A New Heuristic approach for Optimal Reconfiguration of distribution systems for improvement of power delivery efficiency through Loss Reduction

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Abstract— **Power loss reduction is one of the main targets in power industry and so in this paper, the problem of finding the optimal configuration of a radial distribution system for loss reduction is considered. This paper presents a new method for optimal reconfiguration of radial distribution systems (RDS). Optimal reconfiguration involves selection of the best set of branches to be opened, one each from each loop, which is based on the calculation of voltage at the buses, real and reactive power flowing through lines, real power losses and voltage deviation, using distribution load flow (DLF) program such that the resulting RDS has the desired performance. The developed load flow program is integrated with known heuristic techniques in a new heuristic search methodology for deter-mining the minimum loss configuration of a radial distribution system. The technique consists of two parts; one is to determine the best switching combinations in all loops with minimum computational effort while the other is a power loss and voltage profile calculation of the best switching combination found in part one by load flows. The solutions get converged very early on; therefore execution time is very small. In this paper an implementation of the algorithm presented by [16] is applied To demonstrate the validity of the proposed algorithm, computer simulations are carried out on a IEEE 33-bus system. The results show that the performance of the proposed method is better than that of the other methods.**

Keywords-component; Distribution system network reconfiguration, Distribution load flow; power loss reduction; heuristic technique.

I. INTRODUCTION

This distribution system 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; sectionalize 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 and improve voltage profile. 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 the total number of tie switches is in the system. However, investigating 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. A branch and bound type heuristic algorithm was suggested by Civanlar et al. [2]. . 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. McDermott et al. [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. Lin and Chin [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 overloads, voltage problem, and for load balancing simultaneously. Wagner et al. [9] proposed a new linear programming method using transportation techniques. In Ref. [10] Broadwater presented a reconfiguration algorithm that calculates switching pattern as a function of time. Peponis and Papadopoulos [11] designed a method for optimization of MV distribution networks

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operation. Mary and Babu [12] proposed a systematic methodology to derive the optimal switching criterion to reduce the energy loss for short and long terms operation of distribution systems. Jen-Hao Teng [14] proposed a direct approach for distribution system load flow solutions. This approach has been integrated with graph theory [15] to follows changes in system structure during reconfiguration. Load flow solutions for the 33-bus test system [4] are different in the different methods [5, 6, 16–19].

The present paper describes a new heuristic network reconfiguration method for radial distribution system, in which the choice of the switches to be opened is based on the calculation of voltage at the buses, real and reactive power flowing through lines, real power losses and voltage deviation, using distribution load flow program. An IEEE 33-bus radial distribution test system is taken as a study system for performing the test of DLF program. The proposed reconfiguration algorithm has been found to give better network reconfiguration result than those obtained by some other recent methods reported in literature.

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. In this paper, the problem formulation is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which were developed based on the topological structure of the distribution systems and is widely implemented for the load flow analysis of the distribution systems. The details of both matrices can be found in [10].

. For bus S_i, the complex load is expressed by:

$$S_i = (P_i + jQ_i), \qquad i=1.........\text{N} \tag{1}$$

At each bus i, the corresponding equivalent current injection is specified by:

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^* \qquad i=1, 2, 3...\text{n} \tag{2}$$

Where, V_i is the node voltage, $P_i + jQ_i$ is the complex power at each bus i, n is the total number of buses. The equivalent current injection of bus i, can be separated into real and imaginary parts.

The branch current B is calculated with the help of BIBC matrix. The BIBC matrix is the result of the relationship between the bus current injections and branch currents. The elements of BIBC matrix consist of '0's or '1's:

$$[B]_{nb\times 1} = [BIBC]_{nb\times(n-1)}.[I]_{(n-1)\times 1} \tag{3}$$

Where, nb is the number of the branch, [I] is the vector of the equivalent current injection for each bus except the reference bus.

It can be seen that the bus voltage can be expressed as a function of branch currents, line parameters, and the substation voltage. Similar procedures can be performed on other buses; therefore, the relationship between branch currents and bus voltages can be expressed as:

$$\Delta V = [Z]_{nb\times(n-1)}.[B]_{(n-1)\times 1}. \tag{4}$$

The voltage drop from each bus to the reference bus is obtained with BCBV and BIBC matrices as:

$$[\Delta V]_{(n-1)\times 1} = [BCBV][BIBC].[I] \tag{5}$$

Where, BCBV matrix is responsible for the relations between branch currents and bus voltages.

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

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

The total power loss in a distribution system having 'n' number of branches is given by

$$P_{TL} = \sum_{i=1}^{n} I_i^2 R_i \tag{6}$$

I_i is the current magnitude and R_i is the resistance. I_i can be obtained from load flow study. The branch current has two components: active component I_a and reactive component I_r. The total losses associated with these two components can be written as

$$P_{TL} = P_{La} + P_{Lr} \tag{7}$$

$$P_{TL} = \sum_{i=1}^{n} I_{ai}^2 R_i + \sum_{i=1}^{n} I_{ri}^2 R_i \tag{8}$$

P_{La} and P_{Lr} is the loss associated with the active and reactive component of branch current respectively.

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;
5. Identify the open tie switch across which the voltage difference is maximum and its code p (i.e. $\Delta V_{tie,\max} = \Delta V_{tie}(p)$).
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 $P_{Lq} - P_{Lq+1} < 0$, the optimal branch opening in loop is the sectionalize switch adjacent to node V_x;
    Otherwise swap (P_{Lq} , 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.

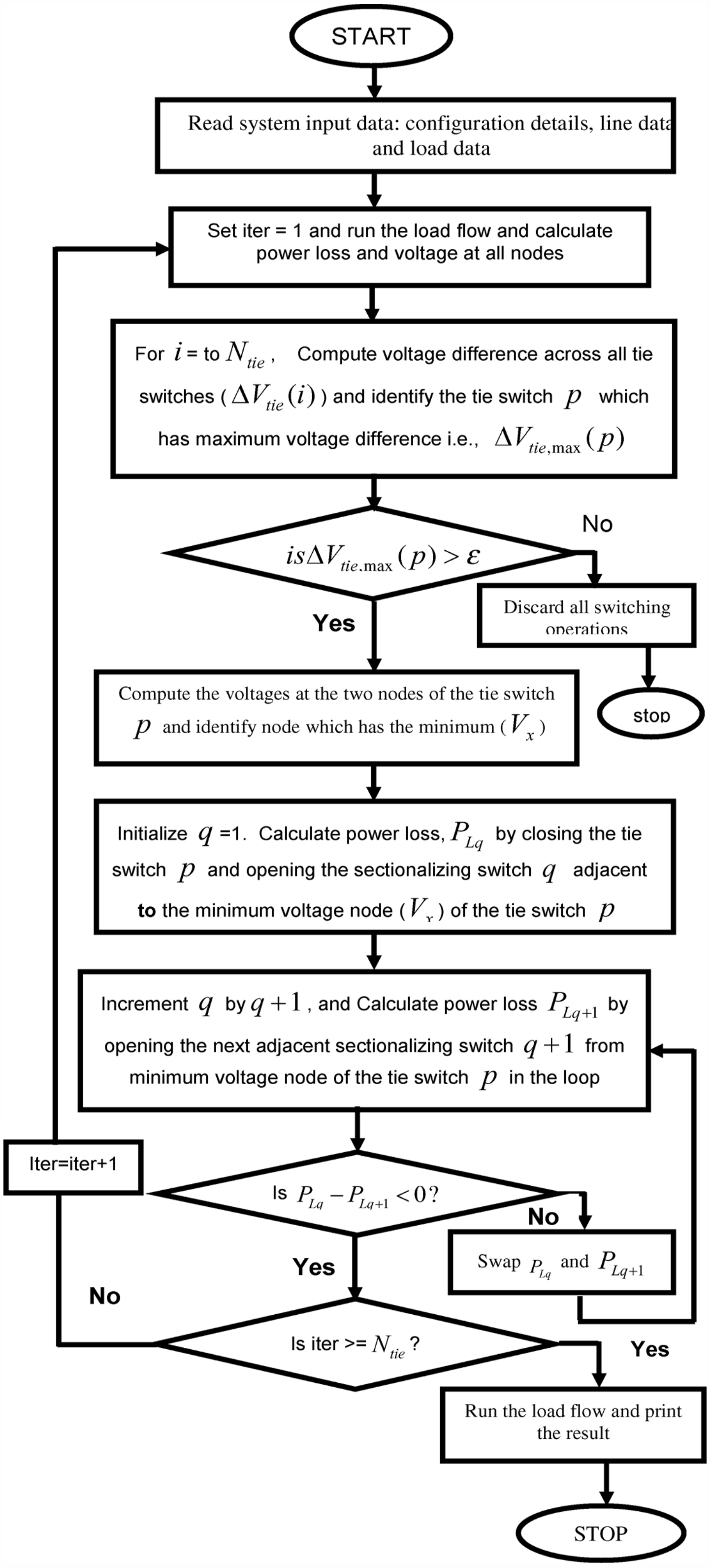

Fig.2 Flow chart of the solution for loss minimization of the proposed algorithm

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, 2.66-GHz computer with 1.99 GB RAM. The distribution network for reconfiguration consists of 33-buses and 5 tie lines; the total loads are 3715 kW and 2300 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. For this base case, the initial losses are 210.84 kW. The line and load data of 33-bus system are given in [19].

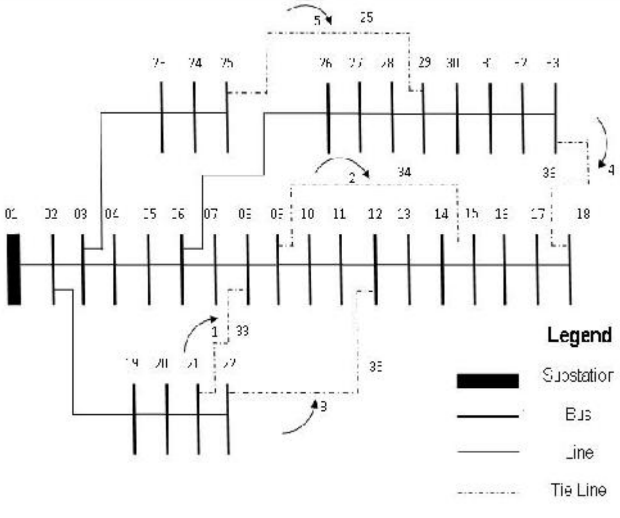

Fig. 3. 33–Bus Initial configuration of the radial distribution system

The voltage differences across all tie switches are computed for the network shown in fig. 3 and are shown in Table I. It is observed that the maximum voltage difference (0.0739 p.u.) occurs across the 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 I
Voltage Difference across all open Tie Switches after First Switching

Sl. No	Tie switch number	Voltage difference across tie switch
1	33	0.0599
2	34	0.0181
3	**35**	**0.0739**
4	36	0.0126
5	37	0.0440

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_{L_q+1}) due to current objective is greater than the previous objective (P_{L_q}). 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 V. In same manner, next adjacent sectionalize branches 11-10 is opened and power loss is computed and shown in the Table V. As the power due to sectionalize branch 11-10 is greater than 12-11, the optimal opening branch in the loop is between the nodes 12 and 11. Further opening of the branches beyond the branch 11-10 in the loop, is giving either more power loss than the minimum already obtained at the branch 12-11 or infeasible solution. Hence, the opening of the remaining branches10-9, 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 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 12 and 11. 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 II.

TABLE II
Voltage Difference across the Tie Switches after Second Switching

Sl. No	Tie switch number	Voltage difference across tie Switch (Vtie)
1	33	0.030063
2	34	0.014622
4	36	0.034809
5	**37**	**0.036101**

From Table II, 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 V. 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 27 and 28.

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 III. 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 III
Voltage Difference across the Tie Switches after Third Switching

Sl. No	Tie switch number	Voltage difference across tie switch
1	33	0.014788
2	34	0.00067669
4	**36**	**0.033379**

The voltage difference across the remaining two tie switches 34 and 33 are shown in Table IV. For fourth switching operation, tie switch 33 is considered as the voltage difference across it is greater than 34 and it is also greater than the specified value. The minimum voltage node of 33 is 8 and is shown in Table V. In this case the optimal configuration of the loop is obtained by closing the tie switch 33 and opening the sectionalize branch between the nodes 7-8.

TABLE IV
Voltage Difference across the Tie Switches after Fourth Switching

Sl. No	Tie switch number	Voltage difference across tie switch
1	**33**	**0.013104**
2	34	0.0051499

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 V
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 (KW)
35	12	**12-11**	**210.09**
		11-10	210.42
37	29	29-28	145.87
		28-27	**142.87**
		27-26	150.27
36	33	**33-32**	**141.24**
		32-31	141.05
		31-30	139.7
33	8	**8-7**	**136.03**
		7-6	137.39

The optimal radial configuration of the network after all the switching operations is shown in figure 4. Table VI 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 210.84 kW and reconfiguration is 121.43 kW. From the results it is observed that reduction in power loss is 89.41 kW which is approximately 42.40 %.

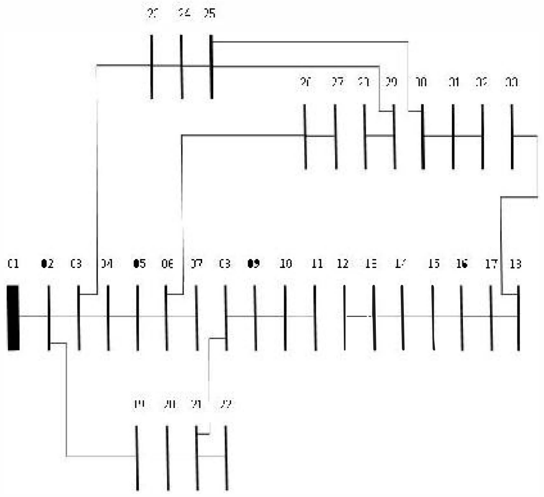

Fig. 4. 33-Bus final radial configuration of distribution system

The voltage profiles before and after reconfiguration is shown in from fig.5. It is observed that the minimum voltage before reconfiguration is 0.90394 p.u and after reconfiguration is 0.93347 p.u. This shows that the minimum voltage in the network is improved by 3.163 % after reconfiguration.

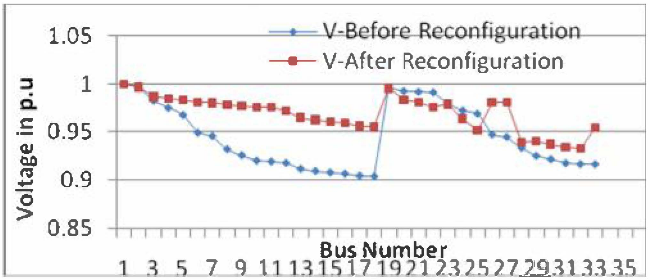

Fig. 5. 33-bus system voltage profile

TABLE VI
SIMULATION RESULTS

	33-bus test system
Loss in the base configuration	210.84 KW
Loss in the optimal configuration	121.43 KW
Optimal configuration	34,7,11,27,32
Loss reduction	89.41 KW
Loss reduction [%]	42.40
CPU Time	0.3720
Number of load flow	8

Table VII
Comparison proposed method with other methods using 33-bus system data.

Method	Final open switches	Total loss savings (%)	CPU Time (s)
Proposed	**34,711,27,32**	**42.40**	**0.372130**
Srinivasa [16]	33,14,8,32,28	33.10	0.42
Goswami [5]	7,9,14,32,37	30.76	0.87
Gomes [18]	7,9,14,32,37	32.60	1.66
McDermott [6]	7,9,14,32,37	32.60	1.99
Chun Wang [17]	7,9,14,32,37	31.17	0.50
Kashem [19]	7,14,11,32,28	26.14	4.56

The proposed method is compared with the methods proposed by Goswami [5], McDermott [6], Srinivasa [16], Chun Wang [17], Gomes [18], and Kashem [19]. The load at feeder head-section in this paper is 3715+ j2300 kVA [19].

V. CONCLUSION

In this paper, a new heuristic approach based on known heuristic rules and a developed load flow algorithm, giving precise branch currents, node voltages and system power loss. 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 switching operations, load flow runs and the CPU time needed is small compared to that in all publications. Comparison of different methods for distribution network reconfiguration suggested that heuristic approaches may not determine global optimum but they are suitable for real time distribution system reconfiguration for loss minimization. Therefore, the proposed technique represents an improved, more efficient method which can easily solve the distribution network reconfiguration problem compared with other methods.

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