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A New Heuristic Approach for Optimal Network Reconfiguration in Distribution Systems

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***Abstract*—**This paper presents a novel approach for optimal reconfiguration of radial distribution systems. Optimal reconfiguration involves the selection of the best set of branches to be opened, one each from each loop, such that the resulting radial distribution system gets the desired performance. In this paper an algorithm is proposed based on simple heuristic rules and identified an effective switch status configuration of distribution system for the minimum loss reduction. This proposed algorithm consists of two parts; one is to determine the best switching combinations in all loops with minimum computational effort and the other is simple optimum power loss calculation of the best switching combination found in part one by load flows. To demonstrate the validity of the proposed algorithm, computer simulations are carried out on 33-bus system. The results show that the performance of the proposed method is better than that of the other methods.

***Keywords*—**Distribution system, network reconfiguration, power loss reduction, radial network, heuristic technique.

I. INTRODUCTION

THIS distribution systems deliver power to the customers from a set of distribution substations and these are normally configured radially for effective co-ordination of their protective systems.

There are two types of switches used in primary distribution systems; sectionalizing switches (normally closed) and tie switches (normally open). They are designed for both protection and configuration management in the system. Under normal operating conditions, feeders are frequently reconfigured by changing the open/closed state of each switch in order to reduce line losses or to avoid the overloading network branches. Since there are many candidate-switching combinations possible in a distribution system, finding the operating network reconfiguration becomes a complicated combinatorial, non-differentiable constrained optimization problem. In such system the possible number of switching combinations is 3^m, where 'm' is the total number of tie switches in the system. However, all possible options are not practicable, as they require long computational time for line loss calculation.

The radial constraint and discrete nature of the switches prevent the use of classical techniques to solve the reconfiguration problem. Most of the algorithms in the literature are based on heuristic search techniques.

Distribution system reconfiguration for loss reduction was first proposed by Merlin and Back [1]. They employed a blend of optimization and heuristics to determine the minimal-loss operating configuration for the distribution system represented by a spanning tree structure at a specific load condition. Since then, many techniques have been proposed. A branch and bound type heuristic algorithm was suggested by Civanlar, Grainger, Yin, and Lee[2], where a simple formula was developed for determination of change in power loss due to a branch exchange. Shirmohammdi and Hong [3] applied optimal power flow analysis to network reconfiguration for loss minimization. Baran and Wu [4] proposed an algorithm to identify branches to be exchanged using heuristic approach to minimize the search for selecting the switching options. Goswami and Basu [5] reported a heuristic algorithm that was based on the concept of optimum flow pattern. The optimum flow pattern with single loop formed by closing a normally open switch was found out, and this flow pattern was established in the radial network by opening a closed switch. This procedure was repeated until the minimum loss configuration was obtained. McDermott, Drezga, and Broadwater [6] proposed a heuristic constructive algorithm that started with all maneuverable switches open, and at each step, the switch that resulted in the minimum increment in the objective function was closed. The objective function was defined as the ratio of incremental losses to incremental load served. Lin, Chin and Yu [7] designed heuristic based switching indices, by utilizing fuzzy notations for the distribution system loss reduction. Taylor and Lubkeman [8] proposed a switch exchange type heuristic method to determine the network configuration for over loads, voltage problem, and for load balancing simultaneously. Its solution scheme set up a decision tree which represented the various operations available, and a best-first search and heuristic rules were used to find feasible switching operations.

In this paper, a new heuristic search methodology is proposed for determining the minimum loss configuration of a radial distribution system. The proposed solution starts with

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initial configuration with all tie switches are in open position. The voltage differences across all tie switches and the two node voltages of each tie switch are computed using load flow analysis. Among all the tie switches, a switch with maximum voltage difference is selected first subject to the condition that the voltage difference is greater than the pre-specified value. The tie switch with the maximum voltage difference is closed and the sectionalize switches are opened in sequence starting from the minimum voltage node of the tie switch. The power losses due to each sectionalize switch are calculated and the opening sectionalize switches are stopped when the power loss obtained due to previous sectionalizing is less than the current one. As the power loss due other sectionalize switches is more than the current, it is not necessary to open the sectionalize switches further in the loop. Based on the above procedure, the best switching combination of the loop is noted. The same procedure is repeated to all the remaining tie switches. This procedure favors the solution with a fewer switching operations. Another advantage with the algorithm is that the number of load flow computations is less and subsequently the computational effort is drastically reduced. The proposed algorithm is tested on a 33-bus system and results are compared with the different methods available in the literature.

The remaining part of the paper is organized as follows: Section II gives the problem formulation, Section III discusses the proposed algorithm, Section IV develops the reconfiguration results and discussions and Section V discusses the conclusions.

II. FORMULATION OF OPTIMIZATION MODEL FOR LOSS MINIMIZATION

The network reconfiguration problem in a distribution system is to find a configuration with minimum loss while satisfying the operating constraints under a certain load pattern. The operating constraints are voltage drop, current capacity and radial operating structure of the system. The mathematical formulation for the minimization of power loss reconfiguration problems is presented in the literature in different ways. In this paper, the problem formulation is presented as

$$Minimize \quad f = min(P_{T,Loss}) \tag{1}$$

$$Subjected\ to \quad V_{min} \le |V_i| \le V_{max} \tag{2}$$

$$|I_i| \le |I_{i,max}| \tag{3}$$

where

$P_{T,Loss}$ is the total real power loss of the system;

$|V_i|$ Voltage magnitude of bus *i;*

V_{min}, V_{max} are bus minimum and maximum voltage limits respectively;

$I_i, I_{i,max}$ are current magnitude and maximum current limit of branch *i* respectively;

A set of simplified feeder-line flow formulations is employed. Considering the single-line diagram depicted in Fig. 1, the recursive equations (4) to (6) are used to compute the power flow [4].

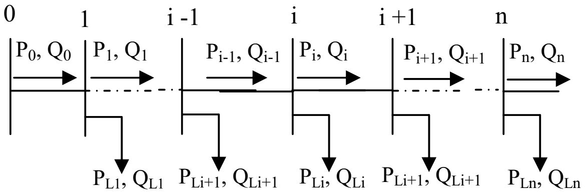

Fig. 1 Single-line diagram of a main feeder

Because of the complexity of the large scale distribution system, network reconfiguration problem is normally assumed as symmetrical system and constant loads. Therefore, the distribution lines are represented as series impedances of the value ($Z_{i,i+1} = R_{i,i+1} + jX_{i,i+1}$) and load demand as constant and balanced power sinks $S_L = P_L + jQ_L$. The real and reactive power flows at the receiving end of branch *i+1*, P_{i+1}, and Q_{i+1}, and the voltage magnitude at the receiving end, $|V_{i+1}|$ is expressed by the following set of recursive equations [4]:

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1}.\frac{(P_i^2 + Q_i^2)}{|V_i|^2} \tag{4}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1}.\frac{(P_i^2 + Q_i^2)}{|V_i|^2} \tag{5}$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(R_{i,i+1}.P_i + X_{i,i+1}.Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2).\frac{(P_i^2 + Q_i^2)}{|V_i|^2} \tag{6}$$

Equations (4) – (6) are known as the *Distflow equations.* Hence, if P_0, Q_0, V_0 at the first node of the network is known or estimated, then the same quantities at the other nodes can be calculated by applying the above branch equations successively. This procedure is referred to as a *forward update.*

Similar to forward update, a *backward update* is expressed by the following set of recursive equations [4]:

$$P_{i-1} = P_i + P_{Li} + R_{i,i+1}.\frac{(P_i'^2 + Q_i'^2)}{|V_i|^2} \tag{7}$$

$$Q_{i-1} = Q_i + Q_{Li} + X_{i,i+1}.\frac{(P_i'^2 + Q_i'^2)}{|V_i|^2} \tag{8}$$

$$|V_{i-1}|^2 = |V_i|^2 + 2(R_{i-1,i}.P_i' + X_{i-1,i}.Q_i') + (R_{i-1,i}^2 + X_{i-1,i}^2).\frac{(P_i'^2 + Q_i'^2)}{|V_i|^2} \tag{9}$$

where $P_i' = P_i + P_{Li}$ *and* $Q_i' = Q_i + Q_{Li}$

Note that by applying backward and forward update schemes successively one can get a power flow solution.

The power loss of the line section connecting between buses i and $i+1$ is computed as

$$P_{Loss}(i,i+1)=R_{i,i+1}\cdot\frac{(P_i^2+Q_i^2)}{|V_i|^2} \qquad (10)$$

The total power loss of the feeder $P_{F,\ Loss}$ is determined by summing up the losses of all line sections of the feeder, which is given by

$$P_{F,Loss}=\sum_{i=0}^{n-1}P_{Loss}(i,i+1) \qquad (11)$$

where the total system power loss $P_{T,\ Loss}$ is the sum of power losses of all feeders in the system.

III. PROPOSED METHOD

In general, many tie or sectionalize switches are to be closed or opened to obtain the feasible network reconfiguration. If the reconfigured network leaves any branches unconnected or forms a closed loop it will lead to an infeasible switching combination for network reconfiguration. Hence, to avoid the infeasible switching combinations, the connectivity from the source to all the nodes and radial structure of the network must be checked. The optimal switching strategies for network reconfiguration proposed by most of the researchers need to consider every candidate switch to evaluate the effectiveness of loss reduction. Such strategies require extensive numerical computation. In the present work, a simple heuristic rules are formed to select the optimal switches that give the minimum power loss without searching all the candidate switches in the network. The details of the proposed algorithm with heuristic rules are explained in the following section:

For the given radial network with all tie switches open, by running the load flow, the voltage difference ([$\Delta V_{tie}(i)$], for i=1, 2, . . . , N_{tie}) across all of the open tie switches are computed. Then, the open tie switch from the vector ΔV_{tie} that has the minimum voltage difference is detected. If the maximum voltage difference of any tie switch in the vector is greater than a specified value, then that tie switch is considered first. Because of the largest voltage difference, this switching (closing) of the tie switch will cause maximum loss reduction, improve minimum system voltage and provide the better load balancing. In the next iteration, the same procedure is repeated for the remaining tie-switches and so forth. If, in any iteration, this maximum voltage difference across any tie switch is less than the specified value (ε), then that tie-switch operation is discarded and automatically other tie-switch operations are discarded because the voltage difference across all other open tie switches is less than ε.

The proposed method involves the following steps:

1. read the system input data;
2. run the load flow program for the radial distribution network;
3. compute the Power loss and voltage at various nodes;
4. compute the voltage difference across the open tie switches (i.e., $\Delta V_{tie}(i)$, for i=1, 2, . . . , N_{tie}). N_{tie} represents the total number of tie switches;

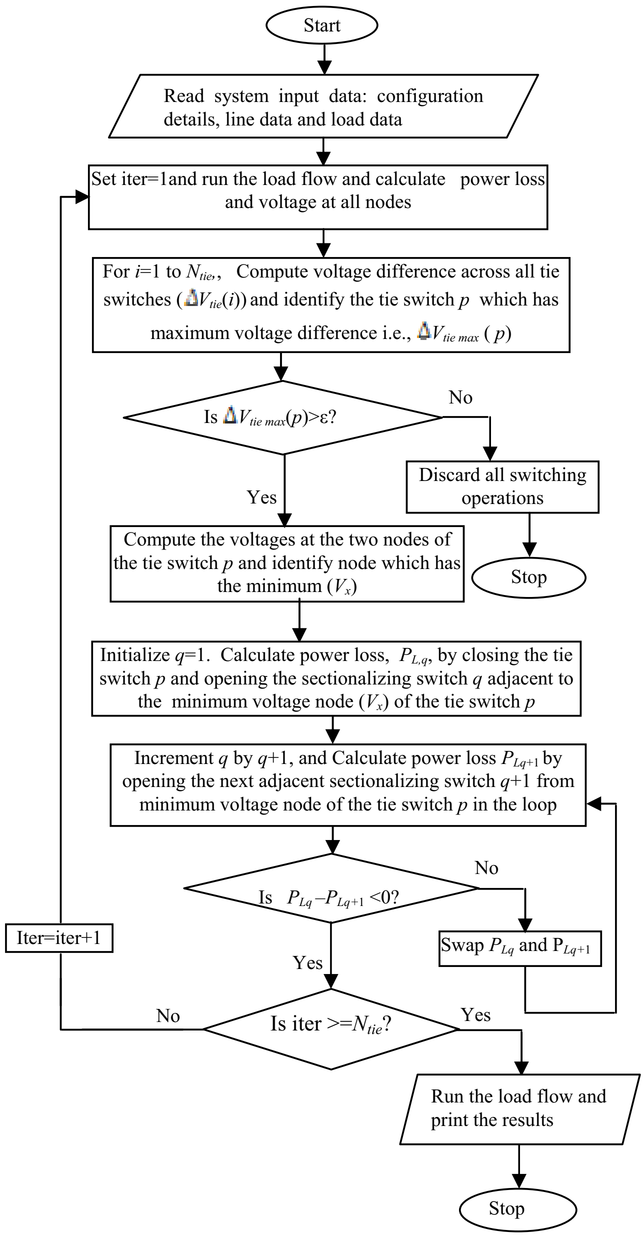

Fig. 2. Flowchart of the solution for loss minimization of the proposed algorithm

5. identify the open tie switch across which the voltage difference is maximum and its code p (i.e., $\Delta V_{tie,max}$=

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$\Delta V_{tie}(p)$);

6. if $\Delta V_{tie,max} > \varepsilon$ (a specified a value), go to step 7; otherwise discard all switching operations and go to step13;
7. pick the two nodes of the tie switch p and check the node which has the minimum voltage, let it be V_x;
8. close the tie switch p to form the loop and open the sectionalize switch q (to retain radiality) adjacent to V_x. Then, calculate the power loss and store it in P_{Lq};
9. now close current sectionalize switch q and open the next adjacent sectionalize switch q+1 in that loop and calculate the power loss and store it in P_{Lq+1};
10. if $P_{L,q} - P_{L,q+1} < 0$, the optimal branch opening in that loop is the sectionalize switch adjacent to node V_x; Otherwise swap $(P_{L,q}, P_{Lq+1})$ go to step 9
11. if the number of iterations (n) is less than or equal to number of tie switches (N_{tie}), set n as n+1 and go to step 2 to repeat the program for the rest of the tie switches;
12. run the load flow and the print the results;
13. stop.

The flow chart for the proposed algorithm is shown in fig. 2.

IV. Test Results and Discussions

The distribution network presented in [4] is used to demonstrate the validity and effectiveness of the proposed method. The proposed method is programmed in MATLAB on a PC Pentium IV, 3-GHz computer with 0.99 GB RAM. The distribution network for reconfiguration consists of 33-buses and 5 tie lines; the total loads are 5084.26 kW and 2457.32 kVAr. The normally open switches are 33, 34, 35, 36, and 37 represented by the dotted lines and normally open switches 1 to 32 are represented by the solid lines as shown in figure 3.

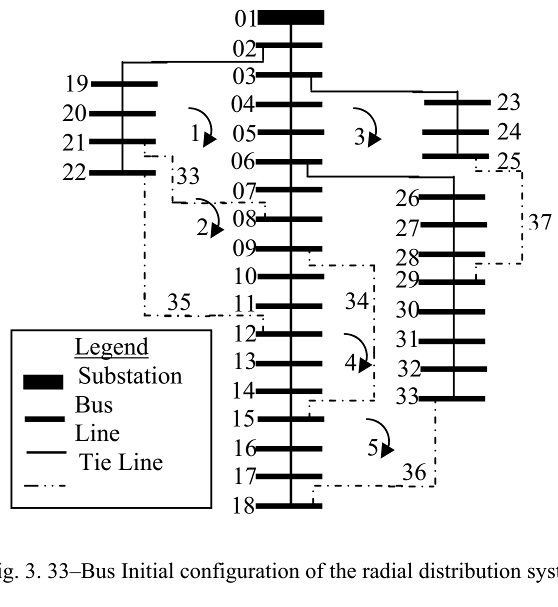

Fig. 3. 33–Bus Initial configuration of the radial distribution system

For this base case, the initial losses are 202.71 kW. The line and load data of 33-bus system are given in Table I.

TABLE I
NETWORK DATA FOR 33 – BUS SYSTEM

Line No.	From Bus	To Bus	R (Ω)	X (Ω)	Load at Receiving End Bus: Real Power Load (kW)	Load at Receiving End Bus: Reactive Power Load (kVAR)
1	1	2	0.0922	0.0477	100.0	60.0
2	2	3	0.4930	0.2511	90.0	40.0
3	3	4	0.3660	0.1840	120.0	80.0
4	4	5	0.3811	0.1941	60.0	30.0
5	5	6	0.8190	0.070	60.0	20.0
6	6	7	0.1872	0.6188	200.0	100.0
7	7	8	1.7114	1.2351	200.0	100.0
8	8	9	1.0300	0.7400	60.0	20.0
9	9	10	1.0400	0.7400	60.0	20.0
10	10	11	0.1966	0.0650	45.0	30.0
11	11	12	0.3744	0.1238	60.0	35.0
12	12	13	1.4680	1.1550	60.0	35.0
13	13	14	0.5416	0.7129	120.0	80.0
14	14	15	0.5910	0.5260	60.0	10.0
15	15	16	0.7463	0.5450	60.0	20.0
16	16	17	1.2890	1.7210	60.0	20.0
17	17	18	0.7320	0.5740	90.0	40.0
18	2	19	0.1640	0.1565	90.0	40.0
19	19	20	1.5042	1.3554	90.0	40.0
20	20	21	0.4095	0.4784	90.0	40.0
21	21	22	0.7089	0.9373	90.0	40.0
22	3	23	0.4512	0.3083	90.0	50.0
23	23	24	0.8980	0.7091	420.0	200.0
24	24	25	0.8960	0.7011	420.0	200.0
25	6	26	0.2030	0.1034	60.0	25.0
26	26	27	0.2842	0.1447	60.0	25.0
27	27	28	1.0590	0.9337	60.0	20.0
28	28	29	0.8042	0.7006	20.0	70.0
29	29	30	0.5075	0.2585	200.0	600.0
30	30	31	0.9744	0.9630	150.0	70.0
31	31	32	0.3105	0.3619	210.0	100.0
32	32	33	0.3410	0.5302	60.0	40.0
33*	21	8	0.0000	2.0000		
34*	9	15	0.0000	2.0000		
35*	12	22	0.0000	2.0000		
36*	18	33	0.0000	2.0000		
37*	25	19	0.0000	2.0000		

* Tie Lines, Substation Voltage=12.66 kV

The voltage differences across all tie switches are computed for the network shown in fig. 3 and are shown in Table II. It is observed that the maximum voltage difference occurs across tie switch 35 which is greater than the specified value (ε). Hence, the tie switch 35 is closed first as the voltage differences across the remaining tie switches are smaller in magnitude.

TABLE II
VOLTAGE DIFFERENCE ACROSS ALL OPEN TIE SWITCHES AFTER FIRST SWITCHING

S. No	Tie switch number	Voltage difference across tie switch (pu)
1	33	0.050963
2	34	0.017961
3	**35**	**0.064754**
4	36	0.003451
5	37	0.043900

Now, if the tie switch 35 is closed, a loop will be formed and total number of branches including tie branch in the loop will be 14. These branches are 12-11, 11-10, 10-9, 9-8, 8-7, 7-6, 6-5, 5-4, 4-3, 3-2, 2-19, 19-20, 20-21, 21-22 and 22-12. Opening of each branch in this loop is an option. But opening of some of the branches causes the violation of the constraints and gives the infeasible solution. Also, opening of all branches in the loop in sequence order or in any another order increases the computational burden. In this algorithm, sectionalize branches are opened (to retained the radiality) either left or right of the selected tie switch based on the minimum voltage node of the tie switch. This procedure is explained as follows.

The two node voltages of the tie switch 35 are evaluated and the minimum of two node voltages is noted. In this case, the minimum node voltage of the tie switch 35 is 12. Therefore, one branch at a time in the loop is opened starting from the node 12 and power loss due to each objective is obtained till the power loss (P_{Lq+1}) due to current objective is greater than the previous objective (P_{Lq}). In this loop, the first sectionalize branch (12-11) is opened as it adjacent to the node 12 and power loss is computed and shown in Table VI. In same manner, next adjacent sectionalize branches 11-10, 10-9, 9-8, and 8-7 are opened one at a time in sequence and power loss is computed and shown in the Table VI. As the power due to sectionalize branch 8-7 is greater than 9-8, the optimal opening branch in the loop is between the nodes 9 and 8. Further opening of the branches beyond the branch 8-7 in the loop, is giving either more power loss than the minimum already obtained at the branch 9-8 or infeasible solution. Hence, the opening of the remaining branches 7-6, 6-5, 5-4, 4-3, 3-2, 2-19, 19-20, 20-21, 21-22 and 22-12 are discarded. The optimal radial loop for the first switching operation is obtained by closing the tie switch 35 and opening the branch between the nodes 9 and 8. The advantage of this procedure is that it is not necessary to visit all the sectionalizing switches in the loop. Therefore, the search space of sectionalizing switches in the loop is drastically reduced. For the second switching operation, the voltage difference across remaining tie switches (discarding tie switch 35) are computed and shown in Table III.

TABLE III
VOLTAGE DIFFERENCE ACROSS THE TIE SWITCHES AFTER SECOND SWITCHING

S. No	Tie switch number	Voltage difference across tie switch (pu)
1	33	0.018891
2	34	0.008328
4	36	0.017159
5	**37**	**0.033793**

From Table III, it is observed that the maximum voltage difference occurs across tie switch 37 and it is greater than the specified value (ε). The minimum voltage node of the tie switch 37 is 29 and is shown in Table VI. Repeating the same procedure as in case of tie switch 35, the optimal radial configuration for the second switching operation is obtained by closing the tie switch 37 and opening the sectionalize branch between the nodes 28 and 29.

Among the tie switches 33, 34 and 36, the voltage difference across tie switch 36 is greater than remaining two and is shown in Table IV. Therefore, the tie switch 36 is selected for the third switching operation as voltage difference is greater than the specified value. The minimum voltage node of tie switch 36 is 33 and is shown in Table V. Repeating the same procedure as in case of tie switch 35, the optimal radial configuration for third switching operation is obtained by closing the tie switch 36 and open the sectionalize branch between the nodes 33 and 32.

TABLE IV
VOLTAGE DIFFERENCE ACROSS THE TIE SWITCHES AFTER THIRD SWITCHING

S. No	Tie switch number	Voltage difference across tie switch (pu)
1	33	0.004505
2	34	0.008328
4	**36**	**0.010081**

The voltage difference across the remaining two tie switches 34 and 33 are shown in Table V. For fourth switching operation, tie switch 34 is considered as the voltage difference across it is greater than 33 and it is also greater than the specified value. The minimum voltage node of 34 is 15 and is shown in Table VI. In this case the optimal configuration of the loop is obtained by closing the tie switch 34 and opening the sectionalize branch between the nodes 15-14.

TABLE V
VOLTAGE DIFFERENCE ACROSS THE TIE SWITCHES AFTER FORTH SWITCHING

S. No	Tie switch number	Voltage difference across tie switch (pu)
1	33	0.002781
2	**34**	**0.010057**

Since the voltage difference across the tie switch 5 is less than the specified value, the closing of it will not cause any reduction in the power loss. Hence this switching operation is discarded. The algorithm is tested on few examples and it was found that a values of ε=0.01 gives the satisfactory results.

TABLE VI
OPTIMAL POWER LOSS IN EACH LOOP, MINIMUM NODE VOLTAGES OF THE SWITCHES, SWITCHES OPEN

Tie switch (Closed)	Minimum node voltage of the tie switch	Sectionalize switch open between nodes	Power loss (p.u)
35	12	12-11	0.0159
		11-10	0.0157
		10-9	0.0156
		9-8	**0.0155**
		8-7	0.0159
37	29	**29-28**	**0.0157**
		28-27	0.0245
36	33	**33-32**	**0.0149**
		32-31	0.0150
34	15	**15-14**	**0.0148**
		14-13	0.0149

The optimal radial configuration of the network after all the switching operations is shown in figure 4. Table VII shows the simulation results of the base configuration and the optimal configuration. The minimum and the maximum voltages of the two configurations are depicted in fig. 5. The power loss before reconfiguration is 202.71 kW and reconfiguration is 135.78 kW. From the results it is observed that reduction in power loss is 63.93 kW which is approximately 33.1 %. The number of all load flow runs required for the entire process is 26.

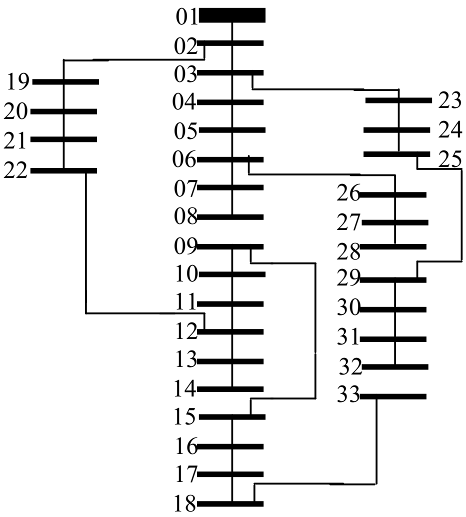

Fig. 4. 33–Bus final radial configuration of distribution system

The voltage profiles before and after reconfiguration is shown in from fig.5. It is observed that the minimum voltage before reconfiguration is 0.9131 p.u and after reconfiguration is 0.9391 p.u. This shows that the minimum voltage in the network is improved by 2.78 % after reconfiguration.

TABLE VII
SIMULATION RESULTS

	33-bus test system
Loss in the base configuration	202.71 kW
Loss in the optimal configuration	135.78 kW
Optimal configuration	33, 14, 8, 32, 28
Loss reduction	66.93 kW
Loss reduction [%]	33.1
CPU Time	0.42 sec
Number of load flow	26

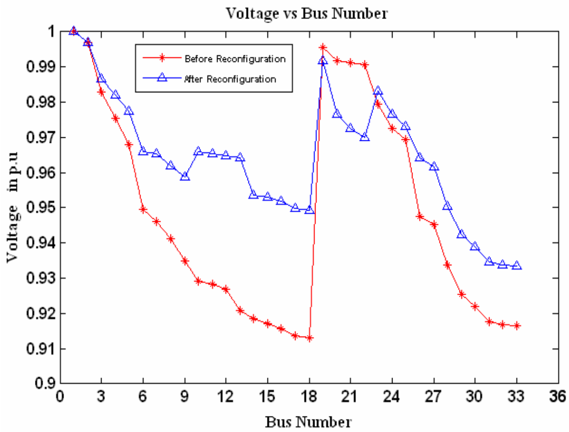

Fig. 5. 33-bus system voltage profile

A. Comparison with other methods

The proposed method is compared with the methods proposed by Goswami [5], Gomes [14], Mcdermott [7] and Kashem[13] for the same 33-bus test system . For effective comparison, the results of the proposed method along with other methods are shown in Table VIII.

TABLE VIII
COMPARISON PROPOSED METHOD WITH OTHER METHODS USING 33-BUS DATA

Method	Final open switches	Total loss savings (%)	CPU Time (s)
Proposed	33,14,8,32,28	33.1	0.42
Goswami[5]	7,9,14,32,37	32.6	0.87
Gomes[14]	7,9,14,32,37	32.6	1.66
McDermott[7]	7,9,14,32,37	32.6	1.99
Chun Wang[9]	7,9,14,32,37	31.17	0.5
Kashem[13]	7,14,11,32,28	26.14	4.56

The saving in total loss by the proposed method is higher than all other methods. The number of tie switch operations obtained by the proposed method and all other methods except Kashem [13] is 4. The number of switching operations in the method proposed by Kashem is 5. The CPU time taken by the proposed method is approximately the same as Chung Wang [9], half the time of Goswami method [5], 4 to 5 times less than the Gomes[14] and Mcdermott[7] methods and much less than the Kashem method [13]. The number of load flows required to get the optimum solution by the proposed algorithm is only 26, whereas it is 29 in case of Baran and Wu [4].

V. CONCLUSIONS

In this paper, a new heuristic approach is developed to minimize the power loss and improve the voltage profile in the system. This algorithm reduces combinatorial explosive switching problem into a realizable one and reduces the switching combinations to a fewer number. The tie branches and its neighboring branches are considered to generate the switching combination and the best combination among them is found with less computational effort. It is observed that the switching combinations in each loop of the network are very much nearer the lower potential of the tie switch. The algorithm gives the optimum solution with a few numbers of load flow runs and CPU time needed is very less. Therefore, this method can be effectively used in real time application of the large distribution system under widely varying load conditions.

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