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A new heuristic approach for optimal reconfiguration in distribution systems

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ABSTRACT

This paper presents a novel approach for optimal reconfiguration of radial distribution systems. As an integral part of the distribution system configuration, a load flow algorithm based on graph theory is presented. The algorithm follows changes in system structure by traversing a directed graph of the system to find the depth-first search discovery order. For each switching-iteration, this discovery order generates down-stream-nodes vectors necessary for dynamic generation of two matrices: one is the branch node incidence matrix and the other the relationship between the bus current injection and branch currents. Thus avoiding creation of unconnected branches or forming closed loops. The developed load flow program is integrated with known heuristic techniques in a new heuristic search methodology for determining 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. Compared to other published articles, the efficient developed load flow reduces the switching combinations searched and gives the optimum solution in few number of load flow runs. 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.

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1. Introduction

Distribution systems deliver power to the customers from a set of distribution substations. 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* is the total number of tie switches 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. Since then, many techniques have been proposed. A branch and bound type heuristic algorithm was suggested by Civanlar et al. [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 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. The objective function was defined as the ratio of incremental losses to incremental load served. 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

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determine the network configuration for overloads, 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. Wagner et al. [9] proposed a new linear programming method using transportation techniques and a new heuristic search method for feeder reconfiguration with loss reduction as objective. They have presented a comparison of different methods and suggested that heuristic approaches are suitable for real time distribution system reconfiguration for loss minimization. In Ref. [10] Broadwater presented a reconfiguration algorithm that calculates switching pattern as a function of time. Both manual and automatic switches are used to reconfigure the system for seasonal studies, whereas only automatic switches are considered for daily studies. Peponis and Papadopoulos [11] designed a method for optimization of MV distribution networks operation, so that variable loads are fed under minimum energy loss. Two different reconfiguration methods are applied and compared. 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. At present, new methods based on artificial intelligence have been used. Dolatdar et al. [13] proposed an approach of network reconfiguration based on a tree model using radial distribution power flow and genetic algorithm. 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 [5,6,13,16–19]. The base system loss was 205.81 kW in [5] and 202.68 kW in [6]. In Ref. [13] it was 211 kW from Newton Raphson load flow and 194 kW when applying the author's adopted radial distribution load flow in complex mode (PAST open source program). The base system load in [16] at feeder head-section was 5084.26+j2457.32 kVA and the base system loss was 205.81 kW. The base system load in [17] at feeder head-section was 3715+j2300 kVA and the base system loss was 202.7 kW. The base system load in [18] at feeder head-section was 5058.25 + j2547.32 kVA and the base system loss was 202.68 kW. The base system load in [19] at feeder headsection was 3715 + j2300 kVA and the base system loss was 210 kW. This discrepancy in load flow solution necessitates the development of a rigorous load flow algorithm. This algorithm should be capable of following changes in system structure during reconfiguration.

In this paper, a load flow program is developed and integrated with known heuristic techniques [13,16,20] into a new heuristic search methodology for determining the minimum loss configuration of a radial distribution system. This emerging heuristic search methodology proved to perform better than [13,16,20] approaches. The developed load flow algorithm is based on algorithm in [14]. The relationship between the bus current injection and branch currents (BIBC matrix) in is obtained by applying Kirchoff's current law (KCL) to the distribution network. However, in the reconfiguration process the network structure is continuously changing and the load flow algorithm generates the corresponding down-streamnodes' vectors necessary for dynamic generation of BN and BIBC's matrices securing radiality of the network and correct current flow direction. The load flow algorithm follows changes in system structure by creating directed graph for the distribution network in each swithing-iteration. The graph is traversed to find the depth-first search (DFS) discovery order. These discovery orders are used to build the vectors of downstream nodes for each node of the graph necessary for building the two matrices: branch node incidence matrix (BN) and the BIBC matrix, thus avoiding creation of additional function for rejection of unfeasible configurations (graph with unconnected branches or forming closed loops).

The proposed solution of the reconfiguration problem starts with 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 a pre-specified value. Closing this tie switch the sectionalize switches in the resulting loop are opened in sequence starting from the minimum voltage node of the tie switch. The power losses due to each sectionalize switch opening are calculated and opening sectionalize switches are stopped when the power loss obtained due to previous sectionalize is less than the current one. Based on the above procedure, the best switching combination of the loop is detected. 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.

In switching processes, 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, as in most of algorithms it will lead to an infeasible switching combination for network reconfiguration. Therefore, these algorithms have to check feasibility of each switching process as additional burden. The proposed method precludes infeasible switching combinations as graph technique produces directed trees securing connectivity from the source to all the nodes and also the correct flow direction of branch currents.

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 2 gives the formulation of load flow model, Section 3 discusses the proposed algorithm, Section 4 develops the reconfiguration results and discussions and Section 5 discusses the conclusions.

2. Formulation of load flow model

The following model, based on algorithm of [14] is used to compute the power flow. Considering the single-line diagram depicted in Fig. 1, a **BN** connection matrix, of dimension (Branches $(B) \times \text{Nodes} (N)$), is constructed, based on graph theory according to the following algorithm:

- 1. Create a directed graph from given distribution network edges and number of nodes [15].
- 2. Traverse the graph to find the depth-first search (DFS) discovery order [15], starting at each node in sequence as obtained from *down-stream-nodes*.
- 3. Find sending and receiving nodes of each element in the discovery order.
- Fill by ones in row equal element in the discovery order and columns equal the sending and receiving nodes of the *BN* connection matrix.

For bus *i*, the complex load *S_i* is expressed by:

$$S_i = (P_i + jQ_i), \quad i = 1 \dots N \tag{1}$$

Corresponding equivalent current injection at the *k*th iteration of solution is:

$$I_{i}^{k} = I_{i}^{r}(V_{i}^{k}) + jI_{i}^{k}(V_{i}^{k}) = \left(\frac{P_{i} + jQ_{i}}{V_{i}^{k}}\right)^{*}$$
(2)

where V_i^k and I_i^k are the bus voltage and equivalent current injection of bus *i* at *k*th iteration, respectively. I_i^r and I_i^i are the corresponding real and imaginary parts of the equivalent current injection.



Fig. 1. Equivalent current injection based model of distribution network.

The relationship between the bus current injections and branch current can be obtained by applying Kirchoff's current law (KCL) to the distribution network. For example the branch currents BC_1 , BC_2 and BC_5 in Fig. 1 can be expressed by equivalent current injections as:

$$BC_1 = I_2 + I_3 + I_4 + I_5 + I_6$$

$$BC_3 = I_4 + I_5$$

$$BC_5 = I_6$$
(3)

Therefore, the relationship between the bus current injections *I* and branch currents *BC* can be expressed as:

$$BC = \mathbf{BIBC} \times I \tag{4}$$

The algorithm for the construction of the **BIBC** matrix can be summarized in the following steps:

- 1. Initialize the **BIBC** matrix of dimension $B \times N 1$.
- 2. Create a directed graph from given distribution network edges and number of nodes [15].
- 3. Traverse the graph to find the depth-first search (DFS) discovery order [15], starting at receiving node of each edge in sequence as obtained from *down-stream-nodes*.
- 4. Fill by ones in row equal sending and of each edge and columns equal the discovery order of the **BIBC** matrix.

The relationship between branch currents and bus voltages can be obtained as follows:

$$V_2 = V_1 - BC_1 \times Z_{12}$$
(5a)

$$V_3 = V_2 - BC_2 \times Z_{23}$$
 (5b)

$$V_4 = V_3 - BC_3 \times Z_{34} \tag{5c}$$

where V_i is the voltage of bus *i*, and Z_{ij} is the line impedance between bus *i* and bus *j*. Substituting (5a) and (5b) into (5c), Eq. (5c) can be written as:

$$V_4 = V_1 - BC_1 \times Z_{12} - BC_2 \times Z_{23} - BC_3 \times Z_{34}$$
(6)

From (6), it can be seen that the bus voltage can be expressed as a function of branch current, line parameters and substation voltage. Similar procedures can be performed on other buses; therefore the relationship between branch currents and bus voltages can be expressed as:

$$\Delta V = \mathbf{B}\mathbf{C}\mathbf{B}\mathbf{V} \times BC \tag{7}$$

BCBV is a matrix reflecting the relationship between branch currents and bus voltages and based on Eq. (6). **BCBV** matrix as **BIBC** matrix can be developed based on the topological structure of distribution systems.

Combining Eqs. (4) and (7), the relationship between bus current injections and bus voltages can be expressed as:

$$\Delta V = \mathbf{BCBV} \times \mathbf{BIBC} \times I$$

$$\Delta V = \mathbf{DLF} \times I$$
(8)

DLF is a matrix reflecting the relationship between bus current injections and bus voltages. It is a multiplication matrix of **BCBV** and **BIBC** matrices and the solution for distribution network load flow can be obtained by solving the following equations iteratively

$$I_{i}^{k} = I_{i}^{r}(V_{i}^{k}) + jI_{i}^{i}(V_{i}^{k}) = \left(\frac{P_{i} + jQ_{i}}{V_{i}^{k}}\right)^{*}$$
(9a)

$$\Delta V^{k+1} = \mathbf{DLF} \times I^k \tag{9b}$$

$$V^{k+1} = V^0 + \Delta V^{k+1} \tag{9c}$$

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

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

The total power loss of the feeder *PF*_{Loss} is determined by summing up the losses of all line sections of the feeder, which is given by:

$$PF_{Loss} = \sum_{i=1}^{N-1} P_{Loss}(i, i+1)$$
(11)

The proposed algorithms of **BN**, **BIBC** and *down-stream-nodes* secure radial structure of the network and correct current flow direction through-over all reconfiguration phases.

3. 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, as in most of algorithms it will lead to an infeasible switching combination for network reconfiguration. The proposed method precludes infeasible switching combinations and secures the correct flow direction of branch currents by applying the developed algorithms of **BN**, **BIBC** and *down-stream-nodes*. The optimal switching strategies for network reconfiguration need to consider every candidate switch to evaluate the effectiveness of loss reduction. Such strategies require extensive numerical computation. In the present work, heuristic rules, based on algorithm of [13,16,20] are formed in conjunction with the developed load flow program to select the optimal switches that give the minimum power loss without searching all the candidate switches in the network. The developed methodology precludes creation of unconnected branches or forming closed loops.

The details of the proposed algorithm with heuristic rules are explained in the following: For the given radial network with all tie switches open, by running the load flow, the voltage difference $([\Delta V_{tie}], \text{ for } i = 1, 2, ..., N_{tie})$ across all of the open tie switches are computed. N_{tie} represents the number of tie switches. Then, the open tie switch from the vector ΔV_{tie} that has the maximum voltage difference of the detected tie switch is greater than a specified value, then that tie switch is considered first. Because, this switching (closing) of the tie switch will cause maximum loss reduction and improve system voltage profile [5]. In the next iteration, the same procedure is repeated for the remaining tie-switches and so forth. If, in any iteration, no power loss reduction, or this maximum voltage difference difference is set.



Fig. 2. 33-Bus initial configuration of the radial distribution system.

Table 1a

Optimal power loss in each loop, minimum node voltages of the tie switches and sectionalize switches open.

Tie switch (closed)	Minimum node voltages of the tie switches	Sectionalize switches open between nodes	Power loss (kW)
35	12	12-11	143.8143
		11–10	150.6952
36	33	33-32	148.3356
		32-31	140.4288
		31-30	142.3603
33	29	29-28	109.5909
		28-27	138.6274

ference 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 .

4. 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, 2.22-GHz computer with 1.99 GB RAM. The distribution network for reconfiguration consists of 33 buses and 5 tie lines. The normally open switches are 33, 34, 35, 36, and 37 represented by the dotted lines and normally closed switches 1 to 32 are represented by the solid lines as shown in Fig. 2. For this base case, the total loads at feeder head-section are 3932.9450 kW and 2448.2604 kVAr. The base network losses are 210.9931 kW. The line and load data of 33bus system are given [14]. Fig. 3 shows the network directed graph before reconfiguration.

The voltage differences across all tie switches are computed for the network shown in Fig. 2. 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. Now, if the tie switch 35 is closed, a loop will be formed. Opening of each branch in this loop is an option. In this algorithm, sectionalize branches are opened (to retain the radiality) either left or right of the selected tie switch based on the minimum voltage node of the tie switch. 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 (0.9177 p.u.) 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 switching is obtained till the power loss due to current switching is greater than the previous switching. In this loop, the first sectionalize branch (12-11) is opened as it is adjacent to the node 12 and power loss is computed (143.8143 kW). In same manner, next adjacent sectionalize branch 11–10 is opened and power loss is computed and shown in Table 1a. The optimal opening branch in the loop is between the nodes 12 and 11. Further opening of the branches beyond the branch 12-11 in the loop, is giving more power loss than the minimum already obtained at the branch 12-11. Hence, opening of the remaining branches 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 sectionalize 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. It is observed that the maximum voltage difference (0.0605 p.u.) occurs across the tie switch 36 and it is greater than the specified value (ε). The minimum voltage (0.9267 p.u.) node of the



Fig. 3. Network directed graph before reconfiguration.

Table 1b Simulation results.

	33-bus test system
Loss in the base configuration	210.9931 (kW)
Loss in the optimal configuration	109.5909 (kW)
Open switches in optimal configuration	34, 37, 11, 31, 28
Loss reduction	101.4022 (kW)
Loss reduction (%)	48.0689
CPU time	0.361408 s
Number of load flow runs	8

tie switch 36 is 33. Repeating the same procedure as in case of tie switch 35, the optimal radial configuration, as obvious from Table 1a for the second switching operation is obtained by closing the tie switch 36 and opening the sectionalize branch between the nodes 32 and 31.

Among the tie switches 33, 34 and 37, the voltage difference across the tie switch 34 is greater than remaining two. Therefore, the tie switch 34 is selected for the third switching operation as voltage difference (0.0283 p.u.) is greater than the specified value. The minimum voltage (0.9560 p.u.) node of tie switch 34 is 15. 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 34 and open the sectionalize branch between the nodes 15 and 14, however discarded due to increase of power loss.

For fourth switching operation, tie switch 33 is considered as the voltage difference (0.0258 p.u.) across it is greater than of tie switch 37 and it is also greater than the specified value. The minimum voltage (0.9471 p.u.) node of 33 is 29. In this case the optimal configuration, as obvious from Table 1a for the fourth switching operation is obtained by closing the tie switch 33 and opening the sectionalize branch between the nodes 29–28.

Since the voltage difference across the tie switch 37 is less than the specified value (0.0093 p.u.), 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 value of ε = 0.01 gives the satisfactory results.

The optimal radial configuration of the network after all the switching operations is shown in Fig. 4 in the form of directed graph. The proposed efficient load flow allowed reaching final configuration after three switching processes only. The number of all load flow runs required for the entire process is 8 Fig. 4.

Table 1a details optimal power loss, tie switches closed and sectionalize switches open. Table 1b shows the simulation results of the base configuration and the optimal configuration. The power loss before reconfiguration is 210.9931 kW and after reconfiguration is 109.5909 kW. From the results it is observed that reduction in power loss is 101.4022 kW which is approximately 48.0689%.

The voltage profiles before and after reconfiguration is shown in from Fig. 5. It is observed that the minimum voltage before reconfiguration is 0.9038 p.u. and after reconfiguration is 0.9463 p.u. This shows that the minimum voltage in the network is improved by approximately 5.0% after reconfiguration. Fig. 5 also compares the active flow along the network before and after reconfiguration, and the reactive flow along the network before and after reconfiguration.

4.1. A Comparison with other methods

The proposed method is compared with the methods proposed by Goswami [5], Mcdermott [6], Dolatdar [13], Srinivasa [16], Chun Wang [17], Gomes [18], and Kashem [19]. Method in [5] applied to the 33-bus test system [4] with loss minimization objective. The base system loss was 205.81 kW. Method in [6] applied to [4] system with two line voltage regulators added. The objective



Fig. 4. Network directed graph after reconfiguration.



Fig. 5. Network voltage profile, active and reactive power flow before and after reconfiguration.

was minimization of incremental losses divided by incremental load served. The base system loss was 202.68 kW. Method in [13] applied to [4] system with loss minimization objective. The base system loss was 211 kW from Newton Raphson load flow program and 194 kW when applying the author's adopted radial distribution load flow in complex mode (PAST program). Method of [16] applied to [4] system with loss minimization objective. The load at feeder head-section was 5084.26 + j2457.32 kVA and the base system loss was 205.81 kW. Method in [17] applied to [4] system with loss minimization objective. The load at feeder head-section was 3715 + j2300 kVA and the base system loss was 202.7 kW. Method in [18] applied to [4] system with loss minimization objective. The load at feeder head-section was 5058.25+j2547.32 kVA and the base system loss was 202.68 kW. Method in [19] applied to [4] system with loss minimization objective. The load at feeder head-section was 3715 + j2300 kVA and the base system loss was 210 kW. The base system loss in [13] obtained from PAST program is abnormally different from those given by most of the researchers. However, Dolatdar [13] himself recognized base system loss very close to ours when using Newton Raphson load flow algorithm. Also irrespective of differences in load at feeder head section in [15,18] from one side and [17] from the other side the base system losses are close. The load flow algorithm presented in this paper gives same base system loss as from Newton Raphson.

For effective comparison, the results of the proposed method along with other methods are shown in Table 2. The saving in total loss by the proposed method is higher than all other methods

Table 2
Comparison proposed method with other methods using 33-bus system data.

Method	Final open switches	Total loss savings (%)	CPU Time (s)
Proposed	34,37, 11, 31, 28	48.07	0.361408
Srinivasa [16]	33, 14, 8, 32, 28	33.02	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
Dolatdar [13]	2, 10, 8, 36, 25	61.08*	NA

^{*} Load flow output is completely different from those reported by most of the researchers.

except of Dolatdar [13] where base system loss is abnormally different from those given by most of the researchers. The CPU time taken by the proposed method is less than Srinivasa's [16], and Chun Wang's methods [17], half the time of Goswami method [5], 4 to 5 times less than the Gomes [18] and Mcdermott [7] methods and much less than the Kashem method [19]. The number of load flows required to get the optimum solution by the proposed algorithm is only 8, whereas it is 26 in case of Srinivasa [16] and 29 for the case of Baran and Wu [4]. Since the test case system is small (33 buses) and above results are obtained on 12 years time span the CPU time differences may be understood to be due to development in computers. However, some percent of CPU time difference is only due to this reason, recalling that the proposed algorithm gives the optimum solution with a few numbers of load flow runs (8 compared to 26 runs in Ref. [16]). Therefore, this method can be effectively used in real time application of the large distribution system under widely varying load conditions, where the CPU time will be a major point of comparison.

5. Conclusions

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. The developed load flow follows changes in system structure by creating directed graph for the distribution network in each reconfiguration phase, thus avoiding creation of unconnected branches or forming closed loops. 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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