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Operational Cost Minimization of Electrical Distribution Network during Switching for Sustainable Operation

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Abstract: Continuous increases in electrical energy demand and the deregulation of power systems have forced utility companies to provide high-quality and reliable services to maintain a sustainable operation and reduce electricity price. One way to continue providing the required services while simultaneously reducing operational costs is through minimizing power losses and voltage deviation in the distribution network. For this purpose, Network Reconfiguration (NR) is commonly adopted by employing the switching operation to enhance overall system performance. In the past, work proposed by researchers to attain switching sequence operation was based on hamming distance approach. This approach caused the search space to grow with the increase in total Hamming distance between the initial and the final configuration. Therefore, a method is proposed in this paper utilizing a Mixed Integer Second Order Cone Programming (MISOCP) to attain optimal NR to address this issue. The Hamming dataset approach is opted to reduce search space by considering only radial configuration solutions to achieve an optimal switching sequence. In addition, a detailed economic analysis has been performed to determine the saving after the implementation of the proposed switching sequence. The effectiveness of the proposed technique is validated through simulations on IEEE 33-bus distribution network and a practical 71-bus network in Malaysia. The result shows that the proposed method determined the optimal network configuration by minimizing the power losses for the 33 bus and 71-bus system by 34.14% and 25.5% from their initial configuration, respectively to maintain sustainable operation.

Keywords: cost saving; distribution system; MISOCP; network reconfiguration; switching sequence; sustainable operation

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1. Introduction

Nowadays, human lives are highly dependent on technologies and has thus made electricity instrumental for their livelihood. It also plays a pivotal role in increasing sustainability and economic development in a wide variety of sectors. For example, demand for electricity in Malaysia has increased by an average factor of 5.48% per year for the last 20 years, and it is expected to increase further in the future [1]. Electricity is supplied through a power system which typically consists of three subsystems; the first is the generation, followed by the transmission and distribution system. During power distribution, current flows through a conductor and produces power losses which are in the form of heat. Studies conducted in [2,3] stated that the power loss in the transmission and distribution system is 30% and 70% of the total losses in the power system, respectively. The distribution system provides electricity to residential, commercial, and industrial consumers. Total power losses in a distribution network are reasonably high because it has a low voltage and a high current amplitude than the high voltage network (transmission system). Hence, the performance of the electrical distribution network degrades further due to the reduction in voltage magnitude at heavily loaded feeders, which in turn increases the power loss of the system. Therefore, power losses in the distribution network reduce system efficiency and increase operational costs.

In a modern distribution network, the efficiency of a distribution network is improved by mitigating the power loss using Network Reconfiguration (NR). Network Reconfiguration is a process that alters the distribution network's switching state. The distribution network consists of two types of switches which are sectionalizing switches (normally closed) and tie switches (normally open) [4]. The main concept of NR is to open the sectionalizing switches and close the tie switches while maintaining the radiality of the distribution network. Network Reconfiguration was one of the methods utilized in order to reduce the power loss of the distribution network and balance the load by transferring from heavily loaded feeders to lightly loaded feeders; additionally, it is used to isolate the faulted area and restore the power outage of an un-faulted area in the distribution network. Hence, NR can reduce the power loss and voltage deviation while simultaneously improving the distribution network's reliability, stability, and loadability [5–8]. However, attaining the optimal switches to achieve the previous objectives is a complicated task, especially due to the considerable search space. Hence, a robust method should be adopted to obtain the optimal switching to reduce the power losses and improve the voltage profile. Previously, several techniques had been presented to attain optimal solutions for the power losses problem in [9], another comprehensive comparison studies among meta-heuristic techniques were addressed in [10], where the Equilibrium Optimizer (EO) showed its superiority compared with other meta-heuristic techniques in attaining optimal solutions. Furthermore, the Cuckoo Search Algorithm (CSA) was used in [11] to reduce the active power losses and improve the voltage profile, whereas an improved CSA was utilized in [12] for power loss minimizing. The Firefly Algorithm (FA) [13] and Coyote Optimization Algorithm (COA) in [14] were used for reducing the power loss and improving the voltage profile. Similarly, Cloud Theory was utilized in [15] to reduce the power losses, voltage deviation and improve system reliability. A Mixed Integer Second Order Cone Programming (MISOCP) was proposed in [16], considering NR and optimal capacitor placement to minimize the power losses in addition to operating costs. For more pragmatic solutions, the Distributed Generation (DG) was included in many works alongside NR [17]. For example, the salp swarm algorithm was presented in [18] to reduce the active power loss, and NR was used to enhance the distribution system resilience in [6] to reduce the accumulative cost during the load restoration and DGs operation. Furthermore, heuristic algorithms such as artificial bee colony, differential evaluation, particle swarm optimization (PSO), and genetic algorithm (GA) were addressed in [19] to minimize the real power losses and enhance system performance. Finally, an improved sine–cosine algorithm was used to decrease the power losses and enhance the voltage stability [20].

On the other hand, a switching sequence identifies the switching path from an initial configuration to achieve an optimal NR configuration. It is necessary to maintain the network operational condition during intermittent switching. In the past, most investigations were conducted on obtaining the minimum power loss by using NR, but few have considered the network switching sequence technique [21]. Moreover, the real-time optimal switching sequence was discussed in [22]. The main aim was to minimize the power loss and enhance the voltage profile using different meta-heuristic techniques like the firefly algorithm, GA, and PSO. The pathfinder algorithm (PFA) was utilized in [8] to minimize the total cost of power losses and the changing of the switches. Finally, the switch opening and exchange method was proposed in [23], where the authors in this work attain to find a solution for the multi-hour stochastic distribution NR.

However, most researchers consider the two-level strategy in which NR is used to identify the optimal configuration in the first stage, whereas in the second stage, an algorithm determines the path of the switching sequence based on minimum power loss. The proposed switching technique considers Hamming distance equal to one for switching search space. Thus, it requires a large switching search space, i.e., $2 * \left(\frac{1}{2}h_t\right)! * \left(\frac{1}{2}h_t\right)!$ where h_t is the total Hamming distance between initial and final configuration. Therefore, the large space of the switching sequence requires an optimization method to search and find the optimum results for the problem. The previous works showed a robust method to find the optimal configuration for the network to reduce the power losses. However, the search space was large, and the relation between the number of buses and the search space is direct. Hence, it will take considerable computational time to find the optimal switching. Furthermore, the accuracy in finding the optimal network configuration that gives minimum power loss is difficult with such a large search space.

This study focuses on NR to improve system efficiency by reducing the distribution network's power loss and voltage deviation to ensure sustainable operation. In addition, to cope with the previous work drawbacks, the proposed MISOCP technique attains a switching sequence from the initial configuration based on minimum power loss during intermittent switching. Due to the implementation of the proposed technique, the search space has been reduced significantly, which resulted in obtaining the optimal switching that gives the minimum power loss and voltage deviation. In each switching operation, the radiality of the network is maintained, and the bus voltage is kept within the voltage limit. The performance of the proposed technique is vetted on a 33-bus distribution network, and the practical impact of the proposed technique is evaluated on the practical 71-bus system in Malaysia. The main contributions of this work are outlined as follows:

- NR for a practical 71-bus system in Malaysia has been conducted based on the MISOCP method to minimize the power loss and voltage deviation to acquire sustainable operation.
- Hamming dataset approach with reduced search space based on exhaustive search has been proposed to attain the optimal switching sequence during intermittent switching.
- Economic analysis has been conducted on a practical 71-bus system to minimize operational costs.

The paper is structured as follows; the problem formulation is presented in Section 2, followed by the methodology of the switching sequence in Section 3, then the results and discussion are elaborated in Section 4. Finally, a conclusion to sum up the whole paper is demonstrated at the end of the manuscript.

2. Problem Formulation

This work aims to reduce the total power losses in addition to the voltage deviation in the system and consequently minimize the operational cost while fulfilling the technical and operational constraints. The whole problem formulation is elaborated in this section, beginning with the objective function and then the problem constraints.

2.1. Objective Function

The proposed technique solves NR problems to reduce the total power losses in addition to voltage deviation utilizing the MISOCP. An objective function is defined in Equation (1), where Equation (2) utilized to minimize the voltage deviation. Finally, the cost of power losses is calculated in Equation (3). Because the objective function (Obj) has two parts with different units, the net power loss P_{Loss}^{Ratio} is calculated as the ratio of the system's total active power loss after reconfiguration P_{Loss}^{Rec} to its power loss prior to reconfiguration P_{Loss}^{Base}. Equation (5) denotes to the active power loss after the network reconfiguration.

$$\text{Obj} = \text{Min}\left(\left(P_{Loss}^{Ratio}\right) + VDI\right) \tag{1}$$

$$VDI = Max_{j=1}^{N}\left(\frac{|V_{Cj}| - |V_j|}{|V_{Cj}|}\right) \tag{2}$$

$$Cost_{Loss} = P_{Loss}^{Rec} * E_{tariff} * Y_{Hour} \tag{3}$$

$$P_{Loss}^{Ratio} = \frac{P_{Loss}^{Rec}}{P_{Loss}^{Base}} \tag{4}$$

$$P_{Loss}^{Rec} = \sum_{ij=1}^{N_b}\left(\frac{P_{ij}^2 + Q_{ij}^2}{V_j^2}\right) * R_{ij} * \gamma_{ij} \tag{5}$$

where P_{Loss}^{Ratio} is the ratio of the system's total active power loss; VDI is the voltage deviation index; $Cost_{Loss}$ is the total power loss cost.

E_{tariff} is the electricity tariff (0.224 MYR/kWh); Y_{Hour} is the year in hour (8760 h); V_j is the voltage at the receiving bus.

V_{Cj} is the nominal voltage at bus j j; P_{Loss}^{Rec} is the active power loss after the reconfiguration; P_{Loss}^{Base} is the active power loss before the network reconfiguration; ij is the branch in which i is a sending bus and j is a receiving bus, P_{ij} is the active power passing through the branch ij; Q_{ij} is the reactive power passing through the branch ij; R_{ij} is the branch ij resistance; γ_{ij} is the binary variable, which determines the state of that branch; and N_b is the whole number of branches in the network.

2.2. Constraints

In order to attain the optimum network configuration, the following constraints have to be maintained and fulfilled:

2.2.1. Active and Reactive Power Flows

Inward and outward power flow of ith bus defined in Equations (6) and (7) must be balanced with the generated power and load demand at the particular bus.

$$P_{g,i} - P_{d,i} - \sum_{ij} P_{loss} = \sum_{ij} P_{ij} - \sum_{ki} P_{ki} \quad \forall\, i\epsilon\Omega_b, ij\epsilon\Omega_l \tag{6}$$

$$Q_{g,i} - Q_{d,i} - \sum_{ij} Q_{loss} = \sum_{ij} Q_{ij} - \sum_{ki} Q_{ki} \quad \forall\, i\epsilon\Omega_b, ij\epsilon\Omega_l \tag{7}$$

where $P_{g,i}$ is the active power generations at bus i; $Q_{g,i}$ is the reactive power generations at bus i; $P_{d,i}$ is the active power demand at bus i; $Q_{d,i}$ is the reactive power demand at bus i; P_{loss} is the active power loss; Q_{loss} is the reactive power loss; Ω_b is the set of buses; and Ω_l is the set of branches.

2.2.2. Voltage Limit

The voltage drop in branch $i - j$ can be calculated considering the binary variable γ_{ij}, as shown in Equation (8). Moreover, the voltage should be kept within nominal limits, as defined by Equation (10).

$$V_j^2 = V_i^2 - 2 * \left(R_{ij} * P_{ij} + X_{ij} * Q_{ij}\right) - I_{ij}^2 Z_{ij}^2 - \beta_{ij} \quad \forall\, ij\epsilon\Omega_l \tag{8}$$

$$\beta_{ij} = \begin{cases} 0 & if\ \gamma_{ij} = 1 \\ V_i^2 - V_j^2 & if\ \gamma_{ij} = 0 \end{cases} \ \forall\, ij\epsilon\Omega_l \tag{9}$$

$$V_{min}^2 \le V_i^2 \le V_{max}^2 \quad \forall\, i\epsilon\Omega_b \tag{10}$$

where V_i and V_j are the sending and receiving bus voltages; I_{ij} is the branch current; X_{ij} is the branch reactance; and Z_{ij} is the branch impedance.

2.2.3. Maximum Power Flow of a Branch

The power flow and the current through a branch depends on its current carrying capacity (I_{max}) and its state variable, as defined by Equations (11)–(13).

$$I_{ij}^2 \leq I_{max}^2 * \gamma_{ij} \quad \forall\, ij\epsilon\Omega_l \tag{11}$$

$$-I_{max} * V_{max} * \gamma_{ij} \leq P_{ij} \leq I_{max} * V_{max} * \gamma_{ij} \quad \forall\, ij\epsilon\Omega_l \tag{12}$$

$$-I_{max} * V_{max} * \gamma_{ij} \leq Q_{ij} \leq I_{max} * V_{max} * \gamma_{ij} \quad \forall\, ij\epsilon\Omega_l \tag{13}$$

2.2.4. Radiality of Network

The distribution network should operate in a radial topology. Constraints Equations (14) and (15) define the radiality condition.

$$\sum_{ij\in\Omega l} \gamma_{ij} = N - n_s \tag{14}$$

$$\sum_{ij\in\Omega l} \gamma_{ij} + \sum_{jk\in\Omega l} \gamma_{jk} \geq 1 \quad \forall\, j\epsilon\Omega_b \tag{15}$$

where N is the total number of buses, and n_s is the number of a substation in the distribution network.

2.2.5. Apparent Power Limit

The non-linear equation of the apparent power is defined in Equation(16) and converted into MISOCP using Equation (17).

$$V_j^2 + I_{ij}^2 = P_{ij}^2 + Q_{ij}^2 \quad \forall\, j\epsilon\Omega_b \tag{16}$$

$$\left\| \begin{matrix} 2P_{ij}^2 \\ 2Q_{ij}^2 \\ I_{ij}^2 - V_j^2 \end{matrix} \right\| \leq V_j^2 + I_{ij}^2 \quad \forall\, j\epsilon\Omega_b \tag{17}$$

where P_{ij} and Q_{ij} represent the active and reactive power flows through the branch $i - j$.

3. Methodology of the Switching Sequence Technique

This paper adopts a two-stage methodology to determine the optimum switching sequences to get to the optimum network configuration. In the first stage, the optimum configuration is selected using the MISOCP, while in the second stage, the optimal switching sequence is decided for the optimal configuration found in the first stage, utilizing hamming distance dataset approach with reduced search space. Optimal switching sequence is a technique that identifies the sequence to change the network from its initial configuration to the final one that optimizes the objective function. Hence, only switches that modify their state from the initial configuration will be considered during the searching process in this scenario. Two systems are used to validate the work proposed in this paper, the IEEE 33-bus [24] and the actual small-scale network of a public practical 71-bus system in Malaysia. Two platforms were used in this work, MATLAB and AMPL to perform the proposed methodology.

The maximum number of switches that can modify their state will be twice the number of tie lines in the network since the algorithm searches for pair switching to be open/close. Previous researchers consider Hamming distance equal to one for switching search space. Therefore, it requires a large search space, i.e., $2 * \left(\frac{1}{2}h_t\right)! * \left(\frac{1}{2}h_t\right)!$ where h_t is the total Hamming distance between initial and final configuration. This paper presents a hamming dataset technique that only examines the radial combination; as a result, the search space is significantly reduced. The steps to attain the optimal switching sequence is as follows:

Step 1: Select initial and final configuration from the previous stage. Discard the common switches in the initial and final configuration.
Step 2: Attain the minimum edge of cut for $D \subseteq e(tie_{initial})$, which generates precisely two subgraphs G_1' and G_2', having spanning tree of T_1 and T_2.
Step 3: Select the set $F \subseteq e(tie_{final})$ that connects G_1' and G_2'. e(F) connects T_1 and T_2 and generate a possible switching combination. Repeat steps 2 and 3 to generate all the possible switching combinations have Hamming distance equal to two.
Step 4: Evaluate the fitness of the switching combination based on Equation (1). Select the switching combination which provides the lowest fitness value.
Step 5: Remove $X \subseteq e(tie_{initial})$ and $Y \subseteq e\left(tie_{final}\right)$, where X and Y are the selected edges in this switching step.
Step 6: When $e(tie_{initial})$ and $e\left(tie_{final}\right)$ becomes empty; the process will stop. Otherwise, it will repeat from step 3.

The flowchart of the switching sequence technique is demonstrated in Figure 1. To analyze the complexity of the search space, let us consider the example of the switching step in the small distribution network (33-bus network). The switches changed from the initial configuration (S33, S34, S35, and S36) to the final configuration (S7, S9, S14, and S32) in the distribution network, as shown in Figure 2. It can be observed from Figure 2 that one of the switches from (S33, S34, S35, and S36) is closed first, and in the consecutive stage, one of the switches is open from (S7, S9, S14, and S32) or vice versa. Therefore, the total possible switching sequence for a 33-bus distribution network is 1152. However, the complexity of the search space increases immensely with the increase in tie lines in the extensive distribution system. Moreover, there is a considerable number of possible combinations which is non-radial (non-feasible). Therefore, it is imperative to apply optimization techniques to attain the optimal switching sequence of the network.

In the same manner, as the 33-bus system, Figure 3 demonstrates the topological structure for a practical 71-bus system, and the line and bus data are given in Appendix A, Tables A1 and A2. One of the switches from these tie switches (S70 till S90) is closed first. Then, in the consecutive stage, one of the switches is open from the set of these modified switches (S4, S9, S26, S30, S31, S34, S39, S44, S51, S54) or vice versa. Consequently, the total possible switching sequence for a practical 71-bus system is 3.24×10^{24}.

Nevertheless, this study proposes a hamming dataset approach that only considers the radial combination; thus, search space reduces immensely. For example, from Figures 4 and 5, it can be observed that the search space has been confined to only 18 and 56 possible combinations for the IEEE 33 and a practical 71-bus system, respectively.

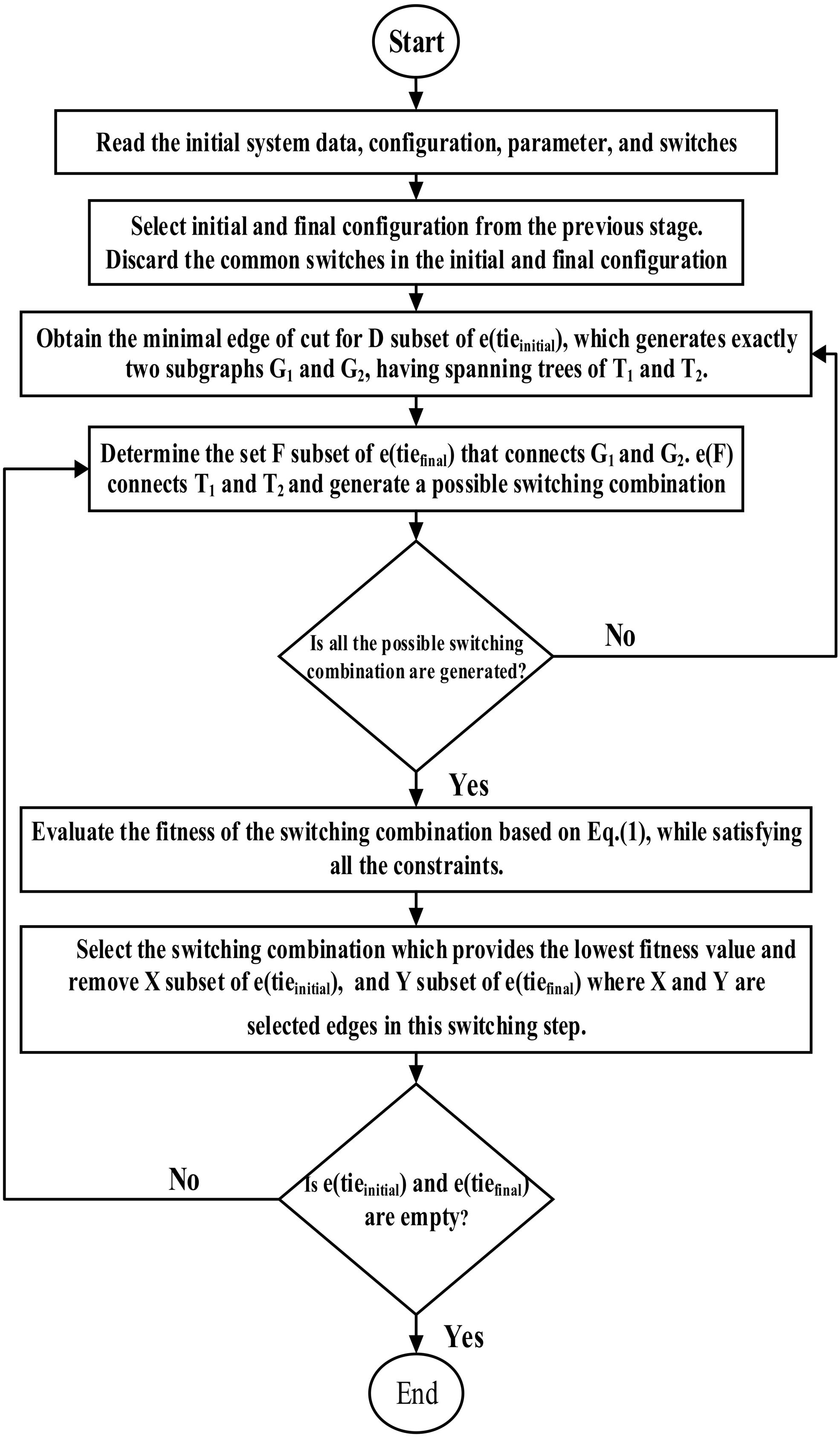

Figure 1. The flowchart of the switching sequence technique.

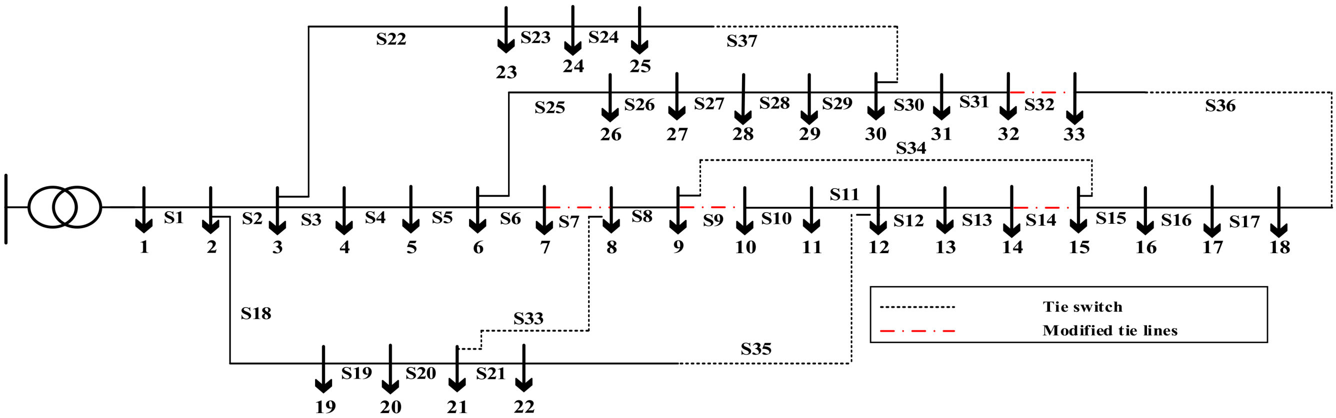

Figure 2. Initial configuration for 33 bus system.

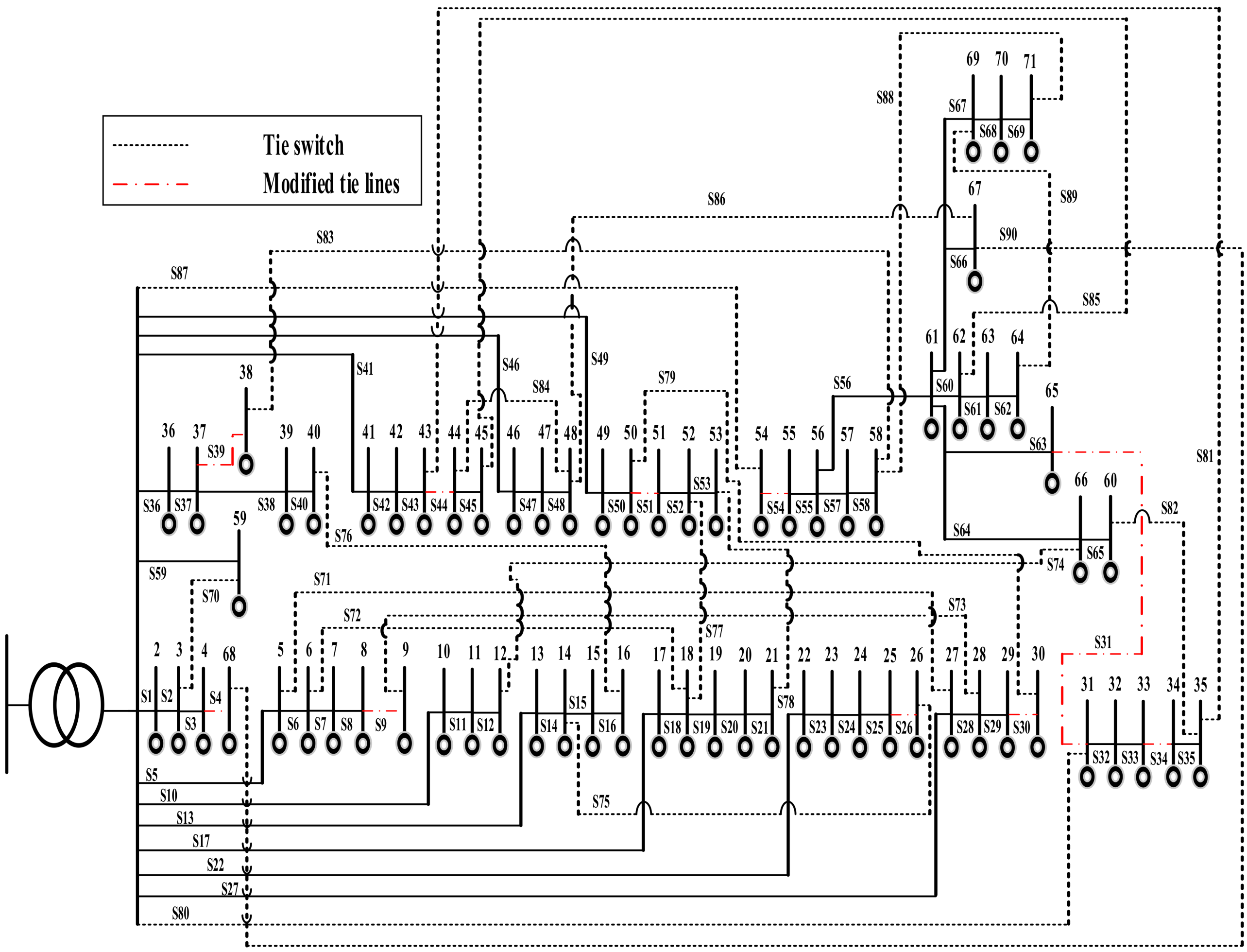

Figure 3. Initial configuration for a practical 71-bus system in Malaysia.

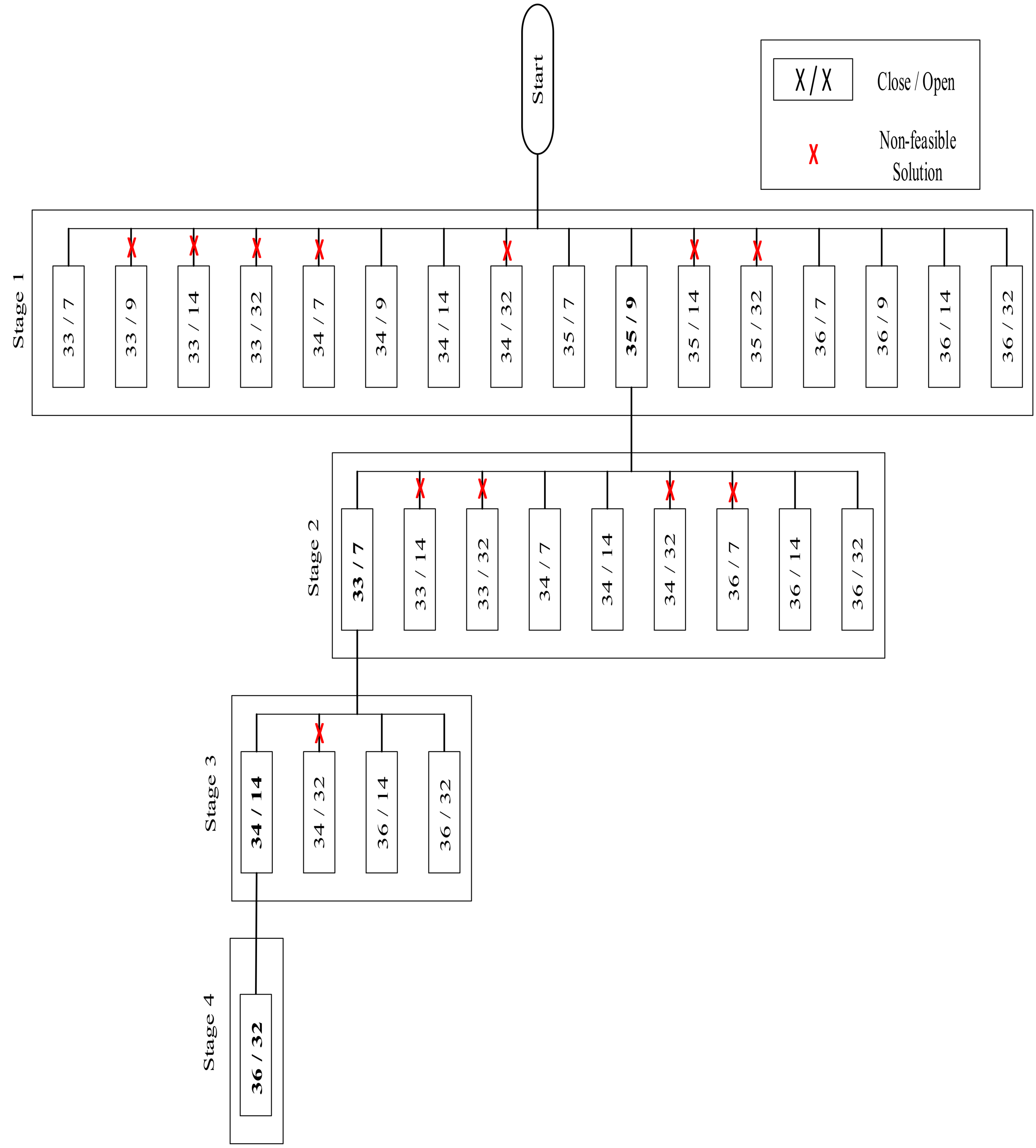

Figure 4. Possible switching sequence for small (33-bus) distribution network considering dataset approach.

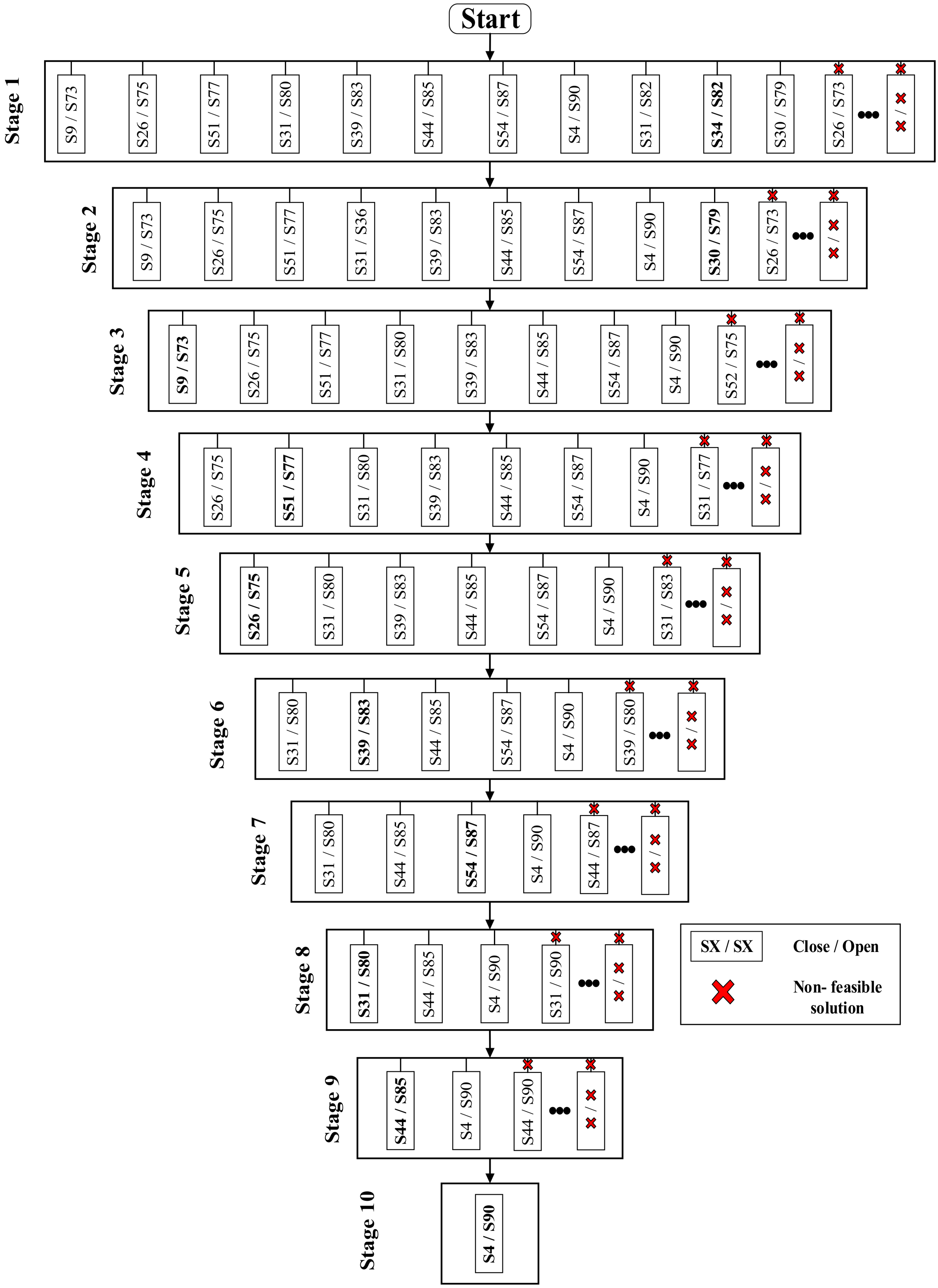

Figure 5. Possible switching sequence for the practical 71-bus distribution system considering dataset approach.

4. Results and Discussion

This section discusses the results obtained by employing the proposed method onto the two distribution networks described early on. The IEEE 33-bus distribution system consists of one 12.66 kV substation, while the practical 71-bus system consists of two 11 kV substations. Sectionalizing and tie switches and modified tie lines are present in these networks to be used as tie switches.

4.1. Network Reconfiguration

4.1.1. IEEE 33-Bus System

Network reconfiguration has been applied to the distribution network to improve efficiency, reduce power loss, and maximize the minimum voltage of the distribution network. The fitness function of the algorithm is calculated according to Equation (1). The active power losses attained from the proposed technique before and after the configuration are 208.459 kW and 138.928 kW, respectively. Figure 6 demonstrates the voltage profile of the 33-bus system before and after the reconfiguration. The lowest voltage of the 33-bus system has been enhanced by 3.46%, where the voltage of buses 19, 20, 21, and 22 reduces after the optimal reconfiguration is achieved. The reason behind that is the load transferred from the middle of the main feeder to the sub-branches. Table 1 summarizes comparative studies of NR techniques conducted on the IEEE 33-bus distribution system and shows the proposed method's superiority.

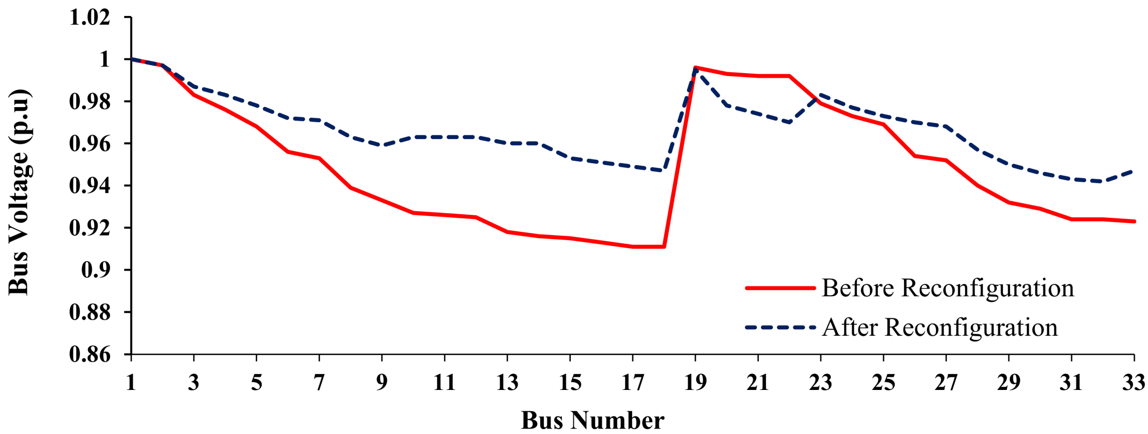

Figure 6. Voltage profile of IEEE 33-bus distribution network.

Table 1. Comparative studies of NR techniques conducted on the 33-bus test network.

Techniques	Switches	Power Loss (kW)	Loss Reduction (%)	Minimum Voltage (p.u)	Maximum Voltage Deviation (p.u)
Base Case	S33, S34, S35, S36, S37	210.98	-	0.9038	0.0962
ITS [25]	S7, S9, S14, S36, S37	141.4	32.15	0.9383	0.0617
HSA [26]	S7, S10, S14, 36, S37	141.9	31.91	0.9383	0.0617
FWA [27]	S7, S9, S14, S28, S32	139.9	32.85	0.9413	0.0587
Heuristics-IHSA [28]	S7, S9, S14, S28, S32	139.98	33.65	0.9413	0.0587
Two stage FA [13]	S7, S9, S14, S28, S32	139.9	33.65	0.9413	0.101
PFA [8]	S7, S9, S14, S28, S32	139.98	33.65	-	0.8992
EO [10]	S7, S9, S14, S32, S37	139.55	33.85	0.9378	0.0622
Proposed Technique	S7, S9, S14, S32, S37	138.9	34.14	0.9423	0.0577

4.1.2. A Practical 71-Bus System in Malaysia

Similarly to the previous test system, NR has been implemented on a practical 71-bus system in Malaysia to enhance system performance, minimize power loss and improve the voltage profile of the distribution network. The objective function of the proposed algorithm is calculated based on Equation (1). The active power loss obtained from the proposed technique using the initial and final configurations is 228.78 kW and 169.91 kW, respectively. Figure 7 illustrates the voltage profile of the practical 71-bus system before and after the reconfiguration. The minimal voltage of the practical 71-bus system at bus 16 has been enhanced by 10.63% after changing the network's topology. On the other hand, it can be noticed that the voltage of buses 7, 16, 28, 38, 50, and 71 increased and improved after the reconfiguration. Therefore, the new configuration of the system reduces the power loss and enhances the overall voltage profile. Table 2 demonstrates the performance of the proposed technique on the practical 71-bus system in Malaysia and highlights the NR before and after the implementation of the proposed method. The comparison with other methods is not considered for this case study because the network belongs to individual authority.

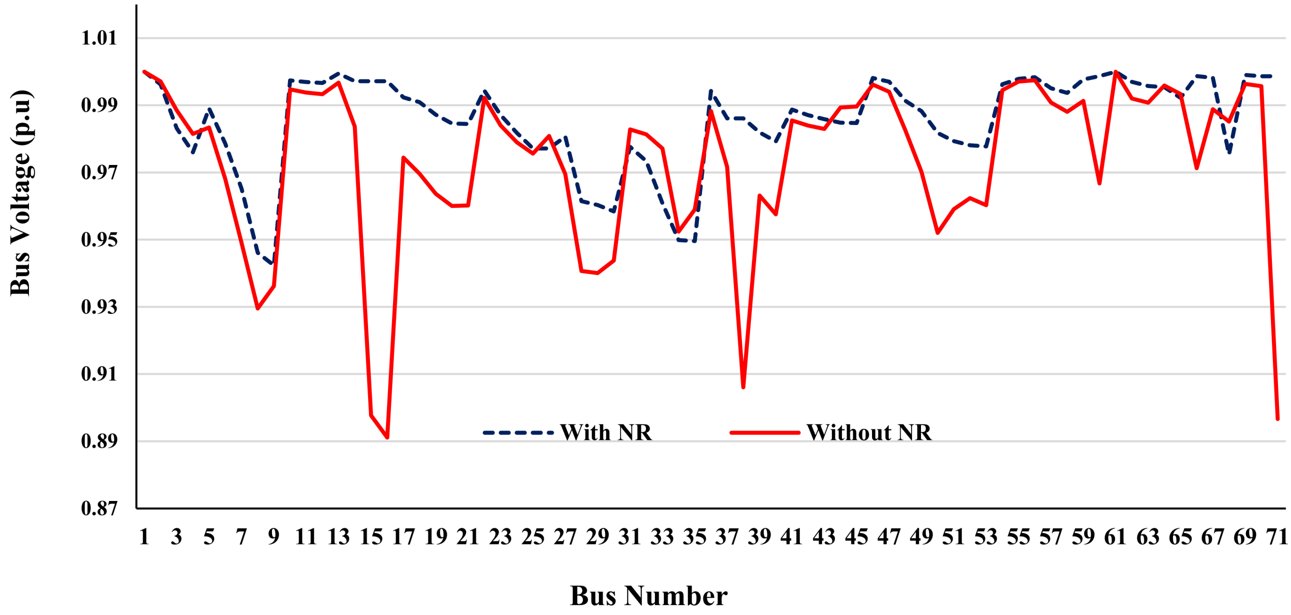

Figure 7. Voltage profile of the practical 71-bus system in Malaysia.

Table 2. A comparison of the power loss before and after implementing the NR on the practical 71-bus system in Malaysia.

Techniques	Switches	Power Loss (kW)	Loss Reduction (%)	Minimum Voltage (p.u)	Maximum Voltage Deviation (p.u)
Base Case	S70, S71, S72, S73, S74, S75, S76 S77, S78, S79, S80, S81 S82, S83 S84, S85, S86, S87 S88, S89, S90	228.78	-	0.891	0.109
Proposed Technique	S4, S15, S16, S21, S34, S39, S44, S51 S54, S62, S69, S80, S71, S72, S74, S76, S80, S81 S84 S86, S88	169.91	25.73	0.942	0.058

4.2. Switching Sequence

This section presents the optimal switching sequence, which attains the minimum power loss during the intermittent switching from the initial to the final configuration.

4.2.1. IEEE 33-Bus System

The maximum switching step required by the proposed technique equals the number of tie lines in the distribution network. However, previous researchers [21,29] require Hamming distance equal to one for switching search space compared to the proposed technique. Therefore, the proposed technique generates a dataset of Hamming distance equal to two for each stage to attain the optimal switching sequence, as shown in Table 3 for the IEEE 33-bus distribution network.

Table 3. Switching sequence for the IEEE 33-bus distribution network.

Distribution Network	Switching Step	Branch Cut	Combination	Power Loss (kW)
IEEE-33 Bus System	1	S7	S33, S35, S36	153.58
		S9	S34, **S35**, S36	
		S14	S34, S36	
		S32	S36	
	2	**S7**	**S33**, S34	145.42
		S14	S34, S36	
		S32	S36	
	3	**S14**	**S34**, S36	141.43
		S32	S36	
	4	**S32**	**S36**	138.92

In the 33-bus distribution network, four tie switches (S7, S9, S14, S32) are modified from the initial configuration (S33, S34, S35, S36). However, the tie switch S37 remains unchanged; thus, it is not included during the switching sequence. The optimum switching sequence is attained for the IEEE 33-bus system. In the first stage, branch S7 is open, generating two spanning trees and combining these two spanning trees, and switches are closed from initial tie switches, i.e., S33, S34, S35, and S36. Tie switch S34 does not have an interconnection with both spanning trees; therefore, it is not selected. A similar procedure is adopted for switches S9, S14, and S32. The total possible combination at stage one is nine combinations. Exhaustive search is utilized to attain the minimum power losses of stage one. The minimum power loss occurs when switch S9 is open and switch S35 is closed, i.e., [S9, S35], and the power loss is 153.58 kW. The optimal switching sequence for 33-bus distribution network is [S9, S35], [S7, S33], [S14, S34] and [S32, S36]. The total power loss during the intermittent switching is 579.35 kW.

In reference to [21], consider the switching sequence search space that is equal to $2 * \left(\frac{1}{2}h_t\right)! * \left(\frac{1}{2}h_t\right)!$, where h_t is the total Hamming distance between the initial and final configuration. Hence, the search space for IEEE 33-bus and a practical 71-bus system is 1152 and $3.24 * 10^{24}$ and the proposed technique reduces the search space to 18 and 56, respectively. Due to the large search space, [21,29] requires optimization to search for the best switching sequence, but the proposed search space is very small. Therefore, an exhaustive search will attain the optimal solution.

Furthermore, when switching, the sequence for the 33-bus is selected randomly, i.e., [S36, S7], [S34, S14], [S35, S9] and [S33, S32], and the total intermittent power loss is 992.59 kW. The minimum voltage at each stage is 0.832 p.u, 0.828 p.u, 0.885 p.u, and 0.942 p.u, whereas the minimum voltage of the initial configuration is 0.91 p.u. On the contrary, the minimum bus voltage with the proposed technique is 0.934, 0.938, 0.938, and 0.942. Hence, improper switching sequence increases the power loss and reduces the bus voltages.

4.2.2. The Practical 71-Bus System in Malaysia

In the practical 71-bus system, ten tie switches (S4, S9, S26, S30, S31, S34, S39, S44, S51, and S55) are modified from the initial configuration (S73, S75, S77, S79, S80, S82, S83, S85, S87, and S90). However, these tie switches (S70, S71, S72, S74, S76, S78, S81, S84, S86, S88, and S89) are kept unaltered; hence, they are not inserted during the switching sequence. To get the optimum switching sequence for the practical 71-bus system, there are 100 possible combinations of two hamming distance in the first stage, out of which only 11 combinations are feasible (i.e., producing radial network). Exhaustive search determines the combination that offers minimum power loss at stage one. The minimum power loss occurs when switch S82 is open and switch S34 is closed, i.e., [S82, S34], and the power loss is 205.15 kW.

The optimal switching sequence for the practical 71-bus system in Malaysia is [S82, S84], [S79, S39], [S73, S9], [S77, S51], [S75, S26], [S83, SS39], [S87, S54], [S80, S31], [S85, S44], and [S90, S4]. Table 4 elaborates the rest of the ten stages where the total power loss during the intermittent switching is 1862.18 kW. Moreover, the voltage profile for the network improved after selecting the optimal switching compared with the initial configuration.

Table 4. Switching sequence for the practical 71-bus system in Malaysia.

Distribution Network	Switching Step	Branch Cut	Combination	Power Loss (kW)
The practical 71-bus system in Malaysia	1	S73	S9	206.15
		S75	S26	
		S77	S51	
		S79	S30	
		S80	S31	
		S82	S31, **S34**	
		S83	S39	
		S85	S44	
		S87	S54	
		S90	S4	
	2	S36	S31	199.50
		S73	S9	
		S75	S26	
		S77	S51	
		S79	**S30**	
		S83	S39	
		S85	S44	
		S87	S54	
		S90	S4	
	3	**S73**	**S9**	192.28
		S75	S26	
		S77	S51	
		S80	S31	
		S83	S39	
		S85	S44	
		S87	S54	
		S90	S4	

Table 4. *Cont.*

Distribution Network	Switching Step	Branch Cut	Combination	Power Loss (kW)
The practical 71-bus system in Malaysia	4	S75	S26	186.32
		S77	**S51**	
		S80	S31	
		S83	S39	
		S85	S44	
		S87	S54	
		S90	S4	
	5	**S75**	**S26**	183.54
		S80	S31	
		S83	S39	
		S85	S44	
		S87	S54	
		S90	S4	
	6	S80	S31	182.30
		S83	**S39**	
		S85	S44	
		S87	S54	
		S90	S4	
	7	S80	S31	181.86
		S85	S44	
		S87	**S54**	
		S90	S4	
	8	**S80**	**S31**	180.94
		S85	S44	
		S90	S4	
	9	**S85**	**S44**	179.36
		S90	S4	
	10	**S90**	**S4**	169.91

4.3. Economic Analysis

The economic analysis for any project is a crucial factor. The planners usually perform their plans based on financial analysis studies and try to find a compromise between the operational costs and system loadability to achieve the expected level of system performance. It is worth mentioning that power losses are responsible for degrading system performance and depleting the budget. Therefore, the main aim for any decision maker is to find the best network configuration that gives better system performance with minimum power losses cost [30].

The proposed NR was conducted on the a practical 71-bus system in Malaysia to solve the power losses problem, where the electricity tariff for the University of Malaya is 0.224 MYR/kWh [31]. Table 5 shows the economic analysis between the power losses and the cost using the proposed NR. For instance, the power loss for the initial configuration when the loading is at the maximum were 228.78 kW and 277.94 kW for the 100% and 110%, respectively. However, after the first pair of switching, the power losses are reduced for the

100% loading by 9.9% compared with the initial configuration. Furthermore, in the second pair of switching, the power losses decreased by 12.8% for the maximum loading, costing around 387,117.56 MYR when the load was 100%. Lastly, the highest reduction in power losses was 169.91 kW for the maximum 100% loading, which reduced by 25.5% compared to the initial configuration, saving around 113,065.17 MYR.

Table 5. The economic analysis between the power losses and the cost using network reconfiguration for a practical 71-bus system in Malaysia.

Proposal	Loading	Power Loss (kW)		Financial Loss (MYR)		Saving (MYR)	
		100%	110%	100%	110%	100%	110%
Initial Configuration	Max	228.78	277.94	443,920.83	539,318.59	-	-
1 pair of switching	Max	206.15 (9.9%)	250.36	400,015.40	485,806.31	43,905.43	53,512.28
2 pair of switching	Max	199.50 (12.8%)	242.24	387,117.56	470,044.44	56,803.27	69,274.15
Max loss reduction	Max	169.91 (25.7%)	206.92	330,855.66	401,503.69	113,065.17	137,814.90

It can be concluded from the results that the optimal switching for the distribution network reduces the total power losses, which positively impacts the system performance and minimize the financial loss.

5. Conclusions

This paper applies a MISOCP method to determine the optimal network reconfiguration while adopting hamming dataset approach to obtain the best switching sequence to reach the optimal network configuration found earlier. The proposed technique was tested using the standard IEEE 33 bus system as well as a practical 71-bus system in Malaysia. Results show that the network total power losses for the 33 bus and a practical 71-bus system reduced by 34.14% and 25.5% from their initial configuration, respectively. The proposed technique additionally managed to determine the optimal switching sequence for the network reconfiguration process and hence reduced the search space from 1152 and $3.24 * 1024$ to only 18 and 56 configurations, respectively, for IEEE 33 bus and practical 71-bus system. Moreover, a comparative study has been conducted with other methods to highlight the effectiveness of the proposed method in attaining optimal solutions. Finally, economic analysis of the practical 71-bus system using different numbers and pairs of switches intended to be modified provide a heads-up on the savings resulting from the network reconfiguration. Therefore, it can be concluded that through the adoption of the proposed technique, it is possible to reduce the power losses, which will result in a reduction in electricity price and ensure the sustainable operation of the distribution network.

The NR and the switching sequence have been done in this work without considering any DGs. Hence, the extension of this work will be focused on implementing DGs into the practical 71-bus system and investigating the impact of the DGs on the NR and switching sequence.

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Abbreviations

Abbreviations for the whole manuscript.

Acronyms	
NR	Network Reconfiguration
MISOCP	Mixed Integer Second Order Cone Programming
EO	Equilibrium Optimizer
CSA	Cuckoo Search Algorithm
COA	Coyote Optimization Algorithm
DG	Distributed Generation
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
PFA	Pathfinder algorithm
Nomenclature	
Obj	Objective Function
P_{Loss}^{Ratio}	The ratio of the system's total active power loss
VDI	The voltage deviation index
$Cost_{Loss}$	The total power loss cost
E_{tariff}	The electricity tariff (0.224 MYR/kWh)
Y_{Hour}	The year in hour (8760 h)
V_j	The voltage at the receiving bus
V_{Cj}	The nominal voltage at bus j
P_{Loss}^{Rec}	The active power loss after the reconfiguration
P_{Loss}^{Base}	The active power loss before the network reconfiguration
ij	The branch in which i is a sending bus and j is a receiving bus
P_{ij}	The active power passing through the branch ij
Q_{ij}	The reactive power passing through the branch ij
R_{ij}	The branch ij resistance
γ_{ij}	The binary variable, which determines the state of that branch
N_b	The whole number of branches in the network
$P_{g,i}$	The active power generations at bus i
$Q_{g,i}$	The reactive power generations at bus i
$P_{d,i}$	The active power demand at bus i
$Q_{d,i}$	The reactive power demand at bus i
P_{loss}	The active power loss
Q_{loss}	The reactive power loss
Ω_b	The set of buses
Ω_l	The set of branches
V_i & V_j	The sending and receiving bus voltages
I_{ij}	The branch current
X_{ij}	The branch reactance
Z_{ij}	The branch impedance
I_{max}	Maximum current capacity
N	total number of buses
n_s	the number of a substation in the distribution network
P_{ij}	active power flows through the branch $i-j$
Q_{ij}	reactive power flows through the branch $i-j$

Appendix A

Table A1. The load data of the practical 71-bus system in Malaysia.

Bus	Active Power (kW)	Reactive Power (kVAR)
2	165.6476	102.6518
3	436.286	270.3664
4	290.5331	180.0433
40	540.4815	334.9364
41	263.8048	163.4799
42	67.27742	41.69182
43	233.4809	144.6881
44	166.3602	103.0934
45	110.6121	68.54632
46	313.3315	194.1715
48	745.2973	461.8607
49	232.2124	143.902
51	294.5516	182.5336
52	181.5532	112.5085
53	74.91237	46.42319
54	180.8376	112.0651
55	126.8992	78.63943
56	116.9312	72.46225
59	563.5933	349.2588
7	594	368.1018
8	736.4677	456.3891
9	253.414	157.0406
10	68.60215	42.51275
11	102.7288	63.66101
12	58.61048	36.32092
18	182.7567	113.2543
19	248.7212	154.1326
20	339.7847	210.5646
21	167.3005	103.6761
22	469.3422	290.8514
23	129.0312	79.96062
25	578.4285	358.4521
28	499.2374	309.3774
29	770.6032	477.5428
30	459.8325	284.9582
31	345.3468	214.0114
32	21.42634	13.27791
33	244.8801	151.7522
34	880.5441	545.6732

Table A1. *Cont.*

Bus	Active Power (kW)	Reactive Power (kVAR)
35	123.9954	76.83997
67	221.0763	137.001
68	407.4347	252.4873
62	145.4336	90.1252
65	199.0734	123.3658
66	123.9126	76.78866
5	107.3387	66.5178
6	99.20699	61.47857
63	103.8495	64.35551
64	93.85484	58.16184
24	107.9301	66.88429
50	138.3871	85.75848
70	117.9839	73.1146
58	155.0645	96.09348
57	125.4059	77.71404
14	183.629	113.7949
36	478.4409	296.4898
27	340.5269	211.0245
1	0	0
13	172.4613	106.8743
15	172.4613	106.8743
16	172.4613	106.8743
17	172.4613	106.8743
26	172.4613	106.8743
37	172.4613	106.8743
38	172.4613	106.8743
39	172.4613	106.8743
47	172.4613	106.8743
60	0	0
61	0	0
69	172.4613	106.8743
71	172.4613	106.8743

Table A2. The line data of the practical 71-bus system in Malaysia.

From	To	R (Ω)	X (Ω)
1	2	8.88×10^{-5}	0.000101
2	3	0.000446	0.000257
3	4	0.000368	0.000213
3	59	0.000147	8.47×10^{-5}
4	68	6.22×10^{-5}	3.59×10^{-5}

Table A2. *Cont.*

From	To	R (Ω)	X (Ω)
1	5	0.000222	0.000252
5	6	0.000309	0.000179
5	27	0.000413	0.000238
6	18	0.000171	9.88×10^{-5}
6	7	0.000436	0.000252
7	8	0.001025	0.000592
8	9	0.000751	0.000434
9	28	0.000239	0.000138
1	10	0.000481	0.000546
10	11	0.000174	0.0001
11	12	0.000233	0.000135
12	66	0.000177	0.000167
1	13	8.65×10^{-5}	9.8×10^{-5}
13	14	0.000465	0.000269
14	26	0.000153	8.84×10^{-5}
14	15	0.000208	0.00012
15	16	0.000395	0.000228
16	40	0.000417	0.000241
1	17	0.000289	0.000327
17	18	7.28×10^{-5}	4.20×10^{-5}
18	52	0.000218	0.000126
18	19	0.000223	0.000129
19	20	0.000227	0.000131
20	21	2.66×10^{-5}	1.53×10^{-5}
21	53	1.33×10^{-5}	7.67×10^{-6}
1	22	0.00014	0.000159
22	23	0.000355	0.000205
23	24	0.000305	0.000176
24	25	0.000329	0.00019
25	26	0.000287	0.000166
1	27	0.000352	0.000399
27	28	0.00055	0.000318
28	29	4.41×10^{-5}	2.55×10^{-5}
29	30	0.000201	0.000116
30	50	0.000218	0.000126
1	31	0.000869	0.000502
31	65	0.000367	0.000348
31	32	0.000169	9.76×10^{-5}
32	33	0.000504	0.000291
33	34	0.00053	0.000306

Table A2. *Cont.*

From	To	R (Ω)	X (Ω)
34	35	0.000173	9.97×10^{-5}
35	43	0.000306	0.000177
35	60	0.000154	0.000146
1	36	0.000166	0.000189
36	37	0.000655	0.000378
37	39	0.000336	0.000194
37	38	0.000307	0.000177
38	58	0.000462	0.000267
39	40	0.000218	0.000126
1	41	0.000571	0.000647
41	42	0.000175	0.000101
42	43	0.000132	7.61×10^{-5}
43	44	0.0002	0.000116
44	45	4.68×10^{-5}	2.70×10^{-5}
44	48	0.00015	8.65×10^{-5}
45	62	0.000186	0.000176
1	46	7.81×10^{-5}	8.85×10^{-5}
46	47	8.29×10^{-5}	4.79×10^{-5}
47	48	0.000434	0.000251
48	67	1.62×10^{-5}	1.53×10^{-5}
1	49	0.000359	0.000407
49	50	0.000402	0.000232
50	51	0.000192	0.000111
51	52	0.000228	0.000132
52	53	0.000186	0.000108
1	54	0.000536	0.000608
54	55	0.00042	0.000242
55	56	7.49×10^{-5}	4.33×10^{-5}
56	61	7.49×10^{-5}	8.49×10^{-5}
56	57	0.000422	0.000244
57	58	0.000328	0.000189
58	71	0.000264	0.00025
1	59	0.000157	0.000178
61	62	0.000279	0.000317
62	63	0.00019	0.00018
63	64	0.000101	9.61×10^{-5}
64	69	7.42×10^{-5}	7.03×10^{-5}
61	65	0.00016	0.000181
61	66	0.000471	0.000534
66	60	9.01×10^{-5}	8.53×10^{-5}

Table A2. *Cont.*

From	To	R (Ω)	X (Ω)
61	67	0.000284	0.000322
67	68	0.000154	0.000146
61	69	0.000231	0.000261
69	70	8.78×10^{-5}	8.32×10^{-5}
70	71	0.000223	0.000211

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