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DYNAMIC RECONFIGURATION OF DISTRIBUTION NETWORKS CONSIDERING THE REAL-TIME TOPOLOGY VARIATION

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Abstract

Electrical distribution networks undergo dynamic transformations due to continuous alteration and variation of loads. These alterations necessitate engineering studies aimed at optimizing the distribution networks. Reconfiguring networks stands as a critical analysis process essential for enhancing and managing distribution systems (DSs). When starting with a stable initial DS, the distribution feeders can be reconfigured by adjusting switch statuses to enhance operational performance. In this study, we introduce a dynamic reconfiguration approach that takes into account real-time variations in the initial topology. This methodology integrates dynamic topology analysis and network reconfiguration to address real-time distribution network optimization issues.. We identify the best configuration to reduce power losses and improve the voltage profile of the real-time distribution network in accordance with network reconfiguration. A new approach to dynamic reconfiguration in distribution systems (DS) is introduced, focusing on real-time changes in the initial topology rather than a fixed network structure. This method restores DS network connectivity by dynamically analyzing topology when changes in the initial configuration are identified. By aligning with the current network structure, the proposed method determines the optimal configuration for minimizing power loss and enhancing voltage profiles. As a result, this approach can be readily applied to the real-time variation in network topology during the reconfiguration of distribution systems.

Index Terms: *Adaptive quantum particle swarm optimization (AQPSO), Distribution Systems (DS)*

I. INTRODUCTION

Several methods of reconfiguring networks have been developed to improve Distribution Systems (DS) performance. These methods seek to lessen power loss, improve power quality, and lessen voltage sag inside the DS.

[1-7] examined the development of diverse network reconfiguration techniques aimed at enhancing the performance of distribution systems (DS). These techniques encompass enhancements in power quality, reduction of power loss, and mitigation of voltage sag, among other goals. [8, 9] asserted that the original topology of distribution systems (DSs) can undergo modifications due to two types of events: the addition and removal of branches. Additionally, [10, 11] discovered that the isolation of a faulted section may lead to the removal of certain isolated loads and the disconnection of some healthy loads. As distribution systems (DSs) expand, incorporating new feeders and substations into the original topology, the real-time changes in the initial topology should be taken into account, as emphasized by [12, 13].

Due to the regular occurrence of forced and scheduled outages in distribution systems (DSs), the removal of one or more faulty branches results in the isolation of some healthy branches. In such situations, the prevailing approach involves employing network reconfiguration to ensure a sufficient supply of power to the isolated branches, as highlighted by [14, 15]. In their study, [16] identified the presentation of a reconfiguration technique utilizing genetic algorithms to address the multi-fault service restoration problem. The primary goal of these methods is to transfer loads in an out-of-service area to neighboring supporting feeders by closing tie switches. From an economic standpoint, it is essential to consider minimizing system power loss during the service restoration process. In the non-dominated sorting genetic algorithm-II, the objectives of network reconfiguration involve the out-of-service loads and system power loss, as noted by [17]. Possibility of another topology change occur wherein one or more branches are incorporated into the original system during the extension of the distribution system (DS). Several endeavors have been undertaken to enhance power loss minimization and voltage profile through reconfiguration techniques in the context of optimal distribution network planning, as discussed by [19-22].

The primary goal of the research is to optimize the real-time distribution network's configuration while accommodating dynamic changes to the initial topological structure. In order to tackle this issue, a novel approach known as dynamic reconfiguration is presented, which successfully combines network reconfiguration with dynamic topology analysis. Conventional network reconfiguration modifies the network topology according to tie switch locations. All buses must stay connected to the source node during the reconfiguration procedure. But the original topology changes dynamically as a result of nodes and branches being added or removed after faults or system expansions, requiring a procedure to bring the network connectivity. In order to optimize system performance, goals like reducing power loss and improving the voltage profile while reconfiguring the network must be taken into account. Dynamic topology analysis is employed in the utilization of a dynamic reconfiguration technique to determine the optimal configuration that upholds the safe, cost-effective, and high-quality operation of the Distribution System in the context of the changing initial topology model.

II. DYNAMIC TOPOLOGY ANALYSIS

2.1 Distribution Network Model

In a topological graph, bus bars and electrical components (feeders, switches, and protection devices) are represented as nodes and branches, respectively, in a Distribution System (DS). There are two different kinds of switches in the system: tie switches on tie-lines that connect two feeders, and sectionalizing switches that connect line segments. In the model, these switches are represented as tie branches and sectionalizing branches.

The Distribution System (DS) typically follows a radial operational pattern. A thorough understanding of a standard distribution network's architecture requires an examination of important topology ideas. We use a connected tree S_G to represent the connectivity of the topology graph G. The nodes within S_G collectively form an electrical island S_D. In contrast, a loop is a closed path that starts at one node, goes through a number of nodes, and ends at the original node. Within the DS, tie branches are closed to create closed loops.

This section presents the idea of a loop vector, which is a collection of branches that together form a closed loop in the network. Crucially, every loop has a single tie branch that is independent of all other loops. As a result, there are exactly as many loops as tie branches. Branches can be divided into two categories: non-loop branches and loop branches.

It is possible to arrange the set of loop vectors into a matrix called the "loop matrix," or L_{op}. There are n nodes and n_{op} tie branches in a DS. Specifically, the row-column dimension of the loop matrix L_{op} is $n_{op} \times m_{op}$, where m_{op} is the total number of branches in the loop with the maximum number of branches. Every row in L_{op} corresponds to a different loop vector, and every element in a row represents a branch of that loop. The tie branches connected to the loops are indicated by the first column elements. The topological parameters are obtained by executing the subsequent steps: [26]

(i) Examine the standard initial data of topology G.

(ii) Set the initial values for connected tree S_{Gk}, electrical island S_{Dk}, root node vector V_r = [], root node $v_r = 1$, and initial label $k = 1$.

(iii) Generate the adjacency matrix $A = (a_{vivj})_{n*n}$ of G. If a branch connects node v_i and node v_j, then $a_{vivj} = 1$. Otherwise, $a_{vivj} = 0$.

(iv) By examining matrix A, find path P_i from root node v_r to an unmarked node v_i ($i \in (2\ldots n)$)

(v) If path P_i is existed, mark node v_i and save it to S_{Dk}, and the corresponding branches are saved to S_{Gk}; otherwise, save it to V_r.

(vi) Check network connectivity. If the electrical island S_{Dk} includes all nodes in the system, then go to (7). Otherwise, go to (8).

(vii) Create the loop matrix L_{op}. The two paths from the root node v_r to the end nodes of a tie branch are extracted. Next, the point where the two paths intersect is identified. By beginning at the intersection, traveling through a group of nodes, and ending back at the starting node, a closed path is created. A loop matrix L_{op} is produced by all closed paths.

(viii) The topological parameters should be output if every node has been marked. Otherwise, update the root node v_r , set $k = k + 1$; and return to (4)

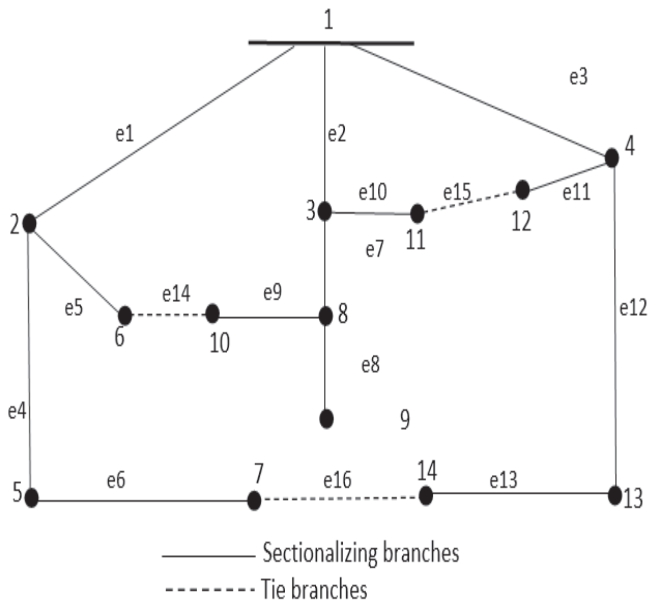

Figure 2.1 General System [26]

Examining Fig. 2.1, we find a basic system consisting of 14 nodes, 13 sectionalizing branches, and 3 tie branches. The connected tree S_G = [e1–e13], electrical island S_D = [1–14], and L_{op} are gained.

$$L_{op}=\begin{bmatrix} e_{14} & e_1 & e_2 & e_5 & e_7 & e_9 & 0 \\ e_{15} & e_2 & e_3 & e_{10} & e_{11} & 0 & 0 \\ e_{16} & e_1 & e_3 & e_4 & e_6 & e_{12} & e_{13} \end{bmatrix} \quad (1)$$

2.2 Dynamic Topology Update

There are two different kinds of events that make up the topology changes in the network:

❖ Cutting off branch and

❖ Adding new branch.

The following is how the changes can be tracked using the topology updating strategy:

A. Removal of a loop branch: Branches are divided into loop and non-loop branches, as was previously indicated. A faulty branch is permanently disconnected when a fault arises within a system segment. These two branch types are taken into consideration in this discussion of the topology update process.

The elimination of loop branch e_i induces modifications to the loop matrix, Lop. Nonetheless, network connectivity remains unaffected as an alternative path connects the terminal nodes of branch e_i. Since the loop matrix is the basis for solution generation in network optimization, the goal is to choose the open loop vector that reduces changes to topology parameters as little as possible.

First, we determine which loop vectors contain the removed branch in order to accomplish this. Subsequently, we pinpoint the open loop vector, denoted as i_{op} characterized by the fewest branches. In an extreme scenario, the removed branch appears in only one loop vector, which is called the open loop vector. In another extreme scenario, where the number of branches in each loop vector is identical, any of them may be chosen as the open loop vector.

Once i_{op} has been identified, the subsequent steps involve updating the topological parameters and reestablishing network connectivity. If e_i happens to be a tie branch, the network's connectivity remains intact, given that tie branches are typically open. In this case, the loop matrix, L_{op}, is adjusted by removing loop i_{op} .

However, if e_i is a sectionalizing branch, restoring network connectivity requires closing the tie branch within loop i_{op} effectively transforming it into a sectionalizing branch. Furthermore, new topological parameters are obtained by utilizing the methods described in the preceding section. In the network depicted in Fig. 2.1, a loop branch e1 is eliminated following the fault. The open loop vector i_{op} containing branch e_1 is dotted by [e_{14}, e_1, e_2, e_5, e_7, e_9]. Since the tie branch e_{14} is changed to a sectionalizing branch, the sectionalizing branches [e_1–e_{13}] can be replaced by SG_G= [e_2–e_{14}]. Lastly, the electrical island S_D = [1– 14] and loop matrix L′op are obtained

$$L'_{op}=\begin{bmatrix} e_{15} & e_2 & e_3 & e_{10} & e_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ e_{16} & e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_9 & e_{12} & e_{13} & e_{14} \end{bmatrix} \quad (2)$$

B. Removal of a non-loop branch: An electrical island that is isolated is formed when a branch without a loop is disconnected. The identification of this isolated island is made easier through the use of a radius search method. In a connected topology represented by G, a line connecting two nodes is assigned a weight value w_{ij} if the respective nodes create an edge. The radius is

$$r_G = \min_{u \in V}, \max_{v \in V} (d(u,v)) \quad (3)$$

where d(u,v) is the distance between nodes u and v and V is the set of nodes in graph G.

Disconnecting a branch without a loop leads to the creation of an isolated electrical island. This island is established by commencing at the terminal node of the disconnected branch, traversing a set of nodes and branches, and reaching the boundary points of the tree, denoted as $n_r = r_G - 1$. All branches within the isolated electrical island are distinct from the original topology. The generation of new topological parameters follows the procedures outlined in Section 2.1.

Branch e8 is eliminated, as seen in Fig. 2.1, and a new electrical island S_{D2} = [9] is found by applying the radius search technique. S_{G1} = [e_1–e_7, e_9–e_{14}] and S_{D1} = [1–8, 10–14] are the topological parameters in real time.

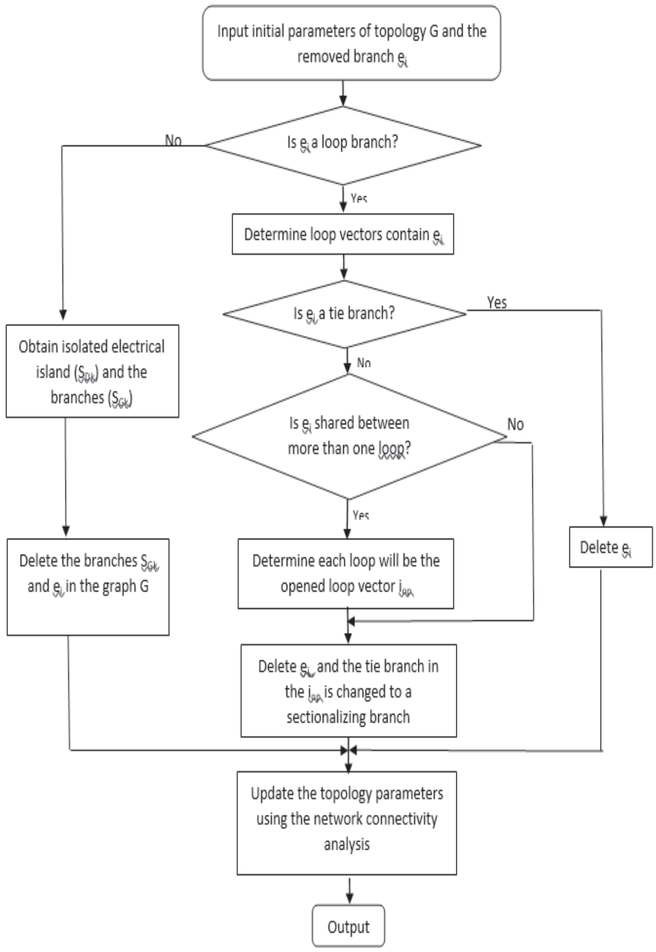

Fig 2.2 Flowchart of Dynamic Topology Update [26]

As a result, when a branch is eliminated, the dynamic topology updating process can be listed as seen in Fig. 2.2.

C. *Addition of a branch*: In order to meet customer requirements, additional feeders and nodes can be integrated into a well-established Distribution System (DS). The focus of this approach is on monitoring topology modifications and acquiring the initial network status in real-time. The following series of actions is used to identify the topological changes that result from the introduction of a new branch ei that connects node v_1 to node v_2.

i. Branch e_i is a tie branch if nodes v_1 and v_2 are part of the same electrical island SD. The branch is typically open to guarantee radial system functionality.

ii. Branches e_i are sectionalizing branches and are typically closed if nodes v_1 and v_2 are part of two distinct electrical islands. The sectionalizing branches and the tie branches are combined in both electrical islands.

By following these procedures, the network connectivity is examined in order to determine the real-time topological parameters.

III. DYNAMIC RECONFIGURATION METHODOLOGY

The network reconfiguration examined in this study deviates from traditional reconfiguration issues that typically involve initial topology adjustments and can be viewed as a dynamic challenge. When tie switches are repositioned in the traditional context of network reconfiguration, all buses must keep their connection to the source node during the process, which causes topology changes.

However, this dynamic approach introduces alterations to the initial topology due to node and branch additions or removals following fault incidents or system expansions. This necessitates a process to restore network connectivity. To enhance operational efficiency, network reconfiguration should address objectives related to minimizing power losses and enhancing voltage profiles.

Through the use of dynamic topology analysis, a dynamic reconfiguration technique is applied to ascertain the best configuration that guarantees the Distribution System (DS) functions within the evolving initial topology model in a safe, cost-effective, and high-quality manner.

3.1 Problem Formulation

The main objective of the dynamic reconfiguration, taking into account the dynamic nature of the initial topology, is to use the dynamic topology analysis to quickly restore network connectivity. Following the restoration of network connectivity, the system's voltage profile enhancement and power loss minimization should be taken into account. The real power, reactive power, and voltage magnitude at the sending end i of a branch are Pi, Qi, and Vi, respectively, based on the power flow calculation in [23]. The following formula is used to calculate the power loss Ploss(i,i+1) of the branch connecting nodes i and i + 1 (receiving end):

$$P_{loss(i,i+1)} = r_i \frac{{P_i}^2 + {Q_i}^2}{{V_i}^2} \quad (4)$$

where Vi is the voltage amplitude of node i, r_i is the resistance of the branch between nodes i and i+1, and Pi and Qi are the active and reactive power flows from node i.

The total power loss of a real-time distribution network $G_r(n,m)$ with n nodes and m branches is calculated by adding up all of the line section losses. The following is an expression for the formulation:

$$min\left(\sum_{i=1, i\in G_r}^{m} k_i r_i \frac{{P_i}^2 + {Q_i}^2}{{V_i}^2}\right) \quad (5)$$

where k_i is the status of branch e_i ; $k_i = 1$ in the case of closed branch, and $k_i = 0$ in the case of an open branch, where m is the number of branches in the real-time network $G_r(n,m)$;

Improving the system profile is maximizing the minimum node voltage amplitude as the objective function, which can be calculated as follows:

$$\max(\min(Vi/Vref), \quad i \in (1, \dots, n)) \quad (6)$$

where Vref is the standard voltage amplitude, and n is the number of nodes in $G_r(n,m)$.

Enhancing the voltage amplitude within the system is interconnected with power loss. A decrease in power loss results in a reduction in voltage drop, thereby enhancing the overall voltage values in the network. The operational constraints that must be met are outlined as follows:

$$I_i \le I_{i,max}$$

$$V_{i.min} \le V_i \le V_{i.max} \quad (7)$$

$$g \in T_{Gr}$$

The subscripts 'max' and 'min' denote the upper and lower bounds, respectively. I_i represents the current flowing through branch e_i. g denotes a network structure, and T_{Gr} is a collection of radial network structures within the real-time topology G_r.

3.2 Dynamic Reconfiguration Optimization Algorithm

To address the optimization challenge of the DS while taking real-time topology changes into account, a method for dynamic reconfiguration is proposed that combines dynamic topology analysis with network reconfiguration. In the event that the original topology is modified, the main objective is to quickly determine and establish network connectivity again.

Following a topology change, network reconfiguration is employed to identify the optimal setup for minimizing power loss and enhancing the voltage profile. The issue is framed as a intricate combinatorial optimization problem. To tackle this problem, an adaptive quantum particle swarm optimization (AQPSO) algorithm is introduced, building upon the principles of particle swarm optimization. The real-time topology variation allows for the dynamic adjustment of the AQPSO's variables. Considering the revised loop matrix L′op, the initial element in each column designates the tie branch. Within each column, the loop is formed by the tie branch and sectionalizing branches. The branches are documented as a sequence of decimal numbers within the loop, ranging from 1 to the total number of branches in the column. To ensure a radial system configuration, it is necessary to open one of the branches within the loop. The particle vector represented by $x = (x_1, x_2, \ldots, x_j)$ is a solution. The position x_j of particle j corresponds to the identification number of the branch intended for opening. Following the principles outlined in [24], the adaptive quantum particle swarm optimization (AQPSO) is capable of attaining the optimal solution through continuous updates to the particle's position. Within the D-dimensional search space, denote the solution vector of particle j as the vector $x_{jd} = (x_{j1}, x_{j2}, \ldots, x_{jD})$. During iteration t, the present best position of particle j is expressed as $p_{jd}(t) = (p_{j1}, p_{j2}, \ldots, p_{jD})$. The global best position is denoted as $mbest(t) = (mbest_{j1}, mbest_{j2}, \ldots, mbest_{jD})$. The revised position of particle j is adjusted using the following equation, determining the position $x_{jd}(t+1)$ in iteration $t+1$ based on its prior position $x_{jd}(t)$.

$$x_{jd}(t+1) = round(p_{jd}(t) \pm \beta * mbest(t) - x_{jd}(t) * In(1/u)) \quad (8)$$

$$mbest(t) = \frac{1}{M} \sum_{j=1}^{M} P_{jd(t)} \quad (9)$$

Here, $x_{jd}(t)$ and $x_{jd}(t+1)$ represent the initial and updated positions of particle j, respectively, while u and φ denote uniformly distributed random numbers within the range [0,1]. The round() function is employed in the integral calculation, and β is utilized to regulate the convergence speed of the algorithm:

The procedure for dynamic reconfiguration is outlined as follows: [26]

1) Initialize the standard topology G, and identify the initial parameters S_G, S_D, and L_{op}.
2) If a modification in the topology is identified, proceed to step (3); otherwise, proceed to step (4).
3) Reestablish network connectivity. This stage promptly assesses the network's connectivity and the status of branches through dynamic topology analysis. By maintaining the states of the branches, the new topology Gr and new loop matrix L ′op can be obtained.
4) Revise the parameters of the AQPSO. Utilizing matrix L′op or Lop, define the solution particle vector as $x = (x_1, x_2, \ldots, x_j)$ and create a random population P comprising M vectors.
5) Examine the radiality of every particle in population P, where each solution serves as a potential topology candidate. The topology graph may be described as an adjacency matrix A_r. The radiality

of solutions is determined based on the determinant of A_r. If the determinant of A_r is equal to 1 or −1, the solution is feasible and go to step (5); otherwise, set the particle's pbest as C (C takes a large positive number).

6) Assess the fitness values ((5) and (6)) for each particle (pbest) and retain the particle possessing the highest fitness value as (mbest).
7) Adjust the position vectors for each particle in accordance with (8) and (9).
8) Iterate through steps (6) and (7) until a termination criterion is met. The resulting x* represents the optimal solution.
9) Examine alterations in the initial topology. If there is a change, revert to step (2); otherwise, output x*.

IV. RESULTS

The provided example in this thesis demonstrate the application of the proposed approach for reconfiguring a real-time distribution network.

1. *65-bus Kohalpur Feeder (Practical Feeder)*

Kohalpur feeder is 11kV distribution feeder under Nepal Electricity Authority. The substation standard voltage is set at 1.0 per unit (p.u.), with voltage limits ranging from 0.82135 to 1 p.u. The branch current constraint is 500 amperes (A), and Ploss represents the active loss of the network, while Vmin signifies the minimum voltage among all nodes.
The cases illustrate the procedure for restoring network connectivity and determining the topological structure when one or more branches are removed. The reconfiguration results, guided by real-time topology, are presented in Table 4.1.

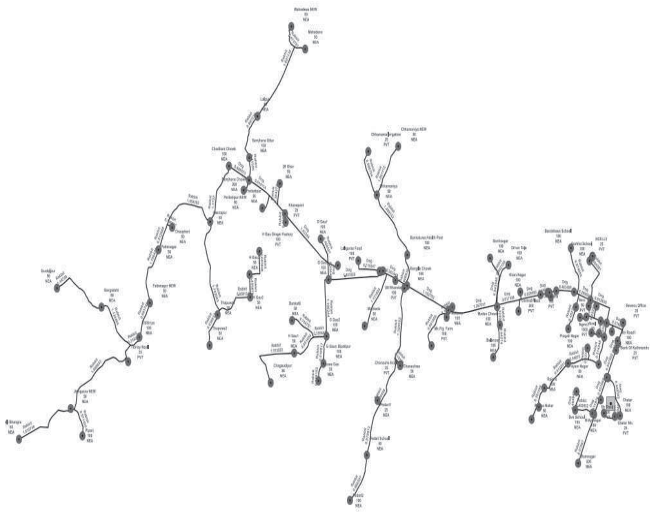

Figure 4.1: Single Line Diagram of 65 bus Kohalpur Feeder.

Case I: Network reconfiguration with no faults: In this case, a fault-free system is the subject of an investigation. Assuming the regular operation of the initial topology, in which all nodes are joined to form the initial topology through sectionalizing branches, the network reconfiguration represents an ideal optimization issue. As a result, the issue is resolved without utilizing the dynamic topology update by following the procedures described in Section 2.2. Table 4.1 displays the findings of the best configuration for this scenario. Losses are reduced by 145.94 kW compared to the original topology, and the minimum voltage value is increased to 0.87981 p.u.

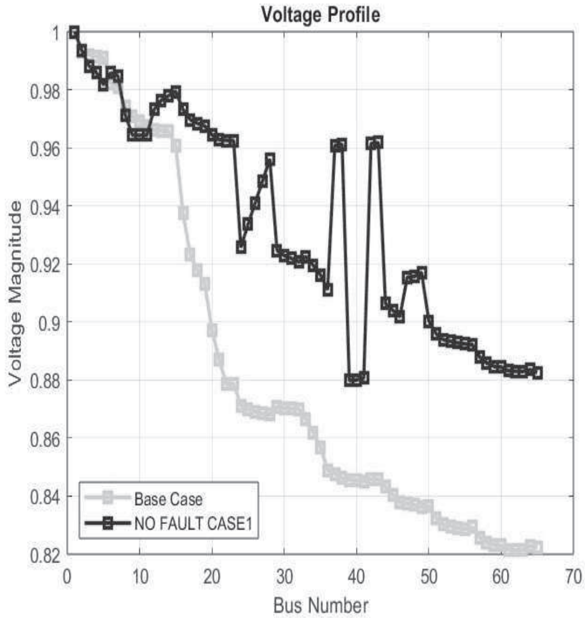

Figure 4.2: Voltage Profile of the reconfigured network for no fault case

Case II: Network reconfiguration with a single branch fault: To address a permanent fault on line e_{26}, the existing sectionalising branch connecting nodes 26 and 27 is removed, resulting in some healthy nodes being without power. The objectives are to restore electric energy to healthy loads and update the initial topology. In this revised initial topology, our method identifies the optimal configuration as [e_{12}, e_{26} ,e_{42}, e_{45}, e_{57}], with a power loss of 240.24 kW. Leveraging the switch operations, the decision maker can restore network connectivity and achieve a high-quality solution, enhancing the operational performance of the system. Figure 4.3 depicts the voltage profile of the reconfigured network and the network reconfiguration leads to an improvement in voltage amplitude.

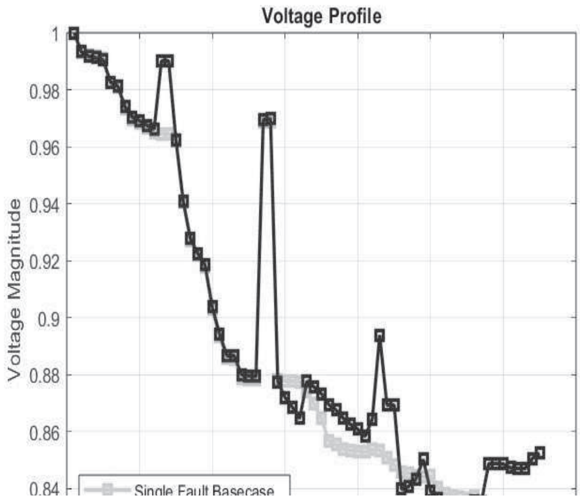

Figure 4.3: Voltage Profile of the reconfigured network for single fault case

Case III: Network reconfiguration with a double-branch fault: Let's consider a scenario where a fault occurs on lines e_{12} and e_{26}. Following reconfiguration, a power loss of 207.19 kW is attained. Figure

4.4 illustrates the voltage profiles of the system for both the initial and optimal cases. The minimum voltage magnitude of the real-time system is 0.85035 p.u.

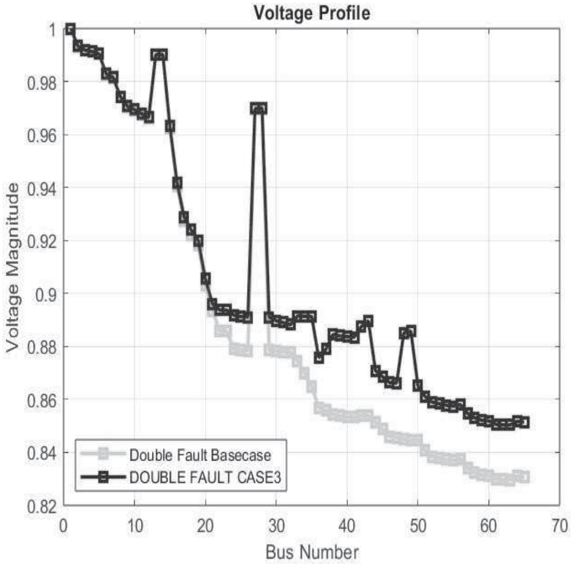

Figure 4.4: Voltage Profile of the reconfigured network for double fault case

Case IV: Network reconfiguration with a node fault: In the depicted system in Figure 4.1, it is assumed that a fault has occurred at node 6, leading to the removal of branches e_5 and e_6 to isolate the fault. Consequently, the power supply to the loads in the node set (nodes 6–65) is disrupted. As outlined in the steps of the dynamic topology update, node 6 is the faulted point, and the supply to the load of this node cannot be restored until the fault is repaired. However, the loads on the remaining nodes without supply (nodes 7–65) can be reinstated by closing the tie branches e_{65}. The proposed algorithm recommends the opening of branches e_5, e_{23}, e_{30}, e_{36}, and e_{58}, resulting in a total power loss of 242.15 kW. Additionally, the minimum voltage magnitude achieved by the proposed method is 0.8732 p.u.

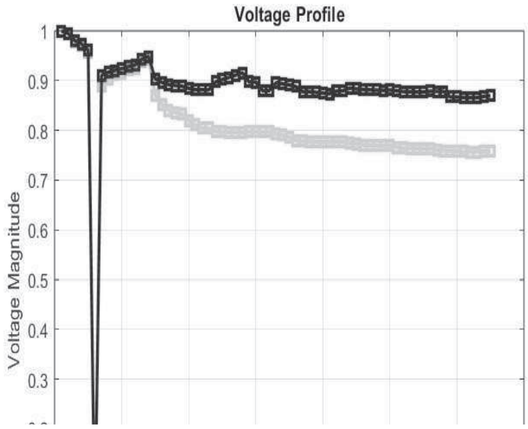

Figure 4.5: Voltage Profile of the reconfigured network for node fault case

Table 4.1 Summary of results for 65-bus Kohalpur Feeder (Practical Feeder)

Item	Final Open Switches	Ploss, kW	V_{min}, p.u.
Initial	e_{65}-e_{69}	261.91	0.82135
Case 1 (fault free)	e_{11},e_{23},e_{36},e_{38},e_{46}	145.94	0.87981
Case 2 (single fault, e_{26})	e_{12}, e_{26},e_{42},e_{45},e_{57}	240.24	0.8294
Case 3 (double fault, e_{12} and e_{26})	e_{12}, e_{26},e_{35},e_{47}, e_{69}	207.19	0.85035
Case 4 (node 6 fault)	e_5, e_{23},e_{30},e_{36}, e_{58}	242.15	0.8732

V. CONCLUSIONS

A new approach to dynamic reconfiguration in distribution systems (DS) is introduced, focusing on real-time changes in the initial topology rather than a fixed network structure. This method restores DS network connectivity by dynamically analyzing topology when changes in the initial configuration are identified. Subsequently, updates are made to the loop matrix, connected tree, and electrical islands based on the real-time topology. By aligning with the current network structure, the proposed method determines the optimal configuration for minimizing power loss and enhancing voltage profiles.

The method under consideration underwent testing on 11kv Kohalpur Feeder under Nepal Electricity Authority, where various initial topology change events were taken into account during the process of network reconfiguration. The simulation results indicate that this approach can swiftly restore network connectivity following a topology change. Additionally, the method demonstrates its ability to accurately identify optimal configurations for diverse real-time topologies. In comparison to traditional methods, this approach offers enhanced flexibility and superior performance. As a result, this approach can be readily applied to the real-time variation in network topology during the reconfiguration of distribution systems

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