
iv) Cost of Switches (x10^3 $)	45.899
v) Total Cost for optimization (x10^3 $)	2077.45
c) With Breaker, Sectional Switches and Tie Lines.	
i) EENS (MWh/year)	62.779
ii) CEENS (x10^3 $)	1267.619
iii) Number of switches optimized (Nos.)	79
iv) Cost of Switches (x10^3 $)	45.899
v) Number of Tie Lines (Nos.)	4
v) Cost of Tie Lines (x10^3 $)	74.8
vi) Total Cost for optimization (x10^3 $)	1388.318

Optimal placement of sectionalizing switches significantly improves distribution network reliability by reducing the impact of faults. The coordinated placement of sectionalizing switches and tie lines provides the maximum reduction in EENS and outage-related costs, making it the most effective reliability enhancement strategy. IGWO consistently achieves lower total optimization cost by identifying solutions that require fewer switches and tie lines. IGWO demonstrates superior scalability and convergence behavior, making it more suitable for large practical feeders with more than 200 buses. For distribution planning problems where the objective is minimum total cost under reliability constraints, IGWO is the preferred algorithm for real-world radial distribution networks

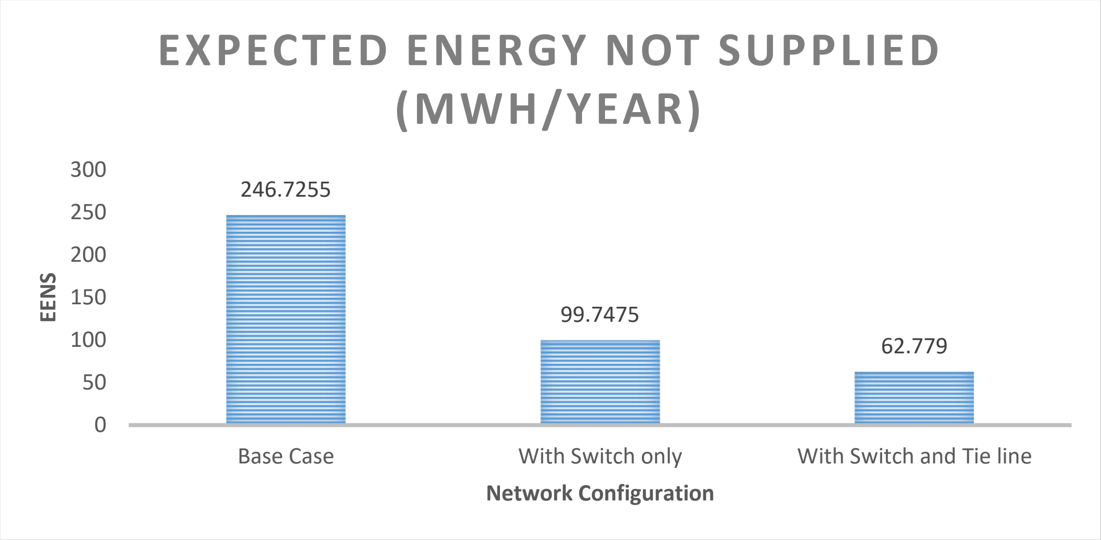

Figure 5.5: Loss comparison for different cases in NEA Feeders.

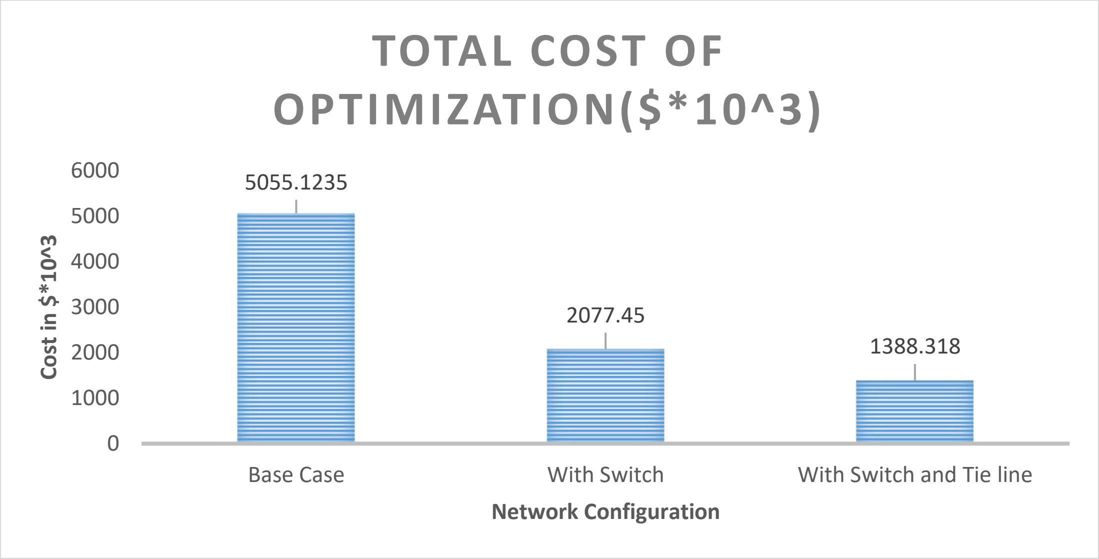

Figure 5.6: Optimization cost comparison for different cases in NEA Feeders

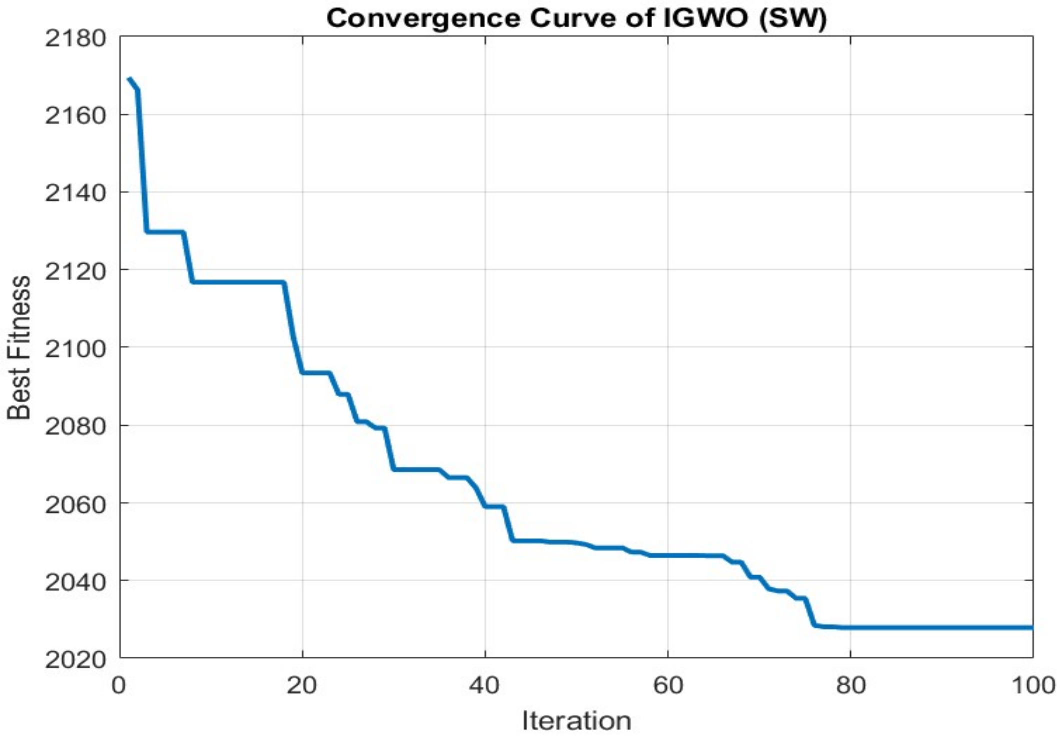

Figure 5.7: Convergence curve for switch in NEA Feeders

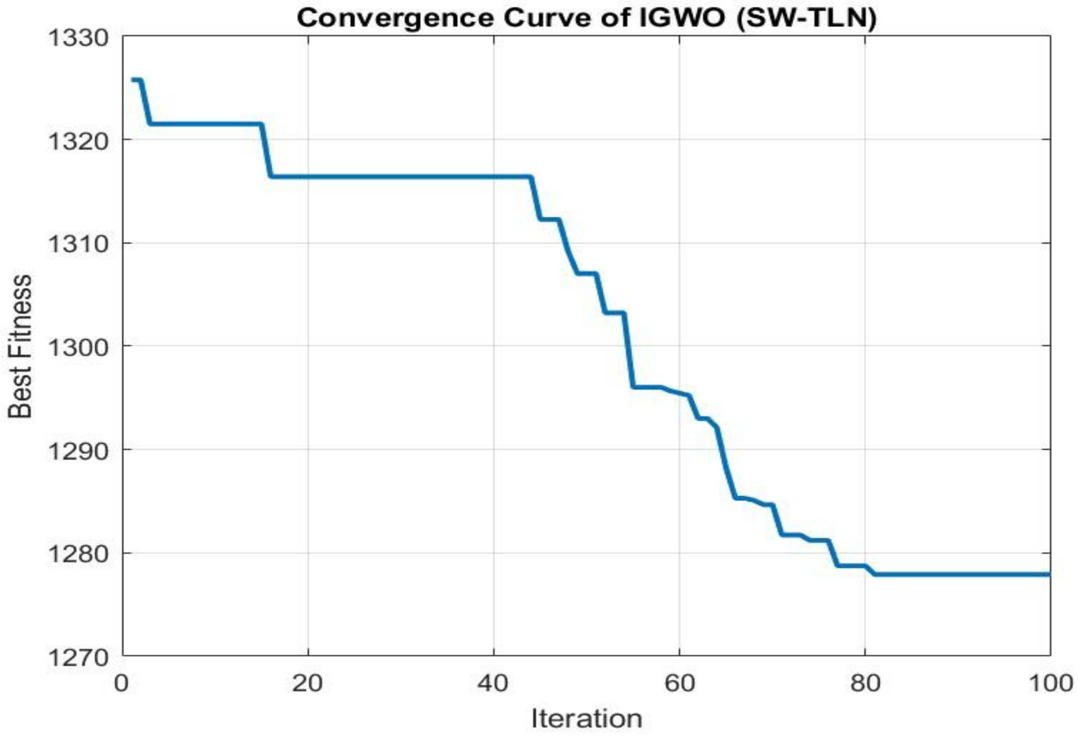

Figure 5.8: Convergence curve for switch and tie line both in NEA Feeders

CHAPTER 6: CONCLUSION

6.1 Conclusions

This thesis presented a comprehensive framework for improving the reliability and economic performance of power distribution networks through the most effective positioning of sectionalizing switches and tie lines within the network based on the Fault Incidence Matrix (FIM). To achieve the objectives of the study, two metaheuristic optimization techniques, Genetic Algorithm (GA) and Improved Grey Wolf Optimization (IGWO) were employed and systematically evaluated. An interactive optimization program was developed in the MATLAB environment using the MATPOWER toolbox. The program accepts network line parameters, bus data, candidate tie-line information, reliability indices, cost functions, and operational constraints as inputs and determines an optimal configuration that minimizes the Cost of Expected Energy Not Supplied (CEENS).

The effectiveness of the proposed methodology was first verified in a distribution network comprising 11 radial feeders and 84 buses. The results demonstrated that the inclusion of sectionalizing switches and tie lines significantly enhances network reliability and reduces outage-related costs. When GA was applied to the TPC network, the Expected Energy Not Supplied (EENS) was reduced by 37.09 % in Case II and by 70.73% in Case III relative to the base case. Correspondingly, the total optimization cost decreased by 37.11% and 57.82% in Case II and Case III, respectively. Using IGWO, EENS reductions of 36.26% and 61.92% were achieved for Case II and Case III, while the total optimization cost decreased by 36.96% and 58.32%, respectively, compared to the base case.

To validate the practical applicability of the proposed framework, the methodology was further applied to real 11 kV distribution feeders-Chyasal, Imadol-2, and Lubhu-of the Nepal Electricity Authority, consisting of 168 buses. Due to the large network size and discrete decision variables, only the IGWO algorithm was used for optimization. The results showed substantial reliability improvements, with EENS reductions of 59.57% in Case II and 74.56% in Case III relative to the base case. Additionally, the total optimization cost was reduced by 58.90% and 72.54% for Case II and Case III, respectively, demonstrating the effectiveness of coordinated sectionalizing switch and tie-line placement in large practical distribution systems.

Overall, the comparative analysis confirmed that IGWO outperforms GA in terms of solution quality, cost efficiency, and robustness. The superior performance of IGWO can be attributed to its ability to handle discrete decision variables effectively, maintain a better balance between exploration and exploitation, and converge reliably even when the Fault Incidence Matrix must be recalculated repeatedly for radial network structures.

In conclusion, the proposed FIM-based optimization framework, combined with IGWO, provides a reliable, scalable, and computationally efficient tool for distribution network planning. The objectives of this thesis have been successfully achieved, and the methodology can serve as a valuable decision-support approach for utilities aiming to enhance system reliability while minimizing outage-related costs.

6.2 Recommendations

Based on the findings and conclusions of this thesis, several recommendations are proposed for utilities, system planners, and future researchers to further enhance the reliability and cost-effectiveness of distribution networks.

1. Adoption of IGWO for Distribution Planning

Electric utilities are recommended to adopt the Improved Grey Wolf Optimization (IGWO) algorithm for planning and upgrading radial distribution networks. The results of this study demonstrate that IGWO consistently provides more economical and reliable solutions than Genetic Algorithm (GA), particularly in networks with discrete decision variables and complex fault interactions. Its superior convergence characteristics and reduced dependence on large numbers of switching devices make IGWO well suited for large-scale practical systems.

2. Integration of Fault Incidence Matrix in Reliability Analysis

Utilities should incorporate the Fault Incidence Matrix (FIM) as a standard tool for reliability assessment and planning. The FIM-based approach offers a systematic way to quantify fault impacts, identify critical network sections, and evaluate customer interruption consequences. Its integration into planning software can significantly improve the accuracy of reliability evaluation and the effectiveness of optimization decisions.

3. Coordinated Placement of Sectionalizing Switches and Tie Lines

Rather than installing sectionalizing switches or tie lines independently, utilities are encouraged to adopt a coordinated planning strategy. The results show that joint optimization of both components yields greater reductions in Expected Energy Not Supplied (EENS) and overall cost than isolated installations. This coordinated approach ensures an optimal balance between fault isolation capability and service restoration flexibility.

4. Prioritization of High-Impact Feeders for Network Upgrades

For systems with limited investment budgets, priority should be given to feeders with high fault rates, heavy load concentrations, or poor reliability indices. Applying the proposed optimization framework selectively to such critical feeders can maximize reliability improvement per unit cost and deliver immediate benefits to a large number of customers.

5. Implementation as a Decision-Support Tool

The MATLAB-based optimization program developed in this thesis can be further enhanced and deployed as a decision-support tool for utility planners. By integrating real-time fault statistics, load growth projections, and maintenance data, the tool can support both long-term planning and short-term operational decision-making.

6. Extension to Automation and Smart Grid Applications

Future system upgrades should consider integrating the proposed methodology with distribution automation and smart grid technologies. The optimized placement of remotely controlled switches and intelligent tie lines can further reduce restoration times and enhance system resilience, especially under multiple fault or extreme weather scenarios.

7. Future Research Directions

Future studies are recommended to extend the proposed framework by incorporating distributed generation, energy storage systems, and renewable energy sources. Additionally, uncertainty in fault rates, load demand, and repair times can be modeled using probabilistic or stochastic approaches to further improve planning robustness.

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APPENDIX

Table 1: Bus data for TPC network

Feeder	Sending End Bus	Receiving end Bus	End bus real load (kW)	End bus reactive load (kvar)	Feeder	Sending End Bus	Receiving end Bus	End bus real load (kW)	End bus reactive load (kvar)
F1	0	1	0	0	F6	0	43	0	0
	1	2	100	50		43	44	30	20
	2	3	300	200		44	45	800	700
	3	4	350	250		45	46	200	150
	4	5	220	100	F7	0	47	0	0
	5	6	1100	800		47	48	0	0
	6	7	400	320		48	49	0	0
	7	8	300	200		49	50	200	160
	7	9	300	230		50	51	800	600
	7	10	300	260		51	52	500	300
F2	0	11	0	0		52	53	500	350
	11	12	1200	800		53	54	500	300
	12	13	800	600		54	55	200	80
	12	14	700	500	F8	0	56	0	0
F3	0	15	0	0		56	57	30	20

	15	16	300	150		57	58	600	420
	16	17	500	350		58	59	0	0
	17	18	700	400		59	60	20	10
	18	19	1200	1000		60	61	20	10
	19	20	300	300		61	62	200	130
	20	21	400	350		62	63	300	240
	21	22	50	20		63	64	300	200
	21	23	50	20	F9	0	65	0	0
	23	24	50	10		65	66	50	30
F4	0	25	50	3		66	67	0	0
	25	26	100	60		67	68	400	360
	26	27	100	70		68	69	0	0
	27	28	1800	1300		69	70	0	0
	28	29	200	120		70	71	2000	1500
F5	0	30	0	0		71	72	200	150
	30	31	1800	1600	F10	0	73	0	0
	31	32	200	150		73	74	0	0
	32	33	200	100		74	75	1200	950
	33	34	800	600		75	76	300	180
	34	35	100	60	F11	0	77	0	0
	35	36	100	60		77	78	400	360

	36	37	20	10		78	79	2000	1300
	37	38	20	10		79	80	200	140
	38	39	20	10		80	81	500	360
	39	40	20	10		81	82	100	30
	38	41	200	160		82	83	400	360
	41	42	50	30					

Table 2: Branch data for TPC network

Feeder	Sending End Bus	Receiving end Bus	Section resistance (Ω)	Section reactance (Ω)	Feeder	Sending End Bus	Receiving end Bus	Section resistance (Ω)	Section reactance (Ω)
F1	0	1	0.1944	0.6624	F6	0	43	0.0486	0.1656
	1	2	0.2096	0.4304		43	44	0.0393	0.0807
	2	3	0.2358	0.4842		44	45	0.131	0.269
	3	4	0.0917	0.1883		45	46	0.2358	0.4842
	4	5	0.2096	0.4304	F7	0	47	0.243	0.828
	5	6	0.0393	0.0807		47	48	0.0655	0.1345
	6	7	0.0405	0.138		48	49	0.0655	0.1345
	7	8	0.1048	0.2152		49	50	0.0393	0.0807
	7	9	0.2358	0.4842		50	51	0.0786	0.1614
	7	10	0.1048	0.2152		51	52	0.0393	0.0807
F2	0	11	0.0786	0.1614		52	53	0.0786	0.1614
	11	12	0.3406	0.6944		53	54	0.0524	0.1076

	12	13	0.0262	0.0538		54	55	0.131	0.269
	12	14	0.0786	0.1614	F8	0	56	0.2268	0.7728
F3	0	15	0.1134	0.3864		56	57	0.5371	1.1029
	15	16	0.0524	0.1076		57	58	0.0524	0.1076
	16	17	0.0524	0.1076		58	59	0.0405	0.138
	17	18	0.1572	0.3228		59	60	0.0393	0.0807
	18	19	0.0393	0.0807		60	61	0.0262	0.0538
	19	20	0.1703	0.3497		61	62	0.1048	0.2152
	20	21	0.2358	0.4842		62	63	0.2358	0.4842
	21	22	0.1572	0.3228		63	64	0.0243	0.0828
	21	23	0.1965	0.4035	F9	0	65	0.0486	0.1656
	23	24	0.131	0.269		65	66	0.1703	0.3497
F4	0	25	0.0567	0.1932		66	67	0.1215	0.414
	25	26	0.1048	0.2152		67	68	0.2187	0.7452
	26	27	0.2489	0.5111		68	69	0.0486	0.1656
	27	28	0.0486	0.1656		69	70	0.0729	0.2484
	28	29	0.131	0.269		70	71	0.0567	0.1932
F5	0	30	0.1965	0.396		71	72	0.0262	0.0528
	30	31	0.131	0.269	F10	0	73	0.324	1.104
	31	32	0.131	0.269		73	74	0.0324	0.1104
	32	33	0.0262	0.0538		74	75	0.0567	0.1932
	33	34	0.1703	0.3497		75	76	0.0486	0.1656
	34	35	0.0524	0.1076	F11	0	77	0.2511	0.8556
	35	36	0.4978	1.0222		77	78	0.1296	0.4416

	36	37	0.0393	0.0807		78	79	0.0486	0.1656
	37	38	0.0393	0.0807		79	80	0.131	0.264
	38	39	0.0786	0.1614		80	81	0.131	0.264
	39	40	0.2096	0.4304		81	82	0.0917	0.1883
	38	41	0.1965	0.4035		82	83	0.3144	0.6456
	41	42	0.2096	0.4304					

Table 3 Tie Line data for TPC Network.

Sending End Bus	Receiving end Bus	Length in K.m.
6	61	0.59
8	68	1.11
13	49	0.47
14	81	2.03
15	86	1.12
16	21	0.35
19	30	0.44
23	94	0.44
32	37	0.67
33	44	0.54
39	52	1.13
60	72	0.39

Table 4: Bus data for Chyasal, Imadol-2 and Lubhu Feeder

Branch Number	Sending End Bus	Receiving end Bus	End bus real load (kW)	End bus reactive load (kvar)	Branch Number	Sending End Bus	Receiving end Bus	End bus real load (kW)	End bus reactive load (kvar)
1	1	2	0	0.00	32	32	33	0	0.00
2	2	3	0	0.00	33	24	34	0	0.00
3	3	4	0	0.00	34	34	35	0	0.00
4	3	5	255	158.03	35	35	36	170	105.36
5	5	6	0	0.00	36	36	37	85	52.68
6	6	7	42.5	26.34	37	37	38	0	0.00
7	6	8	0	0.00	38	38	39	170	105.36
8	8	9	170	105.36	39	38	40	170	105.36
9	8	10	255	158.03	40	40	41	0	0.00
10	10	11	255	158.03	41	41	42	170	105.36
11	11	12	255	158.03	42	42	43	170	105.36
12	12	13	0	0.00	43	43	44	170	105.36
13	13	14	85	52.68	44	44	45	85	52.68
14	13	15	170	105.36	45	45	46	170	105.36
15	13	16	0	0.00	46	41	47	170	105.36
16	16	17	42.5	26.34	47	47	48	85	52.68
17	16	18	85	52.68	48	48	49	0	0.00
18	16	19	170	105.36	49	49	50	255	158.03
19	15	20	0	0.00	50	50	51	0	0.00

20	20	21	170	105.36	51	41	52	170	105.36
21	20	22	0	0.00	52	52	53	85	52.68
22	22	23	0	0.00	53	53	54	170	105.36
23	11	24	170	105.36	54	54	55	170	105.36
24	24	25	170	105.36	55	55	56	85	52.68
25	25	26	170	105.36	56	56	57	170	105.36
26	26	27	170	105.36	57	57	58	170	105.36
27	27	28	170	105.36	58	1	59	255	158.03
28	28	29	170	105.36	59	59	60	170	105.36
29	29	30	170	105.36	60	60	61	170	105.36
30	30	31	212.5	131.70	61	59	62	170	105.36
31	29	32	85	52.68	62	62	63	85	52.68
63	63	64	212.5	131.70	102	102	103	0	0.00
64	64	65	170	105.36	103	102	104	0	0.00
65	65	66	255	158.03	104	104	105	170	105.36
66	66	67	170	105.36	105	105	106	0	0.00
67	67	68	170	105.36	106	106	107	127.5	79.02
68	68	69	170	105.36	107	106	108	0	0.00
69	69	70	255	158.03	108	107	109	170	105.36
70	70	71	85	52.68	109	109	110	0	0.00
71	70	72	170	105.36	110	110	111	170	105.36
72	70	73	0	0.00	111	111	112	85	52.68
73	73	74	170	105.36	112	112	113	170	105.36

74	73	75	170	105.36	113	113	114	170	105.36
75	75	76	170	105.36	114	113	115	0	0.00
76	76	77	170	105.36	115	114	116	0	0.00
77	76	78	170	105.36	116	116	117	170	105.36
78	78	79	170	105.36	117	117	118	0	0.00
79	67	80	170	105.36	118	117	119	170	105.36
80	80	81	170	105.36	119	119	120	212.5	131.70
81	81	82	170	105.36	120	120	121	85	52.68
82	82	83	0	0.00	121	121	122	170	105.36
83	83	84	170	105.36	121	118	123	0	0.00
84	83	85	255	158.03	122	122	123	212.5	131.70
85	85	86	0	0.00	123	123	124	255	158.03
86	86	87	170	105.36	124	124	125	170	105.36
87	86	88	85	52.68	125	123	126	0	0.00
88	88	89	170	105.36	126	126	127	170	105.36
89	67	90	0	0.00	127	126	128	170	105.36
90	90	91	0	0.00	128	122	129	0	0.00
91	91	92	170	105.36	129	129	130	255	158.03
92	90	93	170	105.36	130	130	131	170	105.36
93	93	94	0	0.00	131	130	132	0	0.00
94	93	95	170	105.36	132	132	133	85	52.68
95	93	96	85	52.68	133	132	134	0	0.00
96	96	97	85	52.68	134	134	135	170	105.36
97	98	98	85	52.68	135	135	136	0	0.00

98	93	99	170	105.36	136	136	137	170	105.36
99	1	100	0	0.00	137	137	138	42.5	26.34
100	100	101	255	158.03	138	138	139	255	158.03
101	100	102	0	0.00	139	139	140	0	0.00
140	140	141	255	158.03	155	153	155	0	0.00
141	140	142	0	0.00	156	155	156	85	52.68
142	142	143	255	158.03	157	157	157	170	105.36
143	143	144	85	52.68	158	157	158	170	105.36
144	142	145	42.5	26.34	159	159	159	0	0.00
145	144	146	85	52.68	160	102	160	85	52.68
146	135	147	170	105.36	161	161	161	42.5	26.34
147	147	148	170	105.36	162	162	162	0	0.00
148	148	149	85	52.68	163	163	163	85	52.68
149	148	149	85	52.68	164	164	164	85	52.68
150	105	150	170	105.36	165	164	165	0	0.00
151	150	151	0	0.00	166	161	166	170	105.36
152	151	152	42.5	26.34	167	167	167	0	0.00
153	152	153	170	105.36	168	168	168	0	0.00
154	152	154	170	105.36					

Table 5 Branch data for Chyasal, Imadol-2 and Lubhu Feeder

Branch Number	Sending End Bus	Receiving end Bus	Section resistance (Ω)	Section reactance (Ω)	Branch Number	Sending End Bus	Receiving end Bus	Section resistance (Ω)	Section reactance (Ω)

1	1	2	0.108	0.074	15	13	16	0.014	0.01
2	2	3	0.194	0.134	16	16	17	0.053	0.037
3	3	4	0.069	0.048	17	16	18	0.029	0.02
4	3	5	0.027	0.022	18	16	19	0.095	0.066
5	5	6	0.069	0.048	19	15	20	0.115	0.08
6	6	7	0.022	0.015	20	20	21	0.106	0.073
7	6	8	0.117	0.081	21	20	22	0.084	0.058
8	8	9	0.088	0.06	22	22	23	0.084	0.058
9	8	10	0.088	0.06	23	11	24	0.099	0.068
10	10	11	0.055	0.038	24	24	25	0.011	0.008
11	11	12	0.033	0.023	25	25	26	0.106	0.073
12	12	13	0.069	0.048	26	26	27	0.073	0.05
13	13	14	0.054	0.037	27	27	28	0.071	0.049
14	13	15	0.117	0.081	28	28	29	0.091	0.063
29	29	30	0.116	0.08	67	67	68	0.389	0.268
30	30	31	0.077	0.053	68	68	69	0.104	0.072
31	29	32	0.031	0.021	69	69	70	0.119	0.082
32	32	33	0.055	0.038	70	70	71	0.04	0.028
33	24	34	0.115	0.079	71	70	72	0.119	0.082
34	34	35	0.051	0.035	72	70	73	0.341	0.235
35	35	36	0.021	0.015	73	73	74	0.033	0.023
36	36	37	0.073	0.05	74	73	75	0.013	0.011
37	37	38	0.069	0.047	75	75	76	0.08	0.055

38	38	39	0.115	0.079	76	76	77	0.018	0.013
39	38	40	0.11	0.076	77	76	78	0.077	0.053
40	40	41	0.095	0.066	78	78	79	0.088	0.06
41	41	42	0.063	0.053	79	67	80	0.073	0.05
42	42	43	0.073	0.05	80	80	81	0.067	0.046
43	43	44	0.023	0.016	81	81	82	0.084	0.058
44	44	45	0.115	0.079	82	82	83	0.194	0.134
45	45	46	0.038	0.032	83	83	84	0.033	0.023
46	41	47	0.022	0.015	84	83	85	0.194	0.134
47	47	48	0.121	0.083	85	85	86	0.048	0.033
48	48	49	0.129	0.089	86	86	87	0.066	0.045
49	49	50	0.084	0.058	87	86	88	0.122	0.084
50	50	51	0.069	0.047	88	88	89	0.091	0.063
51	41	52	0.038	0.032	89	67	90	0.034	0.024
52	52	53	0.045	0.031	90	90	91	0.066	0.045
53	53	54	0.015	0.01	91	91	92	0.049	0.034
54	54	55	0.027	0.022	92	90	93	0.01	0.009
55	55	56	0.014	0.016	93	93	94	0.117	0.081
56	56	57	0.086	0.059	94	93	95	0.044	0.03
57	57	58	0.128	0.088	95	93	96	0.049	0.034
58	1	59	0.61	0.421	96	96	97	0.056	0.066
59	59	60	0.254	0.258	97	93	98	0.016	0.011
60	60	61	0.06	0.042	98	98	99	0.077	0.053

61	59	62	0.128	0.088	99	1	100	0.254	0.258
62	62	63	0.132	0.091	100	100	101	0.04	0.028
63	63	64	0.295	0.3	101	100	102	0.095	0.066
64	64	65	0.086	0.059	102	102	103	0.069	0.048
65	65	66	0.08	0.055	103	102	104	0.051	0.035
66	66	67	0.048	0.033	104	104	105	0.015	0.01
105	105	106	0.044	0.03	137	137	138	0.029	0.02
106	106	107	0.042	0.029	138	138	139	0.066	0.045
107	106	108	0.201	0.139	139	139	140	0.095	0.066
108	107	109	0.157	0.108	140	140	141	0.04	0.028
109	109	110	0.037	0.025	141	140	142	0.069	0.048
110	110	111	0.077	0.053	142	142	143	0.044	0.03
111	111	112	0.05	0.042	143	143	144	0.047	0.039
112	112	113	0.022	0.015	144	142	145	0.055	0.038
113	113	114	0.067	0.057	145	144	146	0.111	0.077
114	113	115	0.076	0.064	146	135	147	0.101	0.069
115	114	116	0.256	0.176	147	147	148	0.059	0.041
116	116	117	0.099	0.068	148	148	149	0.106	0.073
117	117	118	0.106	0.073	149	105	150	0.11	0.092
118	117	119	0.032	0.027	150	150	151	0.044	0.03
119	119	120	0.032	0.027	151	151	152	0.099	0.068
120	120	121	0.041	0.035	152	152	153	0.058	0.04
121	118	122	0.05	0.042	153	152	154	0.079	0.054

122	122	123	0.067	0.057	154	153	155	0.055	0.038
123	123	124	0.026	0.018	155	155	156	0.051	0.035
124	124	125	0.063	0.053	156	156	157	0.085	0.072
125	123	126	0.048	0.033	157	156	158	0.072	0.05
126	126	127	0.105	0.089	158	158	159	0.013	0.009
127	126	128	0.037	0.025	159	102	160	0.079	0.054
128	122	129	0.097	0.067	160	160	161	0.091	0.076
129	129	130	0.044	0.03	161	161	162	0.119	0.082
130	130	131	0.133	0.112	162	162	163	0.069	0.048
131	130	132	0.135	0.093	163	163	164	0.04	0.028
132	132	133	0.075	0.052	164	163	165	0.085	0.072
133	132	134	0.077	0.053	165	160	166	0.061	0.042
134	134	135	0.045	0.038	166	166	167	0.029	0.02
135	135	136	0.035	0.03	167	167	168	0.04	0.028
136	136	137	0.088	0.06					

Table 6 Tie line Data

S.N.	Feeder	Start Bus	End Bus	Length in K.m.	Section resistance (Ω)	Section reactance (Ω)
1	Chyasal	41	51	0.107	0.031	0.021
2		53	59	0.14	0.035	0.024
3	Imadol-2	61	167	0.015	0.084	0.058
4		99	155	0.288	0.084	0.058

5		77	159	0.35	0.102	0.071
6		95	159	0.366	0.140	0.096
7		72	133	0.29	0.044	0.030
8		75	119	0.39	0.174	0.120
9		87	148	0.175	0.051	0.043

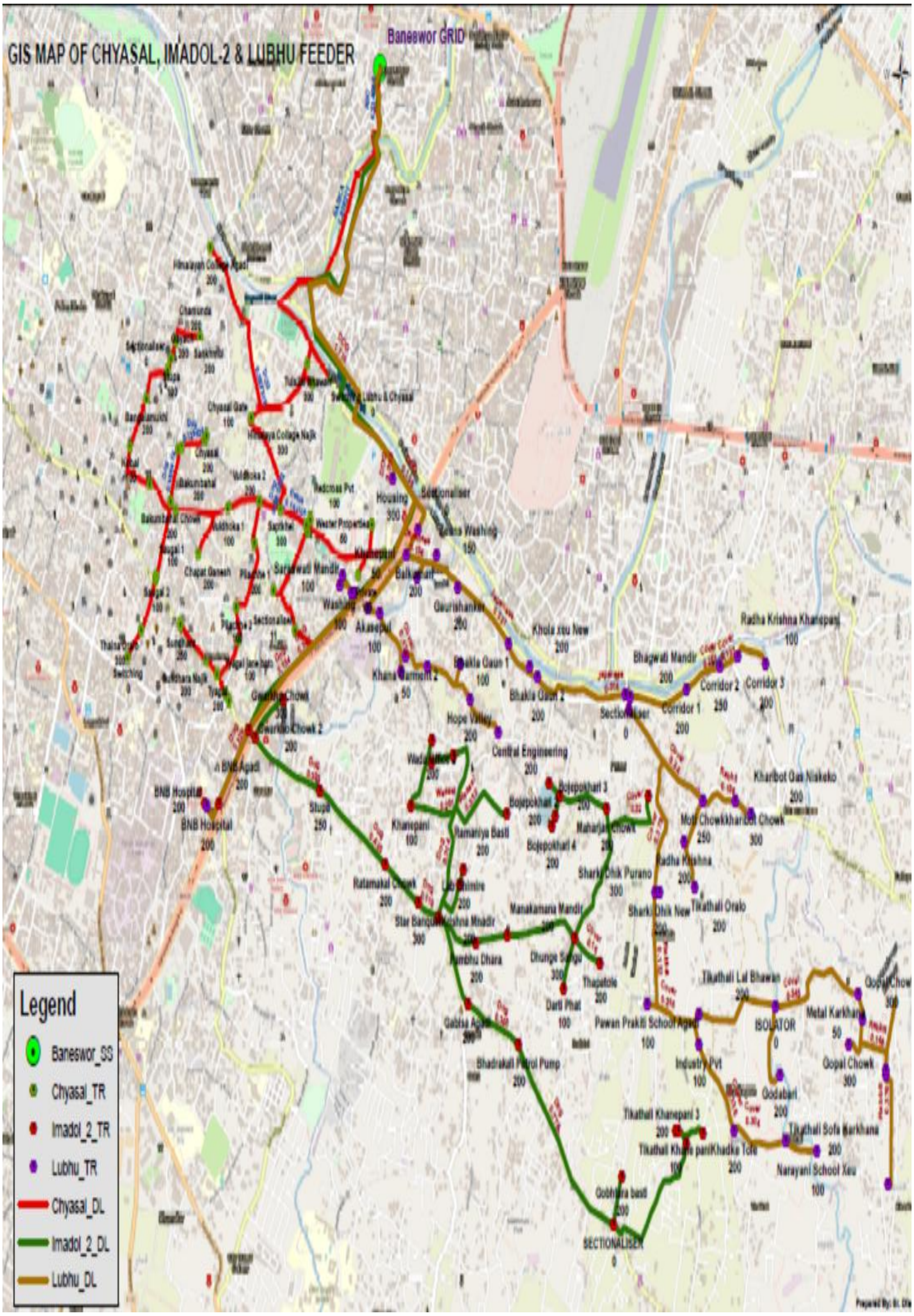

Fig 1: GIS mapping of Chyasal, Lubhu and Imadol-2 Feeders

Table 7: Tripping record of Chyasal Feeder (Year:2079/80)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Asoj	1	1	0	2	0:05	0:05	0:00	0:10	0	0:00
Kartik	0	2	0	2	0:00	0:10	0:00	0:10	2	0:26
Mangsir	0	2	0	2	0:00	0:10	0:00	0:10	3	13:16
Poush	0	2	0	2	0:00	0:10	0:00	0:10	3	2:45
Magh	0	2	0	2	0:00	0:10	0:00	0:10	1	0:43
Falgun	1	2	0	3	0:05	0:10	0:00	0:15	4	7:43
Chaitra	1	2	0	3	0:05	0:10	0:00	0:15	6	6:09
Baisakh	0	2	0	2	0:00	0:10	0:00	0:10	2	0:37
Jesth	1	1	0	2	0:05	0:05	0:00	0:10	4	2:22
Asadh	0	2	0	2	0:00	0:10	0:00	0:10	3	2:42

Table 8: Tripping record of Chyasal Feeder (Year:2080/81)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	1	2	0	3	0:05	0:10	0:00	0:15	9	13:06
Bhadra	2	2	0	4	0:10	0:10	0:00	0:20	6	1:00
Asoj	0	4	0	4	0:00	0:20	0:00	0:20	3	0:33
Kartik	0	0	0	0	0:00	0:00	0:00	0:00	4	1:21
Mangsir	0	0	0	0	0:00	0:00	0:00	0:00	5	0:49
Poush	1	1	0	2	0:05	0:05	0:00	0:10	4	0:49
Magh	0	0	0	0	0:00	0:00	0:00	0:00	1	1:58
Falgun	1	1	0	2	0:05	0:05	0:00	0:10	2	0:42
Chaitra	2	2	0	4	0:10	0:10	0:00	0:20	1	0:38
Baisakh	1	2	0	3	0:05	0:10	0:00	0:15	2	0:45
Jesth	0	3	0	3	0:00	0:15	0:00	0:15	1	1:05
Asadh	0	3	0	3	0:00	0:15	0:00	0:15	1	1:10

Table 9: Tripping record of Chyasal Feeder (Year:2081/82)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute

Asadh	1	9	0	10	0:05	0:45	0:00	0:50	7	4:58
Shrawan	1	1	0	2	0:05	0:05	0:00	0:10	3	1:45
Asoj	3	0	0	3	0:10	0:15	0:00	0:25	2	2:35
Kartik	0	2	0	2	0:00	0:10	0:00	0:10	3	1:51
Mangsir	1	4	0	5	0:00	0:10	0:00	0:10	6	2:53
Poush	2	2	0	4	0:00	0:25	0:00	0:25	4	1:45
Magh	1	2	0	3	0:00	0:35	0:00	0:35	4	4:28
Falgun	2	1	0	3	0:05	0:05	0:00	0:10	3	1:45
Chaitra	3	1	0	4	0:15	0:05	0:00	0:20	5	3:16
Baisakh	1	2	0	3	0:00	0:10	0:00	0:10	3	2:53
Jesth	2	7	0	9	0:10	0:35	0:00	0:45	7	4:08
Asadh	1	6	0	7	0:05	0:25	0:00	0:30	5	4:48

Table 10: Tripping record of Imadol-2 Feeder (Year:2079/80)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shraw	0	5	0	5	0:00	0:25	0:00	0:25	8	2:56

an										
Bhadra	2	7	0	9	0:10	0:35	0:00	0:45	7	4:08
Asoj	3	9	0	12	0:15	0:47	0:00	1:02	9	7:45
Kartik	0	4	0	4	0:00	0:20	0:00	0:20	6	2:26
Mangsir	0	1	0	1	0:00	0:05	0:00	0:05	6	1:39
Poush	0	3	0	3	0:00	0:10	0:00	0:10	14	7:39
Magh	0	4	0	4	0:00	0:20	0:00	0:20	1	0:43
Falgun	0	4	0	4	0:00	0:20	0:00	0:20	1	0:43
Chaitra	0	3	0	3	0:00	0:15	0:00	0:15	8	8:03
Baisakh	1	2	0	3	0:00	0:10	0:00	0:10	3	2:53
Jesth	0	5	0	5	0:00	0:25	0:00	0:25	9	3:35
Asadh	2	6	0	8	0:10	0:30	0:00	0:40	6	3:33

Table 11: Tripping record of Imadol-2 Feeder (Year:2080/81)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	1	10	0	11	0:05	0:50	0:00	0:55	10	4:15

Bhadra	3	1	0	4	0:15	0:05	0:00	0:20	5	3:16
Asoj	0	5	0	5	0:00	0:25	0:00	0:25	8	19:27
Kartik	0	2	0	2	0:00	0:05	0:00	0:05	2	0:45
Mangsir	0	1	0	1	0:00	0:05	0:00	0:05	2	0:37
Poush	4	4	0	8	0:20	0:20	0:00	0:40	7	4:59
Magh	0	2	0	2	0:00	0:00	0:00	0:00	0	0:00
Falgun	2	1	0	3	0:05	0:05	0:00	0:10	6	1:45
Chaitra	3	0	0	3	0:10	0:15	0:00	0:25	6	2:35
Baisakh	2	1	0	3	0:05	0:00	0:00	0:05	2	1:25
Jesth	1	6	0	7	0:05	0:30	0:00	0:35	3	0:00
Asadh	0	4	0	4	0:00	0:20	0:00	0:20	7	2:21

Table 12: Tripping record of Imadol-2 Feeder (Year:2081/82)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	1	4	0	5	0:05	0:25	0:00	0:30	4	2:53
Bhadr	1	5	0	6	0:10	0:30	0:00	0:40	5	1:35

a										
Asoj	2	7	0	9	0:10	0:25	0:00	0:35	4	3:33
Kartik	0	6	0	6	0:10	0:30	0:00	0:40	6	2:20
Mangsir	1	2	0	3	0:00	0:35	0:00	0:35	7	4:28
Poush	1	5	0	6	0:00	0:15	0:00	0:15	8	4:24
Magh	0	4	0	4	0:10	0:15	0:00	0:25	4	2:10
Falgun	2	2	0	4	0:00	0:25	0:00	0:25	7	1:45
Chaitra	0	4	0	4	0:00	0:20	0:00	0:20	9	3:05
Baisakh	1	4	0	5	0:00	0:10	0:00	0:10	6	2:53
Jesth	0	2	0	2	0:00	0:20	0:00	0:20	3	1:35
Asadh	1	3	0	4	0:00	0:25	0:00	0:25	9	5:15

Table 13: Tripping record of Lubhu Feeder (Year:2079/80)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	3	7	0	10	0:15	0:35	0:00	0:50	7	2:56
Bhadra	1	6	0	7	0:05	0:25	0:00	0:30	11	6:00

Asoj	2	11	0	13	0:10	0:45	0:00	0:55	16	5:09
Kartik	3	5	0	8	0:15	0:25	0:00	0:40	11	3:28
Mangsir	3	2	0	5	0:15	0:10	0:00	0:25	1	0:16
Poush	0	5	0	5	0:00	0:25	0:00	0:25	15	5:46
Magh	0	0	0	0	0:00	0:00	0:00	0:00	2	0:04
Falgun	0	0	0	0	0:00	0:00	0:00	0:00	2	0:04
Chaitra	3	7	0	10	0:15	0:39	0:00	0:54	11	4:57
Baisakh	2	7	0	9	0:10	0:35	0:00	0:45	3	4:24
Jesth	4	5	0	9	0:20	0:25	0:00	0:45	10	4:19
Asadh	0	2	0	2	0:00	0:10	0:00	0:10	6	1:51

Table 14: Tripping record of Lubhu Feeder (Year:2080/81)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	1	9	0	10	0:05	0:45	0:00	0:50	7	4:58
Bhadra	3	15	0	18	0:15	1:15	0:00	1:30	6	4:39
Asoj	1	10	3	14	0:05	0:45	0:10	1:00	12	5:33

Kartik	1	1	0	2	0:05	0:05	0:00	0:10	5	2:40
Mangsir	1	1	0	2	0:05	0:05	0:00	0:10	6	2:45
Poush	4	3	3	10	0:10	0:10	0:15	0:35	7	3:41
Magh	1	2	0	3	0:05	0:10	0:00	0:15	9	3:44
Falgun	1	2	0	3	0:05	0:10	0:00	0:15	4	2:45
Chaitra	1	0	0	3	0:05	0:15	0:00	0:20	5	2:20
Baisakh	3	0	0	3	0:10	0:15	0:00	0:25	6	2:35
Jesth	2	8	0	10	0:10	0:35	0:00	0:45	5	3:00
Asadh	0	3	0	3	0:00	0:15	0:00	0:15	2	2:32

Table 15: Tripping record of Lubhu Feeder (Year:2081/82)

Month	Tripping Frequency				Tripping Time				No of shutdown	Time of shutdown
	O/C	E/F	Others		O/C	E/F	Others			
	No	No	No	No	Hr:Minute	Hr:Minute	Hr:Minute	No	No	Hr:Minute
Shrawan	1	4	0	5	0:15	0:30	0:00	0:45	4	1:56
Bhadra	2	5	0	7	0:10	0:25	0:00	0:35	7	3:00

Asoj	2	7	0	9	0:10	0:35	0:00	0:40	8	5:20
Kartik	3	5	0	8	0:10	0:25	0:00	0:35	6	4:28
Mangsir	3	2	0	5	0:10	0:10	0:00	0:20	1	0:30
Poush	1	3	0	4	0:00	0:10	0:00	0:10	9	4:45
Magh	2	1	0	3	0:05	0:00	0:00	0:05	2	1:25
Falgun	2	1	0	3	0:10	0:05	0:00	0:15	4	2:30
Chaitra	3	4	0	7	0:15	0:25	0:00	0:40	16	7:36
Baisakh	3	5	0	8	0:10	0:20	0:00	0:30	8	4:30
Jesth	1	6	0	7	0:20	0:10	0:00	0:30	6	3:46
Asadh	2	11	0	13	0:00	0:10	0:00	0:10	4	2:54

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