

Reliability improvement and loss reduction in radial distribution system with network reconfiguration algorithms using loss sensitivity factor

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ABSTRACT

Studies on load flow in electrical distribution system have always been an area of interest for research from the previous few years. Various approaches and techniques are brought into light for load flow studies within the system and simulation tools are being used to work out on varied characteristics of system. This study concentrates on these approaches and the improvements made to the already existing techniques considering time and the algorithms complexity. Also, the paper explains the network reconfiguration (NR) techniques considered in reconfiguring radial distribution network (RDN) to reduce power losses in distribution system and delivers an approach to how various network reconfiguration techniques support loss reduction and improvement of reliability in the electrical distribution network.

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1. INTRODUCTION

In distribution systems, finding out the best possible status of placing the sectionalizing switch (SS) is determined by the network reconfiguration (NR) which is done to reduce losses and to improve reliability. NR is the process of changing the open or close condition of sectionalizing switches and tie switches in a distribution system for adjusting the network topology and improve distribution system performance based on the limitations considered [1]. Generally, the loss reduction, voltage enhancement, and load balancing are the main objectives of NR [2]. Reconfiguration of the system leads to reduction in power loss in distribution system [3]. Distribution network reconfiguration (DNR) attained considerable focus in the past few years. Most of the techniques considered for the NR process used heuristic, mathematical programming or approximation techniques. DNR using fireworks algorithm, simulated annealing, genetic algorithm based approaches, and particle swarm optimization (PSO) have also been considered.

Ascertained a survey in DNR methods, is considered in [4]. An appropriate survey about encoding techniques for network on different meta-heuristic DNR approaches is explained in [5]. A short idea on various NR techniques are explored in [6]. A brief summary of DNR methods with heuristic approaches is explained in [7]. In [8], [9], analysis of population-based artificial intelligence (AI) techniques to DNR is given. Moreover, these population-based AI techniques include the PSO, genetic algorithm (GA), and ant

colony optimization (ACO) only. Lavorato *et al.* [10] given a literature review on DNR techniques proposing radiality constraints. Brief review on classification of DNR approaches with single or multi-objectives is explained in [11]. A review on loss minimization in distribution systems is presented in [12]. Some patents on power distribution NR (PDNR) methods are viewed in [8], [13]–[17].

The meta-heuristic is usually referred to as an approach to resolve the NR issues. Various meta-heuristic algorithms are proposed within the works of literature for resolving these problems like GA, PSO, fireworks algorithm (FWA), cuckoo search algorithm (CSA), ACO, shuffled frog leaping algorithm (SFLA) [18]–[22] and runner-root algorithm (RRA). Particularly, SFLA for resolving the problems in optimization mainly because of high accuracy in local optimal searching [23], [24].

New technologies for NR are suggested in [25], [26] as they are limited with the results and additional cost to be imposed on the system. But the NR algorithm based on loss sensitivity factor (LSF) condition, there would not be any imposition of additional cost on the system. NR is done only by altering the power flow path in the system which would be more beneficial on the today's power system environment.

This paper proposes a novel NR algorithm that will minimize the losses and enhances the reliability in the distribution system. The algorithm adopts various LSF conditions and simulated using MATLAB environment. The reason of a load flow analysis (LFA) is to determine power loss values, reliability, and voltage profile. Algorithm is developed such that all the constraints considered are satisfied and to find best possible way of having the sectionalizing switch so that the power flow is altered and radiality of the system is maintained.

2. PROBLEM FORMULATION

The key issues addressed in this work are voltage profile enhancement, reduction in power loss, and reliability improvement by NR. Voltage must be kept between the specified minimum and maximum tolerance limits. Radial distribution systems (RDSs) are the only options for getting from the feeder to the customer. With network reconfiguration, power losses and performance indices should be reduced. It is accomplished by picking the configuration that produces the minimal power losses, the lowest failure indices, and satisfies a set of requirements from among all feasible configurations. The objective of minimizing power loss and improving reliability is achieved by considering the following constraints and minimizing real power loss and reliability indices.

- Node voltage constraint:

$$V_{i,\min} \leq V_i \leq V_{i,\max}$$

where $V_{i,\min}$ is the minimum allowable root mean square (RMS) voltages at node i , $V_{i,\max}$ is the maximum allowable RMS voltages at node i .

- Power losses and reliability indices:

$$0 < P_L, Q_L \leq P_{L,b}, Q_{L,b}; \quad 0 < SAIFI \leq (SAIFI)_b; \quad 0 < SAIDI \leq (SAIDI)_b; \quad 0 < CAIDI \leq (CAIDI)_b; \\ 0 < ASUI \leq (ASUI)_b;$$

3. LOAD FLOW AND NETWORK RECONFIGURATION ALGORITHMS

3.1. Load flow analysis (LFA)

Teng [27] describes the bus injection to branch current (BIBC) and branch current to bus voltage (BCBV) matrices. They'll lay out the distribution network. To determine the relationship between bus current injections and branch currents, the bus injection to branch current matrix is employed. To determine the relationship between branch current and bus voltage, the branch current to bus voltage matrix is employed. For load flow analysis, the distribution load flow technique with forward and backward sweep algorithms used in [28] is utilized because it has greater advantages such as efficiency and high convergence.

3.2. Reliability evaluation

Load point indices are considered in the evaluation of system reliability which is stated by Average annual outage time (U), Average failure rate (λ) used in [29],

$$\lambda_{\text{sys},i} = \sum_{k \in S} \lambda_k \tag{1}$$

$$U_{sys,i} = \sum_{k \in S} \lambda_k r_k \quad (2)$$

Average outage time (r)

$$r_{sys,i} = \frac{U_{sys,i}}{\lambda_{sys,i}} \quad (3)$$

where $\lambda_{sys,i}$ represents the failure rate at the i th load point, $U_{sys,i}$ represents the annual outage duration at the i th load point, $r_{sys,i}$ represent the failure rate and average repair time of the k th distributor segment, and S represents the set of distributor segments connected in series until the i th load point. Billinton and Allan [30] lists the performance indexes that are commonly employed.

3.3. Loss sensitivity factor (LSF)

It is stated as the linearization of a nonlinear equation that is centered on original operating point, resulting in smallest number of solution spaces. LSF is defined as active power loss (APL) variation w.r.t real power [31] at i th bus and is given by (4).

$$\alpha_i = \frac{\partial P_{Loss}}{\partial P_i} = 2 \alpha_{ii} P_i + 2 \sum_{\substack{j=1 \\ j \neq i}}^n (\alpha_{ij} P_j - \beta_{ij} Q_{ij}) \quad (4)$$

3.4. Network reconfiguration algorithms

The following network reconfiguration algorithms (NRAs) are examined in this study. The proposed NRA's are considered in the search for better switching combination apart from decreasing losses, it improves voltage stability, voltage profile and network reliability by considering a tie switch and its neighboring sectionalized switches (SS) as shown in Figure 1, one at each time, and the process continues till it finds no improvement in voltage stability and minimization of power loss and performance indices. A LFA should be performed to confirm that the performance indices and losses are minimized before approving the reconfiguration. If not the reconfiguration must reset to the before condition.

3.5. LSF based network reconfiguration algorithm

- Step 1 : Read the bus data, line data, distribution system probability, and set the flag to zero for all tie switches.
- Step 2 : Using the BIBC and BVBC matrices, run the distribution load flow and compute the node voltages, actual power losses, reactive power losses, and reliability indices .
- Step 3 : The voltage must remain within the required range.
 $V_{i,min} \leq V_i \leq V_{i,max}$ i.e. within the 6% of rated voltage; $0.94 \leq V_i \leq 1.06$, if yes then go to step 11.
- Step 4 : Determine the LSF difference between the tie switches' end nodes k and m with the zero flag. The tie switch with the maximum LSF difference is selected.
- Step 5 : Determine whether the LSF at the k th node is greater than the m th node. If yes, proceed to step 7.
- Step 6 : Open the sectionalizing switch between k and $k-1$.
- Step 7 : Open the sectionalizing switch between m and $m-1$.
- Step 8 : Connect the tie switch and set the flag to 1.
- Step 9 : Verify that all tie switches flags are equal to 1, then go to step 10.
- Step 10 : Determine the power losses. If not $0 < P_L, Q_L \leq P_{Lb}, Q_{Lb}$; then go to step 2
- Step 11 : Calculate the system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), average system unavailability index (ASUI), and customer average interruption duration index (CAIDI) dependability indices. If not $0 < SAIFI \leq (SAIFI)_b; 0 < SAIDI \leq (SAIDI)_b; 0 < CAIDI \leq (CAIDI)_b; 0 < ASUI \leq (ASUI)_b$; Move on to step 2.
- Step 12 : Print the values of $|V|$, LSF, P_L , Q_L , SAIDI, SAIFI, ASUI, and CAIDI.

3.6. Algorithm conditions considered for network reconfiguration of distribution system

Maximum LSF difference, considering only adjacent sectionalizing switch; minimum LSF difference, considering only adjacent sectionalizing switch; maximum LSF difference, considering the SS which gives minimum losses; minimum LSF difference, considering the SS which gives minimum losses.

4. RESULTS AND ANALYSIS

The LFA and network reconfiguration algorithms of radial distribution system are implemented in MATLAB. Power loss is calculated for various network reconfiguration algorithms and analysis is done. Our proposed methods are compared with existing methods in literature.

4.1. Power loss of 33-bus RDS base configuration

The load flow algorithm is applied to 33-bus radial distribution system shown in Figure 1 using MATLAB programming. Power loss values are shown in Table 1. Tables 2 and 3 show the performance indices and obtained results of voltage magnitude, phase angle, and LSF of 33-Bus RDS for base configuration.

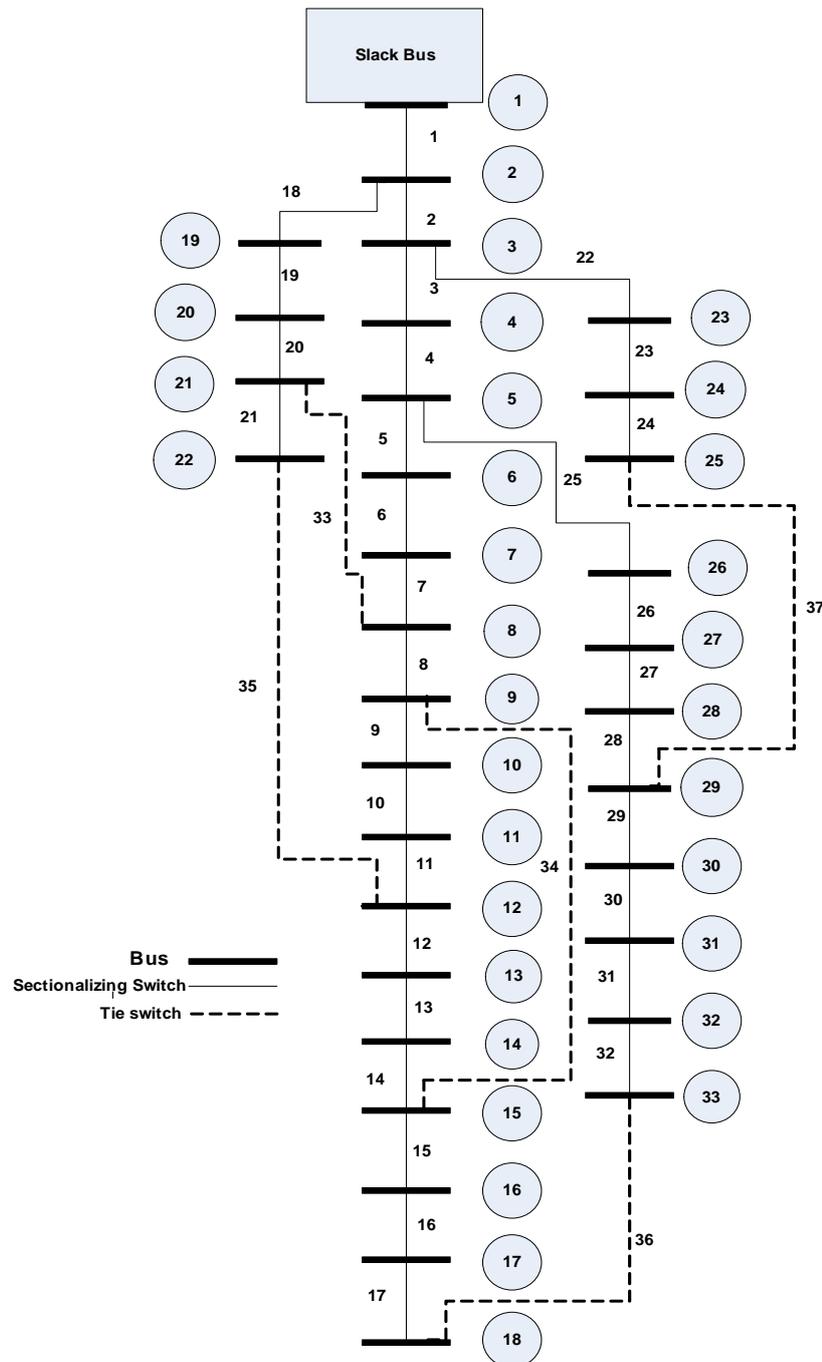


Figure 1. Line diagram of 33 bus RDS

Table 1. Power loss values for base configuration of 33-bus RDS

Parameter	Simulated Result
(APL) (kW)	202.6650
(RPL) (kVar)	135.1327
(TPL) (kVA)	243.5856

Note: APL: active power loss, RPL: reactive power loss, TPL: total power loss

Table 2. Performance indices of 33 bus RDS-base configuration

INDEX	SAIDI	SAIFI	CAIDI	ASUI
Value	2.4126	2.0436	0.8470	2.3328e-4

Table 3. Converged values of, phase angle, voltage magnitude and LSF before NR

Bus No.	Voltage Magnitude (p.u)	Phase Angle (p.u)	LSF	Bus No.	Voltage Magnitude (p.u)	Phase Angle (p.u)	LSF
1	1.00000	0.00000	0.005195100	17	0.91376	-0.00847	0.000850048
2	0.99703	0.00025	0.004314776	18	0.91316	-0.00864	0.000127706
3	0.98295	0.00167	0.010517832	19	0.99651	0.00006	0.002113020
4	0.97548	0.00282	0.012981822	20	0.99293	-0.00111	0.000450873
5	0.96808	0.00398	0.016555203	21	0.99222	-0.00144	0.002336018
6	0.94970	0.00233	0.009489519	22	0.99159	-0.00180	0.004097798
7	0.94621	-0.00168	0.009826005	23	0.97936	0.00113	0.004748190
8	0.94137	-0.00105	0.002870083	24	0.97269	-0.00041	0.003705224
9	0.93511	-0.00233	0.000043342	25	0.96937	-0.00118	0.008270925
10	0.92930	-0.00342	0.001042876	26	0.94777	0.00302	0.003117823
11	0.92844	-0.00329	0.000119320	27	0.94521	0.00400	0.003441634
12	0.92694	-0.00309	0.000979896	28	0.93378	0.00545	0.006031129
13	0.92083	-0.00469	0.003196831	29	0.92556	0.00681	0.002094279
14	0.91857	-0.00606	0.001365677	30	0.92201	0.00864	0.001629334
15	0.91715	-0.00672	0.001161101	31	0.91785	0.00717	0.003172595
16	0.91579	-0.00712	0.001844113	32	0.91694	0.00677	0.003340355
				33	0.91665	0.00664	0.003645279

4.2. Comparison of network reconfiguration algorithms

Load flow analysis and network reconfiguration Algorithm 1 is performed on 33-bus RDS with MATLAB and the output obtained is analyzed. From the obtained results of 33-bus RDS for base case shown in Table 1, Active power loss obtained is 202.6 kW. The LSF difference between 25-29 is largest, and hence initially this tie-switch is closed. As LSF of 25 is higher than LSF of 29, the switch between 29-28 is opened. Then, the active power loss is 172.0631 kW.

In NRA 1, the next switch (tie) closed is 9-15, continue the process and solution are to open switch in branch 15-14. Now the real power loss is 230.9624 kW. Next switch to be closed is 18-33, then repeat the process and the switch to be opened is between 33-32. The power loss value for this switch is 164.5364 kW. The procedure is repeated till final optimal configuration is achieved. Thus, final total real power loss is 164.5364 kW after reconfiguration with NR Algorithm 1. Power loss values after NRA 1 are tabulated in Table 4 respectively.

Table 4. APL and RPL at different tie switches using algorithm 1 [30]

Power Loss	Tie Switch (25-29)	Tie Switch (9-15)	Tie Switch (18-33)	Tie Switch (22-12)	Tie Switch (21-8)
APL (kW)	172.06	166.14	155.62	139.58	137.53
RPL (kVar)	117.06	112.98	104.3	94.18	113.48

Figure 2 represents the line diagram of reconfigured 33 bus RDS using NRA 1. In the second algorithm minimum LSF difference is considered in order to operate the tie switches. The LSF difference between 18-33 is smallest, so first this tie switch is closed. As LSF of 18 is less than the LSF of 33, the switch in between 33-32 is opened. Here, APL is 198.7574 kW.

In NRA 2, next tie switch 21-8 is closed is, then repeat same process and solution is to open switch in branch 8-7. Now the total active power loss is 127.1754 kW. Next close the tie switch 9-15, then continue the process and open switch in between 15-14. The power loss value for this switch is 160.8898 kW. The same process is repeated until optimal configuration is achieved. Thus, final active power loss is 127.1754 kW after reconfiguration with NR Algorithm 2. Power loss values after network reconfiguration Algorithm 2 are given in Table 5. Figure 3 represents line diagram of reconfigured 33 bus RDS using NRA 2.

The third algorithm considers the maximum LSF difference as well as the sectionalizing switch that results in the minimum amount of losses. Because the LSF difference between 25 and 29 is the greatest, this switch is closed. Because the LSF of 25 is greater than the LSF of 29, the switch between 29 and 28 is opened, and the process of calculating the power loss at each SS continues. The optimum case is a sectionalizing switch that produces the least amount of losses. In this case, the power loss after accounting for all switches is 155.17 kW.

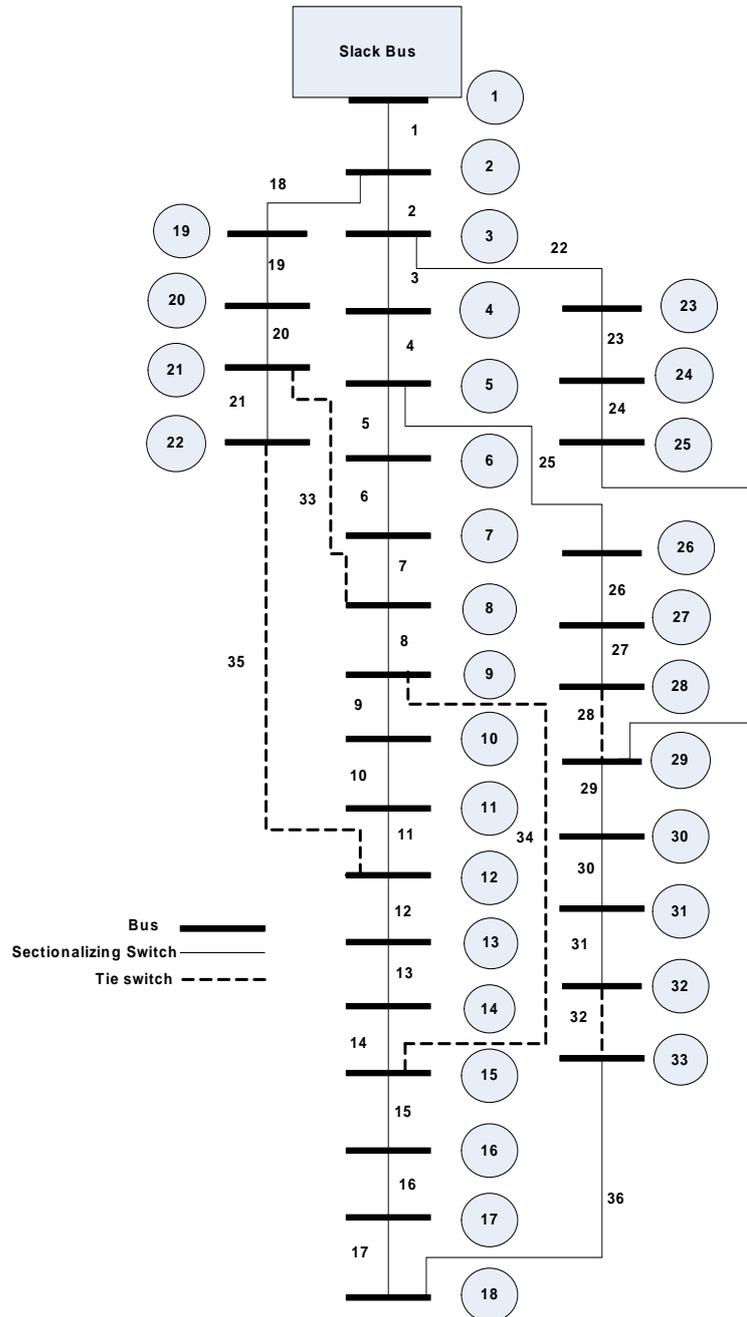


Figure 2. Line diagram of 33-bus RDS after reconfiguration using NRA 1

Table 5. APL and RPL at different tie switches using Algorithm 2

Power Loss	Tie Switch(25-29)	Tie Switch (9-15)	Tie Switch (18-33)	Tie Switch (21-8)	Tie Switch (22-12)
Active Power Loss (kW)	198.75	127.1	160.88	135.25	191.86
Reactive Power Loss (kVar)	132.90	90.58	130.11	98.44	162.46

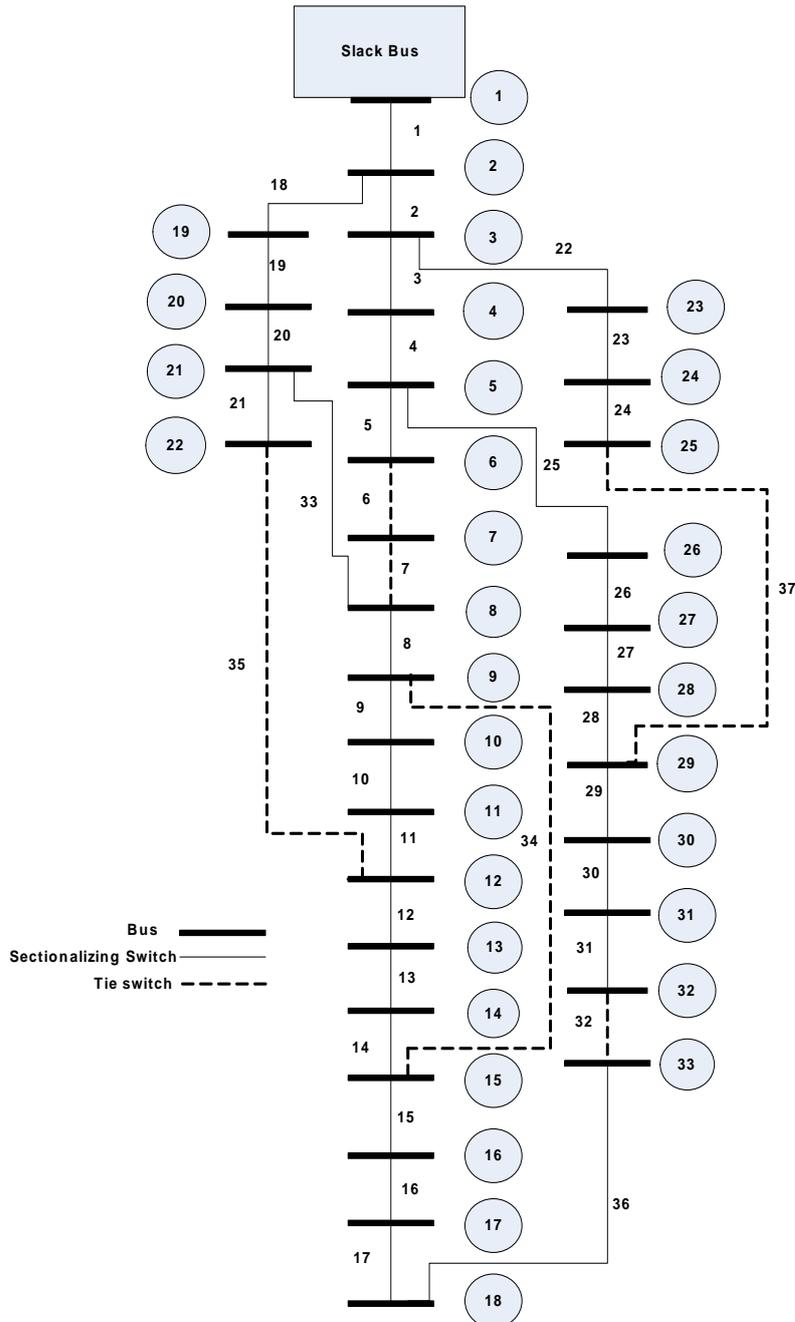


Figure 3. Line diagram of 33-bus RDS after reconfiguration using NRA 2

In NRA 3, the next switch closed is 9-15, then continue the process and open the switch between 14-13. Now the total APL is 147.44 kW. Now close the tie switch 18-33, then continue the process and open the switch in between 31-30. The power loss value for this switch is 156.37 kW. The process is repeated till final optimal configuration is obtained. Thus, final total active power loss is 147.44 kW after reconfiguration with NR Algorithm 3. Power loss values after network reconfiguration Algorithm 3 are given in Table 6.

The line diagram of a re-configured 33 bus RDS employing NRA 3 is shown in Figure 4. The fourth algorithm considers the minimum LSF difference and the sectionalizing transition, which results in the lowest losses. When the base configuration is simulated, the LSF difference tie switch 18-33 is the smallest, thus close this tie switch first. Because the LSF of 18 is smaller than the LSF of 33, the switch between 33 and 32 is opened, and the process of calculating the power loss at each sectionalizing switch continues. The optimum case is a sectionalizing switch that produces the minimum amount of losses. 136.0375 kW is the optimal power loss.

Table 6. APL and RPL at different tie switches using Algorithm 3

Power Loss	Tie Switch (25-29)	Tie Switch (9-15)	Tie Switch (18-33)	Tie Switch (22-12)	Tie Switch (21-8)
Active Power Loss (kW)	155.1	147.4	156.37	186.7	155.49
Reactive Power Loss (kVar)	105.7	107.6	119.56	135.1	120.16

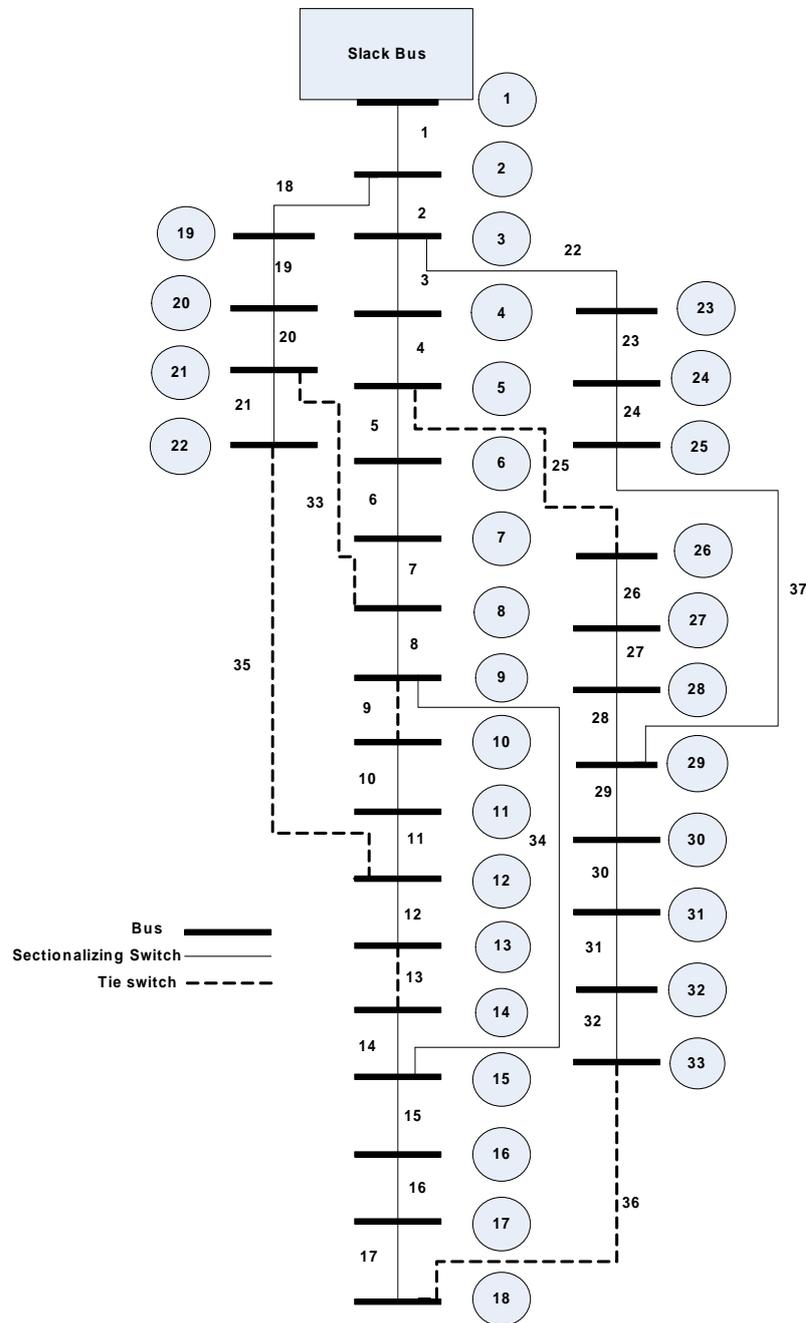


Figure 4. Line diagram of 33-bus RDS after reconfiguration using NRA 3

In this NR, 21-8 tie switch will be closed, then procedure is repeated and the solution is to open the switch in branch 21-20. Now the total APL is 147.129 kW. Tie switch 9-15 is closed next, then continue the process and open the switch in between 13-12. The power loss value for this switch is 134.7413 kW. This process is repeated till final optimal configuration is obtained. Thus, final active power loss is 132.8803 kW after reconfiguration with NR Algorithm 4. Power loss values after network reconfiguration Algorithm 4 are given in Table 7. Figure 5 represents line diagram of reconfigured 33 bus RDS using NRA 4.

Power loss values after NR of four considered algorithms are given in Table 8 respectively. The optimized case is compared with the literature in [30] which shows that the considered algorithm performs better when compared to literature. Figure 6 represents the comparative analysis of all the four considered NR algorithms with their active and reactive power losses. From Table 8, it can be observed that from all the considered NR algorithms NRA 2 shows the better performance when compared with other NRA's. So it can be concluded that NRA 2 gives the optimized performance when compared with the literature [30].

Table 7. APL and RPL at different tie switches using Algorithm 4

Power Loss	Tie Switch (18-33)	Tie Switch (21-8)	Tie Switch (22-12)	Tie Switch (9-15)	Tie Switch (25-29)
Active Power Loss (kW)	136.0	147.1	134.7	150.8	132.8
Reactive Power Loss (kVar)	105.7	107.0	118.0	123.4	117.2

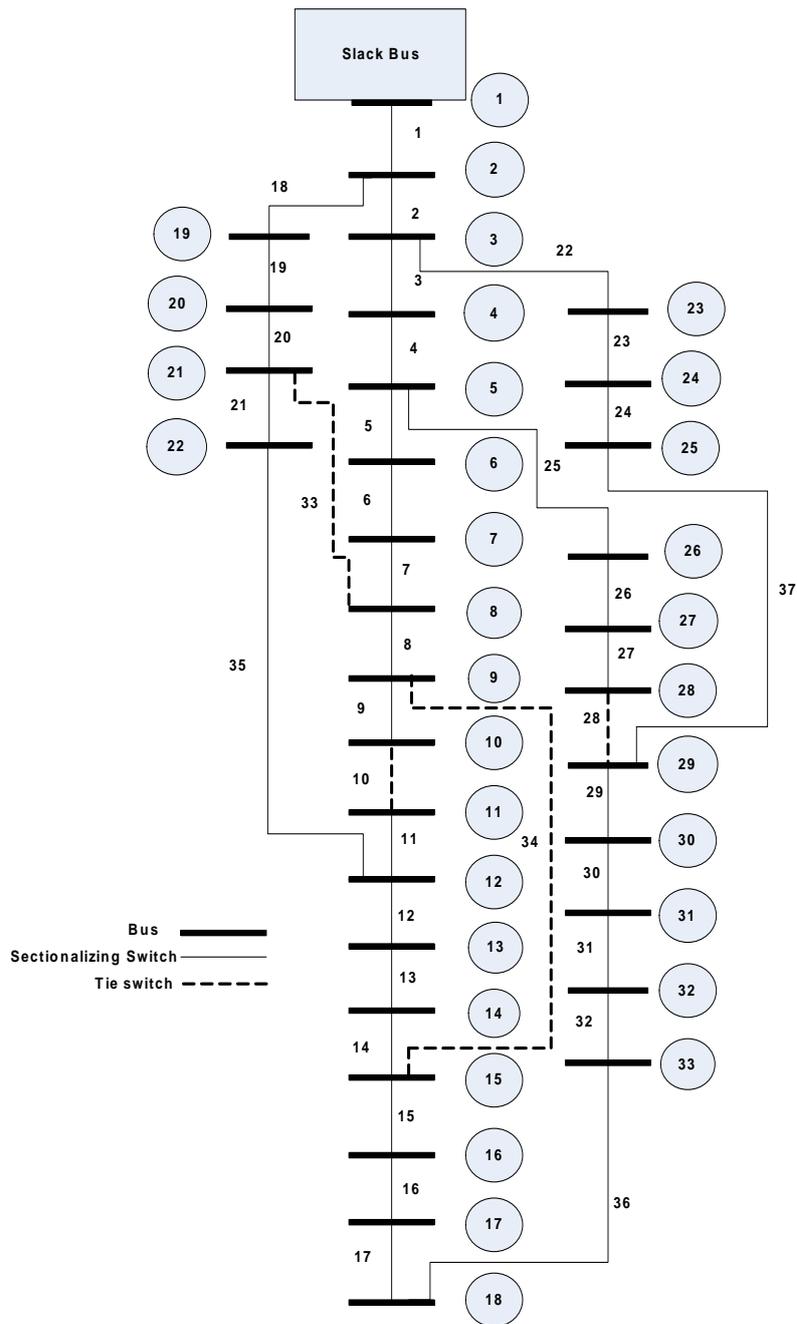


Figure 5. Line diagram of 33-bus RDS after reconfiguration using NRA 4

Table 8. Comparison of APL and RPL using different algorithms

Power Loss	NRA 1 [30]	NRA 2	NRA 3	NRA 4 [31]
Active Power Loss (kW)	137.53	127.1	147.4	132.8
Reactive Power Loss (kVar)	113.48	90.5	107.6	117.2

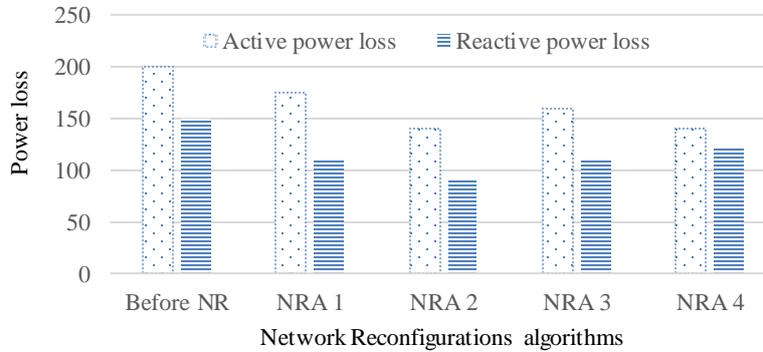


Figure 6. APL and RPL before and after NR

4.3. Reliability analysis

Reliability indices are calculated by using the cutest approach at load points. These indices with and without NR are represented in Table 9. Figure 7 shows the comparison of reliability indices before and after NR1, NR 2, NR 3, and NR 4. Hence from Figure 7 and Table 9 it can be concluded that the reliability indices for NRA 2 is better when compared to the remaining NR algorithms.

Table 9. Comparison of reliability indices before and after NR

S. No.	Index	Before NR	After NR1	After NR 2	After NR 3	After NR 4
1	SAIFI	2.41	2.29	2.18	2.65	2.80
2	SAIDI	2.04	2.02	1.67	1.92	2.06
3	CAIDI	0.84	0.88	0.76	0.72	0.73
4	ASAI	0.99	0.99	0.99	0.99	0.99
5	ASUI	2.3e-04	2.3e-04	1.9e-04	2.1e-04	2.3e-04

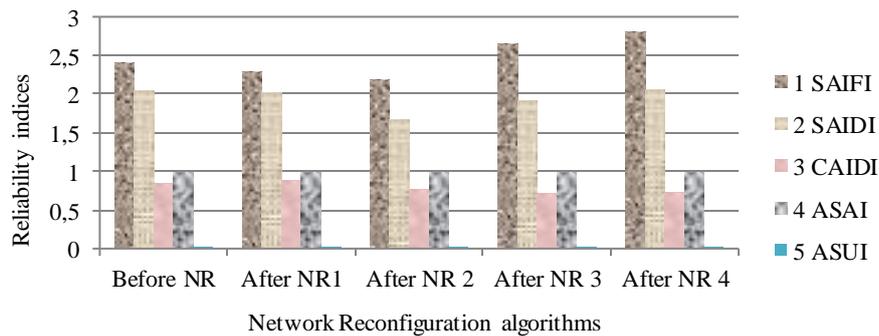


Figure 7. Reliability indices before and after NR

5. CONCLUSION

This paper presents a brief analysis on various network reconfiguration algorithms that work on LSF condition for switching action of tie switch and sectionalizing switch to reconfigure the network without changing its radial nature. Here, among the considered algorithms, Algorithm 2 with minimum LSF difference, considering only adjacent sectionalizing switch gives the optimal solution. The algorithms are implemented using MATLAB environment and arrived at minimum loss and better reliability performance when compared to literature.

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