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Reliability Enhancement of Radial Distribution Systems through Network Reconfiguration

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***Abstract* - Distribution Network Reconfiguration is an effective operational strategy for reducing power losses and improving service reliability in radial distribution systems. This paper presents a reliability study of 6-bus, 11 bus, and 14-bus radial distribution systems using the Branch Exchange Network Reconfiguration (BENR) technique. The primary objective is to enhance system reliability by identifying optimal switching operations that minimize power losses and improve service continuity while maintaining the radial structure of the network. The proposed methodology employs branch exchange-based network reconfiguration to modify feeder topology through the strategic opening and closing of sectionalizing and tie switches. Reliability performance is evaluated using standard reliability indices, including the effect of reconfiguration on customer-oriented reliability indices is evaluated using SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI. For the 6-bus system, the active power loss is reduced from 0.6962 kW to 0.6450 kW, corresponding to a loss reduction of 7.35%. For the 11-bus system, the active power loss is reduced from 324.0249 kW to 319.7065 kW, corresponding to a loss reduction of 1.33%. For the 14-bus system, the active power loss is reduced from 511.4435 kW to 466.1354 kW, corresponding to a loss reduction of 8.86%. The reliability results also show notable improvements after reconfiguration. For the 6-bus system, SAIFI, SAIDI, and CAIDI improve by 4.83%, 6.76%, and 2.04%, respectively. For the 11-bus system, these indices improve by 4.23%, 6.18%, and 2.03%, respectively. For the 14-bus system, SAIFI, SAIDI, and CAIDI improve by 7.60%, 13.48%, and 6.36%, respectively. The EENS and AENS values are also reduced, while ASAI increases and ASUI decreases in all three systems. The comparative results confirm that the proposed reconfiguration method improves both operating efficiency and distribution reliability, with the 14-bus system showing the highest overall improvement due to greater switching flexibility.**

Keywords: Distribution network reconfiguration, radial distribution system, reliability indices, SAIFI, SAIDI, CAIDI, EENS, BIBC matrix, power-loss reduction.

I. INTRODUCTION

Electric power distribution systems represent the final and most extensive stage of the power delivery chain. These systems are responsible for supplying electrical energy from substations to domestic, commercial, agricultural, and industrial consumers. In practical operation, most distribution systems are operated radially because radial operation simplifies protection coordination, fault isolation, system restoration, and maintenance. However, radial distribution networks generally have high resistance-to-reactance ratios, long feeder routes, uneven loading, voltage drops, and considerable active power losses. These limitations directly affect feeder efficiency, voltage profile, and customer supply reliability.

Distribution network reconfiguration (DNR) is one of the most effective and economical operational techniques for improving the performance of radial distribution systems. It is carried out by changing the open and closed status of sectionalizing and tie switches while maintaining radiality and load connectivity. The basic concept of feeder reconfiguration for loss reduction was introduced by Civanlar et al.[1], where suitable switching operations were shown to reduce distribution feeder losses.

Shirmohammadi and Hong [2]further developed a practical heuristic approach for reducing resistive line losses in electric distribution networks. Baran and Wu [3]formulated distribution system reconfiguration as an optimization problem for both loss reduction and load balancing.

The DNR problem is nonlinear, combinatorial, and constrained. It involves discrete switch-status variables, nonlinear load-flow equations, bus-voltage limits, branch-current limits, connectivity constraints, and radiality requirements. Liu et al. [4]studied loss minimization in distribution feeders and explained the optimality conditions and algorithmic aspects of the reconfiguration problem. Apart from loss minimization, reliability enhancement is also an important objective because distribution networks are directly connected to end consumers. Tsai and Lu [5]demonstrated that network reconfiguration can improve distribution system reliability by changing supply paths and reducing the impact of interruptions on customers.

In modern distribution system operation, reconfiguration is not limited to power-loss reduction alone. It is also used for voltage improvement, feeder load balancing, reliability enhancement, service restoration, distributed generation accommodation, and operational flexibility. Reliability indices such as SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI are commonly used to quantify the effect of network topology on customer supply continuity. Hence, a reconfiguration strategy should be evaluated not only in terms of loss reduction but also in terms of improvement in reliability indices.

The present work applies a branch exchange reconfiguration method to three radial distribution systems: a single-feeder 6-bus system, a two-feeder 11-bus system [1]and a three-feeder 14-bus system[1]. For all the three systems, active power loss and reliability indices are calculated before and after reconfiguration. The main objective is to demonstrate that network topology modification can improve both technical performance and customer-oriented reliability. The results show that the proposed reconfiguration approach reduces active power loss and improves SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI in the test systems.

II. LITERATURE REVIEW

Mathematical programming methods have been widely applied to distribution network reconfiguration because they provide systematic optimization frameworks. Borges et al. [6]proposed an optimal reconfiguration approach using mathematical programming, where the switching status of distribution branches was selected to improve system operation. Lavorato et al. [7]discussed the importance of radiality constraints in distribution system optimization problems. Since radial operation is a mandatory condition in most distribution systems, proper modelling of radiality constraints is essential for obtaining feasible reconfiguration solutions. López et al. [8]developed a robust optimization method for distribution system reconfiguration with reliability constraints, showing that reliability requirements can be incorporated into the network reconfiguration problem.

Heuristic methods have gained attention because they reduce the computational burden compared with exact mathematical programming approaches. Zin et al. [9]proposed a minimum-current circular-updating mechanism for radial distribution network reconfiguration. This method identifies branches carrying lower current and uses switching operations to obtain a lower-loss radial configuration. Ferdavani et al. [10]extended this idea by proposing two minimum-current neighbour-chain updating methods for distribution system reconfiguration. These current-based heuristic approaches are attractive because they reduce the need for repeated exhaustive search and provide fast solutions.

Switch-opening and branch-exchange methods have also been used for improving reconfiguration efficiency. Zhan et al. [11]proposed a switch-opening and exchange method for stochastic distribution network reconfiguration. Their method considered uncertainty and used switching operations to obtain improved radial configurations. Harsh and Das [12]proposed a simple and fast two-stage heuristic approach for radial distribution network reconfiguration. In the first stage, all switches are closed and minimum-current switches are opened sequentially while preserving radiality. In the second stage, branch exchange is performed using the Bus Injection to Branch Current matrix to further reduce active power loss. This method was tested on 33-bus, 69-bus, 84-bus, 136-bus, and 417-bus systems and showed very low computational time.

The effect of reconfiguration on loss allocation and system operation has also been studied. Savier and Das [13]investigated the impact of network reconfiguration on loss allocation in radial distribution systems. Their work showed that topology modification affects not only the total power loss but also the distribution of losses among feeders and network sections. Kahouli et al. [14]proposed a reliability-improvement and loss-reduction approach using genetic algorithm and particle swarm optimization. Their study considered both power loss and reliability-related performance, showing that reconfiguration can support multiple operating objectives.

Metaheuristic algorithms have been extensively used for solving complex reconfiguration problems. Nguyen and Nguyen [15]applied an improved cuckoo search algorithm for distribution network reconfiguration. The method demonstrated the ability of swarm-based algorithms to search large switching combinations and obtain improved network configurations. Jakus et al. [16]proposed a hybrid heuristic-genetic algorithm for optimal reconfiguration of distribution networks. Such hybrid approaches combine heuristic knowledge with evolutionary search to improve solution quality. However, metaheuristic algorithms generally require parameter tuning and may involve higher computational effort compared with simple heuristic approaches.

Several review studies have classified distribution network reconfiguration methods and highlighted recent research directions. Mahdavi et al. [17]presented a comprehensive review and classification of electric power distribution system reconfiguration methods. Their work classified DNR methods based on objectives, constraints, system models, and solution techniques. Mahdavi et al. [18]reviewed metaheuristic methods for reconfiguration and compared them with an efficient genetic algorithm-based approach. These review papers show that DNR continues to be an active research area due to its relevance in modern power distribution systems.

Recent studies have also emphasized static and dynamic reconfiguration in smart distribution networks. Behbahani et al. [19]reviewed static and dynamic distribution network reconfiguration methodologies and discussed the importance of flexibility, automation, and real-time operation. Lotfi et al. [20]reviewed power distribution network reconfiguration techniques and summarized recent developments, objectives, and challenges. These works indicate that reconfiguration is becoming increasingly important in the presence of renewable energy sources, electric vehicles, energy storage systems, smart switches, and automated distribution management systems.

From the literature, it is observed that many studies focus mainly on active power-loss reduction, whereas reliability indices are often considered as secondary objectives. In addition, many metaheuristic methods require large computational effort and parameter tuning. Therefore, the present work applies the fast two-stage heuristic method reported in [12]to 6-bus and 11-bus radial distribution systems and evaluates both power-loss reduction and reliability-index improvement. The novelty of the work lies in applying the same reconfiguration principle to small radial systems and presenting a comparative reliability assessment using SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI.

III. DISTRIBUTION NETWORK RECONFIGURATION

Distribution network reconfiguration is the process of changing the status of switches in a distribution network while maintaining a radial structure. The switches are generally classified as:

- **Sectionalizing switches:** Normally closed switches used to connect feeder sections.
- **Tie switches:** Normally open switches used to provide alternative supply paths.

The objective of reconfiguration is to obtain a topology that minimizes active power loss while satisfying radiality, voltage, and branch-current constraints.

The active power loss of a distribution network can be expressed as:

$$P_{loss} = \sum_{i=1}^{N_b} |I_i|^2 R_i \qquad (1)$$

where P_{loss} is the total active power loss,I_i is the current in branch i, R_i is the resistance of branch i, and N_b is the number of branches.

The optimization problem may be written as:

$$\text{Minimize } P_{loss} = \sum_{i\in\Omega_S} |I_i|^2 R_i \qquad (2)$$

Subject to:

$$V_i^{min} \le |V_i| \le V_i^{max}$$

$$|I_i| \le I_i^{max}$$

where Ω_S is the set of switchable branches, V_i is the voltage magnitude at bus (i), and I_i^{max} is the current limit of branch i.

In the adopted method, the network radiality is maintained by ensuring that the number of closed branches remains equal to the number of buses minus one.

IV. RELIABILITY INDICES

Reliability indices are used to evaluate the continuity and quality of power supply experienced by customers. In this work, the following indices are used.

4.1 System Average Interruption Frequency Index

SAIFI represents the average number of interruptions experienced by each customer during a specified period.

$$SAIFI = \frac{\sum_{i=1}^{n} \lambda_i N_i}{\sum_{i=1}^{n} N_i} \qquad (3)$$

where λ_i is the failure rate of load point i, N_i is the number of customers connected to load point i, and n is the number of load points.

4.2 System Average Interruption Duration Index

SAIDI indicates the average interruption duration experienced by each customer.

$$SAIDI = \frac{\sum_{i=1}^{n} U_i N_i}{\sum_{i=1}^{n} N_i} \qquad (4)$$

where U_i is the annual outage duration at load point i.

If failure rate and repair time are known:

$$U_i = \lambda_i r_i \qquad (5)$$

where r_i is the average repair or restoration time.

4.3 Customer Average Interruption Duration Index

CAIDI represents the average restoration time per customer interruption.

$$CAIDI = \frac{SAIDI}{SAIFI} \qquad (6)$$

4.4 Expected Energy Not Supplied

EENS represents the expected amount of energy not supplied to customers due to interruptions.

$$EENS = \sum_{i=1}^{n} L_i \, U_i \qquad (7)$$

where L_i is the load connected at load point i.

4.5 Average Energy Not Supplied

AENS represents the average unsupplied energy per customer.

$$AENS = \frac{EENS}{\sum_{i=1}^{n} N_i} \qquad (8)$$

4.6 Average Service Availability Index

ASAI represents the fraction of time for which the system is available to customers.

$$ASAI = \frac{8760 - SAIDI}{8760} \qquad (9)$$

A lower value of SAIFI, SAIDI, CAIDI, EENS, AENS, and ASUI indicates improved reliability, whereas a higher ASAI indicates better service availability.

V. NETWORK RECONFIGURATION ALGORITHM

The proposed methodology applies a branch exchange network reconfiguration approach to improve the technical and reliability performance of 6-bus, 11-bus and 14-bus radial distribution systems.

5.1 Network Reconfiguration Algorithm:

A complete algorithm for the proposed method of the Branch Exchange Network Reconfiguration (BENR) process is given below:

Step 1: Read the line data and bus data.

Step 2: Run the load-flow program to find the nodal voltages, branch currents and power flows. Also find the total losses of the system.

Step 3: Compute the voltage difference across all the open tie switches.

Step 4: Identify the open tie-switch across which, the voltage difference is maximum.

Step 5: If this voltage difference is greater than ∈r, then this switch “k” is considered first and go to Step (6); otherwise, go to Step (10).

Step 6: Identify the number of branches on HV side of the tie switch (NHV) and number of branches on LV side of the tie switch (NLV). In the present work, only NLV number of branches on LV side of the tie switch is considered including the tie branch when the tie-switch “k” is closed.

Step 7: Open one branch at a time and evaluate the Real Power Loss. Continue this process, until the start of increase in real power loss, after reaching a minimum value.

Step 8: Obtain the optimal solution for the operation of tie-switch “k”

Step 9: Go to Step (2) and repeat the same procedure for all othertie switches.

Step 10: Print the results of network reconfiguration.

5.2 Reliability Evaluation

After obtaining the final reconfigured topology, the reliability indices are calculated using the load-point failure rates, restoration rates, customer data, and connected loads. The indices before and after reconfiguration are compared to determine the percentage improvement:

$$\% \text{ Improvement} = \frac{X_{before} - X_{after}}{X_{before}} \times 100 \qquad (10)$$

For indices such as ASAI, where a higher value is better, improvement is interpreted based on increase in service availability.

VI. RESULTS AND DISCUSSION

The proposed methodology is applied to two radial distribution systems: a single-feeder 6-bus system and a two-feeder 11-bus system. The results are discussed separately.

6.1 Case Study 1: Single-Feeder 6-Bus Distribution System

The 6-bus system consists of 6 buses, 1 feeder, 5 branches, and 1 tie switch. The base voltage is 12.66 kV and the base MVA is 100 MVA. The initial tie switch is branch 6, while after reconfiguration the final tie switch becomes branch 4. The active power loss in the initial configuration is 0.6962 kW, whereas the active power loss after reconfiguration is reduced to 0.6450 kW. Power-Loss Comparison for 6-Bus System is tabulated in Table 1.

Table 1: Power-Loss Comparison for 6-Bus System

Parameter	Before Reconfiguration	After Reconfiguration
Tie switch	**6**	**4**
Active power loss	0.6962 kW	0.6450 kW
Loss reduction	—	0.0512 kW
Loss reduction percentage	—	7.35 %

The loss reduction is calculated as:

$$\Delta P_{loss} = 0.6962 - 0.6450 = 0.0512 \text{ kW}$$

$$\% \, P_{loss} \text{ reduction} = \frac{0.0512}{0.6962} \times 100 = 7.35\%$$

Thus, the reconfigured network reduces power loss by approximately 7.35%.

Single line diagram of Single-Feeder 6 bus system before and after Reconfiguration are presented in Figure-1 and Figure-2 respectively. The line data, load data and the Reliability data of Single-Feeder 6-bus system is tabulated in Table-A3.

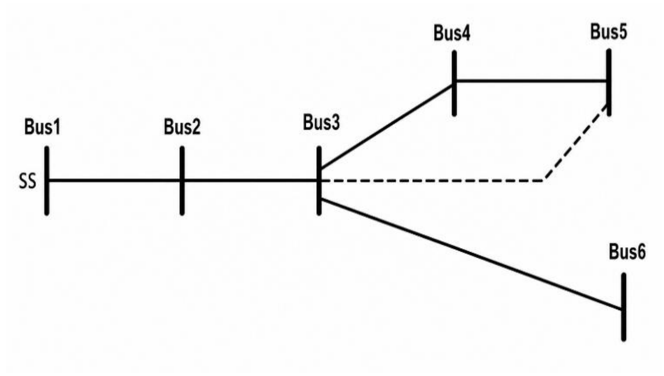

Figure 1: Single line diagram of Single-Feeder 6 bus system before Reconfiguration

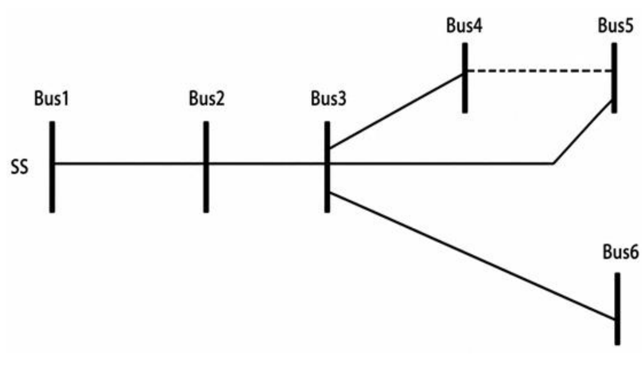

Figure 2: Single line diagram of Single-Feeder 6 bus system after Reconfiguration

Reliability Indices of 6-Bus System Before and After Reconfiguration is tabulated in Table 2.

Table 2: Reliability Indices of 6-Bus System Before and After Network Reconfiguration (BENR)

Reliability Index	Before BENR	After BENR	Improvement
SAIFI (interruptions/ customer-year)	0.4945	0.4707	**4.83%**
SAIDI (hours/ customer-year)	0.3882	0.3619	**6.76%**
CAIDI (hours/ interruption)	0.7849	0.7690	**2.04%**
EENS (kWh/year)	0.0002	0.0002	**6.09%**
AENS (kWh/ customer-year)	0.0000	0.0000	**6.09%**
ASAI	0.999956	0.999959	**Improved**
ASUI	0.000044	0.000041	**Improved**

The reduction in SAIFI from 0.4945 to 0.4707 interruptions/customer-year indicates that the reconfigured system experiences fewer average interruptions per customer. SAIDI decreases from 0.3882 to 0.3619 hours/customer-year, which confirms that the average interruption duration is also reduced. CAIDI decreases from 0.7849 to 0.7690 hours/interruption, showing that the restoration duration per interruption is slightly improved.

The ASAI value increases from 0.999956 to 0.999959, while ASUI decreases from 0.000044 to 0.000041. These results indicate better service availability after reconfiguration. Therefore, for the 6-bus system, reconfiguration improves both power-loss performance and customer reliability.

6.2 Case Study 2: Two-Feeder 11-Bus Distribution System

The 11-bus system [1] consists of 11 buses, 2 feeders, 10 branches, and 1 tie switch. The base voltage is 23 kV and the base MVA is 100 MVA. The initial tie switch is branch 11, while the final tie switch after reconfiguration is branch 10. The active power loss is reduced from 324.0249 kW to 319.7065 kW. Single line diagram of Two-Feeder 11 bus system before and after Reconfiguration are presented in Figure-3 and Figure-4 respectively. The line data, load data and the Reliability data of Two-Feeder 11-bus system is tabulated in Table-A1.

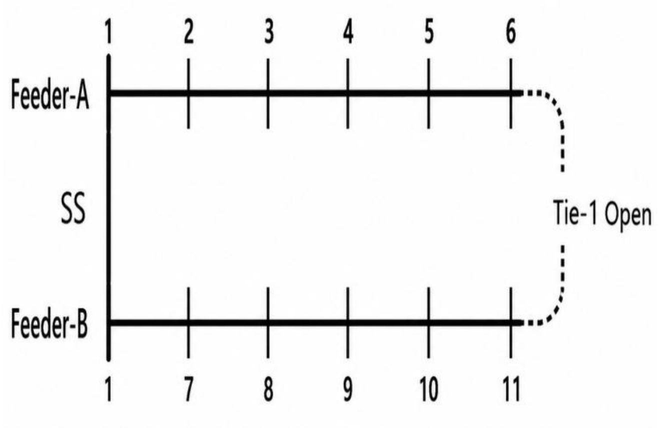

Figure 3: Single line diagram of Two-Feeder 11 bus system before Reconfiguration

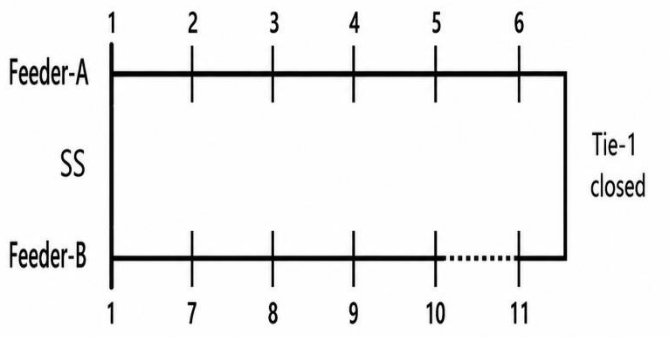

Figure 4: Single line diagram of Two-Feeder 11 bus system after Reconfiguration

Power-Loss Comparison for 11-Bus System is tabulated in Table 3.

Table 3: Power-Loss Comparison for 11-Bus System

Parameter	Before Reconfiguration	After Reconfiguration
Tie switch	**11**	**10**
Active power loss	324.0249 kW	319.7065 kW
Loss reduction	—	4.3184 kW
Loss reduction percentage	—	1.33 %

The loss reduction is calculated as:

$$\Delta P_{loss} = 324.0249 - 319.7065 = 4.3184 \text{ kW}$$

$$\% \ P_{loss} \text{ reduction} = \frac{4.3184}{324.0249} \times 100 = 1.33\%$$

Thus, the reconfigured network reduces power loss by approximately 1.33%. Reliability Indices of 11-Bus System Before and After Reconfiguration is tabulated in Table 4.

Table 4: Reliability Indices of 11-Bus System Before and After Reconfiguration

Reliability Index	Before BENR	After BENR	Improvement
SAIFI (interruptions/ customer-year)	0.8797	0.8424	**4.23%**
SAIDI (hours/ customer-year)	0.6287	0.5898	**6.18%**
CAIDI (hours/ interruption)	0.7147	0.7002	**2.03%**
EENS (kWh/year)	0.0105	0.0101	**3.48%**
AENS (kWh/ customer-year)	0.0000	0.0000	**3.48%**
ASAI	0.999928	0.999933	**Improved**
ASUI	0.000072	0.000067	**Improved**

The 11-bus system shows a decrease in SAIFI from 0.8797 to 0.8424 interruptions/customer-year. This indicates a reduction in the average frequency of customer interruptions. SAIDI decreases from 0.6287 to 0.5898 hours/customer-year, showing that the total interruption duration experienced by customers is reduced. CAIDI decreases from 0.7147 to 0.7002 hours/interruption, indicating improved restoration performance. EENS decreases from 0.0105 to 0.0101 kWh/year, which confirms that the expected unsupplied energy is reduced after reconfiguration. ASAI increases from 0.999928 to 0.999933, while ASUI decreases from 0.000072 to 0.000067. Therefore, the reconfigured 11-bus system provides improved service continuity and better operating reliability.

6.3 Case Study 3: Three-Feeder 14-Bus Distribution System

The 14-bus system [1] consists of 14 buses, 3 feeders, 13 branches, and 3 tie switches. The base voltage is 23 kV and the base MVA is 100 MVA.

The initial tie switches are branches 14, 15, and 16, while the final open switches after reconfiguration are branches 7, 8, and 16. The active power loss is reduced from 511.4435 kW to 466.1354 kW, whereas the reactive power loss is reduced from 590.3670 kVAr to 544.8996 kVAr.

The single line diagrams of the Three-Feeder 14-bus system before and after reconfiguration are presented in Figure 5 and Figure-6 respectively. The line data, load data and the Reliability data of Three-Feeder 14-bus system is tabulated in Table A2.

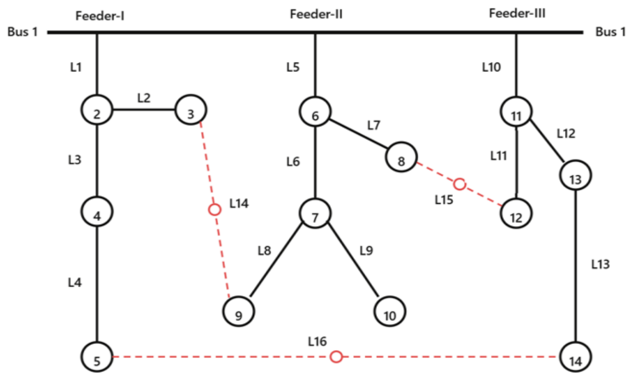

Figure 5: Single line diagram of Three-Feeder 14-bus system before Reconfiguration

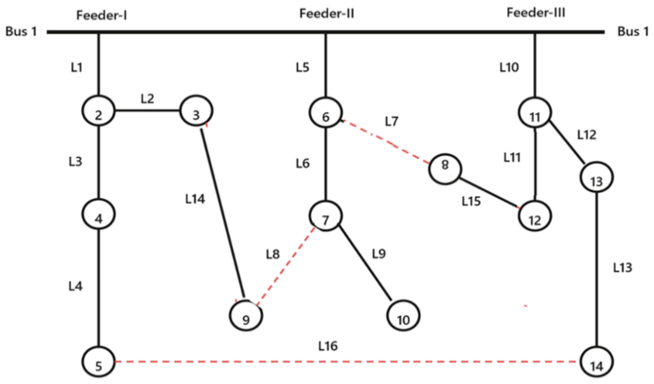

Figure 6: Single line diagram of Three-Feeder 14-bus system after Reconfiguration

The power-loss comparison for the 14-bus system is tabulated in Table 5.

Table 5: Power-Loss Comparison for 14-Bus System

Parameter	Before Reconfiguration	After Reconfiguration
Tie/Open switches	**14, 15, 16**	**7, 8, 16**
Active power loss	511.4435 kW	466.1354 kW
Active power-loss reduction	—	45.3081 kW
Loss reduction percentage	—	8.86%

The loss reduction is calculated as: $\Delta P_{loss} = 511.4435 - 466.1354 = 45.3081$ kW

$$\% P_{loss} \text{ reduction} = \frac{45.3081}{511.4435} \times 100 = 8.86$$

Thus, the reconfigured network reduces the active power loss by approximately 8.86%. The final open switches after reconfiguration are 7, 8, and 16, replacing the initial open switches 14, 15, and 16.

The reliability indices of the 14-bus system before and after reconfiguration are tabulated in Table 6.

Table 6: Reliability Indices of 14-Bus System Before and After Reconfiguration

Reliability Index	Before BENR	After BENR	Improvement
SAIFI (interruptions/ customer-year)	0.4951	0.4575	**7.60%**
SAIDI (hours/ customer-year)	0.6238	0.5397	**13.48%**
CAIDI (hours/ interruption)	1.2599	1.1798	**6.36%**
EENS (kWh/year)	0.0002	0.0002	**4.37%**
AENS (kWh/ customer-year)	0.0000	0.0000	**4.37%**
ASAI	0.999929	0.999938	**Improved**
ASUI	0.000071	0.000062	**Improved**

The 14-bus system shows a decrease in SAIFI from 0.4951 to 0.4575 interruptions/customer-year. This indicates a reduction in the average frequency of customer interruptions after reconfiguration. SAIDI decreases from 0.6238 to 0.5397 hours/customer-year, showing that the total interruption duration experienced by customers is reduced. CAIDI decreases from 1.2599 to 1.1798 hours/interruption, indicating improved restoration performance. EENS shows an improvement of 4.37%, which confirms that the expected unsupplied energy is reduced after reconfiguration. Similarly, AENS also improves by 4.37%, indicating a reduction in the average unsupplied energy per customer.

ASAI increases from 0.999929 to 0.999938, while ASUI decreases from 0.000071 to 0.000062. Therefore, the reconfigured 14-bus system provides improved service continuity and better operating reliability. The results clearly show that the proposed reconfiguration method improves both technical and reliability performance. The reduction in active and reactive power losses confirms improved feeder operating efficiency, while the improvement in SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI confirms enhanced customer-oriented reliability.

6.4 Comparative Discussion

The comparative results of the 6-bus, 11-bus, and 14-bus radial distribution systems show that the proposed reconfiguration method improves both power-loss performance and reliability indices. The overall comparison of the 6-bus, 11-bus, and 14-bus systems is tabulated Table 7.

Table 7: Overall Comparison of 6-Bus, 11-Bus, and 14-Bus Systems

Parameter	**6-Bus System**	**11-Bus System**	**14-Bus System**
Initial power loss	0.6962 kW	324.0249 kW	511.4435 kW
Final power loss	0.6450 kW	319.7065 kW	466.1354 kW
Power-loss reduction	7.35%	1.33%	8.86%
SAIFI improvement	4.83%	4.23%	7.60%
SAIDI improvement	6.76%	6.18%	13.48%
CAIDI improvement	2.04%	2.03%	6.36%
EENS improvement	6.09%	3.48%	4.37%
AENS improvement	6.09%	3.48%	4.37%

Among the three systems, the 14-bus system shows the highest percentage reduction in active power loss. The 14-bus system achieves approximately 8.86% power-loss reduction, followed by the 6-bus system with approximately 7.35% reduction and the 11-bus system with approximately 1.33% reduction. Therefore, the 14-bus system shows the most significant improvement in active power-loss reduction after reconfiguration.

In terms of reliability improvement, the 14-bus system also shows better performance compared with the 6-bus and 11-bus systems. The SAIFI improvement is 7.60% for the 14-bus system, 4.83% for the 6-bus system, and 4.23% for the 11-bus system. Similarly, SAIDI improves by 13.48% in the 14-bus system, whereas the 6-bus and 11-bus systems show improvements of 6.76% and 6.18%, respectively. This indicates that the reconfigured 14-bus system provides a greater reduction in interruption duration experienced by customers.

The results demonstrate that the proposed reconfiguration method is effective for all three systems. The reconfiguration process changes the supply paths by modifying the open and closed switch positions, thereby reducing feeder losses and improving the reliability performance of the network. The 14-bus system gives the highest power-loss reduction because the presence of three feeders and three tie switches provides more switching flexibility compared with the 6-bus and 11-bus systems. This additional switching flexibility allows the network to obtain a more efficient radial configuration after reconfiguration.

The improvement in reliability indices is also consistent for all three systems. The reduction in SAIFI indicates that the average frequency of customer interruptions is reduced after reconfiguration. The reduction in SAIDI shows that the total interruption duration experienced by customers is reduced. In all three systems, the percentage improvement in SAIDI is higher than the improvement in CAIDI. This indicates that the reconfiguration process mainly reduces the total customer interruption duration rather than only reducing the average restoration time per interruption.

The 14-bus system shows the highest SAIDI improvement of 13.48%, which confirms that the reconfigured topology significantly improves service continuity. The CAIDI improvement is also highest for the 14-bus system at 6.36%, indicating better restoration performance compared with the other two systems. The EENS and AENS values also improve in all three systems, confirming that the expected unsupplied energy and average unsupplied energy per customer are reduced after reconfiguration.

Overall, the comparative analysis confirms that the proposed reconfiguration method is useful for reducing active power loss and enhancing distribution system reliability. The method provides better feeder utilization, improved service continuity, and reduced interruption impact on customers. Among the three systems, the 14-bus system gives the best overall performance in terms of active power-loss reduction and reliability-index improvement, followed by the 6-bus and 11-bus systems.

VII. CONCLUSION

This paper presented a reliability-oriented performance evaluation of 6-bus, 11-bus, and 14-bus radial distribution systems after applying a fast heuristic network reconfiguration method. The adopted method is based on sequential switch opening and branch exchange using the Bus Injection to Branch Current (BIBC) matrix. The objective of the study was to reduce active power loss while improving important customer-oriented reliability indices such as SAIFI, SAIDI, CAIDI, EENS, AENS, ASAI, and ASUI. For the 6-bus system, the active power loss was reduced from 0.6962 kW to 0.6450 kW, corresponding to approximately 7.35% loss reduction. The 11-bus system showed a reduction in active power loss from 324.0249 kW to 319.7065 kW, corresponding to approximately 1.33% loss reduction. In the case of the 14-bus system, the active power loss was reduced from 511.4435 kW to 466.1354 kW, corresponding to 45.3081 kW reduction and approximately 8.86% loss reduction. The reactive power loss of the 14-bus system was also reduced from 590.3670 kVAr to 544.8996 kVAr, showing that the reconfigured topology improves both active and reactive power-loss performance. In addition to power-loss reduction, all three systems showed improvement in major reliability indices. For the 6-bus system, SAIFI, SAIDI, and CAIDI improved by 4.83%, 6.76%, and 2.04%, respectively. For the 11-bus system, SAIFI, SAIDI, and CAIDI improved by 4.23%, 6.18%, and 2.03%, respectively. For the 14-bus system, SAIFI, SAIDI, and CAIDI improved by 7.60%, 13.48%, and 6.36%, respectively. The 14-bus system achieved the highest reliability improvement among the three test systems, particularly in SAIDI, which indicates a significant reduction in customer interruption duration. The EENS and AENS values also improved in all three systems, confirming that the expected unsupplied energy and average unsupplied energy per customer were reduced after reconfiguration. Furthermore, ASAI increased and ASUI decreased after reconfiguration, indicating improved service availability and reduced service unavailability. The results confirm that network reconfiguration is a simple, fast, and cost-effective technique for improving both operating efficiency and customer reliability in radial distribution networks. The comparative analysis shows that the proposed reconfiguration method is effective for small and medium radial distribution systems. Among the considered systems, the 14-bus system provides the best overall improvement in both active power-loss reduction and reliability enhancement due to the presence of more feeders and tie-switching flexibility. Future work may extend the method to larger IEEE test systems, distribution networks with distributed generation, renewable energy sources, electric vehicle charging stations, and energy storage systems. Further research may also formulate a multi-objective optimization model considering active power loss, reactive power loss, voltage deviation, reliability indices, switching cost, and operational constraints.

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APPENDIX

Table-A1: The line data, load data Reliability data of Two-Feeder 11-bus system

Branch No	S.E node	R.E. node	Resistance (Ω)	Reactance (Ω)	Load at R.E. node		Failure Rate (failures/year)	Recovery Rate (Hrs.)	No. of Customers (at R.E.)
					P_L (kW)	Q_L (kVAr)			
			Feeder-A						
1	1	2	0.3968	0.5290	2000	600	0.05	1	500
2	2	3	0.4232	0.5819	3000	1300	0.30	1	400

3	3	4	0.4761	0.6348	2000	500	0.22	0.5	600
4	4	5	0.2116	0.2116	1500	300	0.23	0.5	350
5	5	6	0.1587	0.1587	500	100	0.51	0.5	350
			Feeder-B						
6	1	7	0.5290	0.5290	2500	900	0.11	1	500
7	7	8	0.2910	0.5819	3000	400	0.44	1	400
8	8	9	0.4761	0.6348	2500	600	0.64	0.5	600
9	9	10	0.5819	0.5819	1500	200	0.65	0.5	500
10	10	11	0.5290	0.5290	1000	200	0.12	0.5	500
			Tie-branch						
11	6	11	0.2116	0.0529	------	------	0.30	0.20	------

Table-A2: The line data, load data Reliability data of Three-Feeder 14-bus system

Branch No	S.E node	R.E. node	Resistance (Ω)	Reactance (Ω)	Load at R.E. node		Failure Rate (failures/year)	Recovery Rate (Hrs.)	No. of Customers (at R.E.)
					P_L (kW)	Q_L (kVAr)			
			Feeder-I						
1	1	2	0.3968	0.5290	2000	1600	0.1658	0.8307	210
2	2	3	0.4232	0.5819	3000	400	0.1788	0.8957	200
3	2	4	0.4761	0.9522	2000	-400	0.2465	1.2135	210
4	4	5	0.2116	0.2116	1500	1200	0.2335	1.1485	200
			Feeder-II						
5	1	6	0.5819	0.5819	4000	2700	0.3143	1.5313	210
6	6	7	0.4232	0.5819	5000	1800	0.3110	1.5150	200
7	6	8	0.5819	0.5819	1000	900	0.3473	1.6873	210
8	7	9	0.5819	0.5819	600	-500	0.1568	0.7197	200
9	7	10	0.4232	0.5819	4500	-1700	0.2028	0.9407	210
			Feeder-III						
10	1	11	0.5819	0.5819	1000	900	0.1598	0.8067	200
11	11	12	0.4761	0.6348	1000	-1100	0.2405	1.1895	210
12	11	13	0.4232	0.5819	1000	900	0.2438	1.2058	200
13	13	14	0.2116	0.2116	2100	-800	0.2985	1.4585	200
			Tie-branch						
14	3	9	0.2116	0.2116	------	------	0.1018	1.4748	----
15	8	12	0.2116	0.2116	------	------	0.1045	1.6795	----
16	5	14	0.4232	0.5819	------	------	0.1788	0.8957	----

Table-A3: The line data, load data Reliability data of Single-Feeder 6-bus system

Branch No	S.E node	R.E. node	Resistance (Ω)	Reactance (Ω)	Load at R.E. node		Failure Rate (failures/year)	Recovery Rate (Hrs.)	No. of Customers (at R.E.)
					P_L (kW)	Q_L (kVAr)			
1	1	2	0.0922	0.0470	100	600	0.05	1	500
2	2	3	0.4930	0.2511	90	1300	0.30	1	400
3	3	4	0.3660	0.1864	120	500	0.22	0.5	600

4	4	5	0.3811	0.1941	60	300	0.23	0.5	350
5	3	6	0.8190	0.7070	60	100	0.51	0.5	350
			Tie-branch						
6	3	5	0.5000	0.5000	------	------	0.30	0.20	------

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