Electric Power Systems Research 78 (2008) 1953–1958

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A new heuristic approach for distribution systems loss reduction

Juan Andrés Martín[1], Antonio José Gil*

Department of Electrical Engineering, University of Cádiz, Escuela Politécnica Superior de Algeciras, Avda. Ramón Puyol, s/n, 11202 Algeciras (Cádiz), Spain

ARTICLE INFO

Article history:
Received 24 April 2007
Received in revised form 10 January 2008
Accepted 8 April 2008
Available online 27 May 2008

Keywords:
Reconfiguration
Heuristics
Distribution systems
Switching operations
Loss minimization

ABSTRACT

This paper presents a new approach to solve the reconfiguration problem by a switching operation in order to reduce the power loss of distribution systems. By using the proposed heuristic technique, based on the direction of the branch power flows, a better network configuration is obtained. This reconfiguration algorithm starts with a radial topologic by opening all tie switches. At each step, after a normally open switch is closed, the heuristic procedure establishes the switching-options significantly reducing (in most cases) the number of candidate branches to be opened within a loop. Finally, the choice of the most effective switching-option for loss minimization is obtained from the calculation of a few power flows. The solution procedure is illustrated on a simple example and several test systems used by others authors are included to demonstrate the effectiveness of the proposed method. The results obtained are satisfactory and show that the method is very robust, in spite of its simplicity.

1. Introduction

In distributions systems, switches are used for both protection, to isolate a fault and for configuration management, to reconfigure the network. The network reconfiguration can be oriented to different objectives. Under normal operating conditions, the network is reconfigured to reduce the losses of the system and/or to balance load in the feeders. While distribution systems are structurally meshed, they are normally operated as radial networks; however, changing the state of network switches changes configuration during operation.

As consumer demands vary with time, each type of load has a different time profile and each feeder serves a different set of loads, then the load pattern on each feeder varies constantly, and with a different variation on each feeder. The operating conditions change can be used to minimize, or at least reduce the system losses by reconfiguring the system from time to time.

This would not only improve the operating conditions of the system, but it would also be used in planning studies, service restoration and distribution automation when remote-controlled switches are employed.

Combinatorial nature of the non-linear and discrete problem, with large number of integer and continuous variables, has led researchers to explore heuristic solution techniques, because they can be easily implemented. As well as this, they also are suitable for real-time applications. If it is intended to determine an optimal solution, a method of discrete optimization can be used. Nevertheless, the time in computational resources is too high and thus, impractical. On the other hand, methods based on heuristic techniques allow to find a viable solution with a limited requirement of CPU time, so they are more adequate to be used in on-line processes. Although, heuristic techniques are simpler and faster, in general, these methods converge to a local optimum and no convergence to a global optimum is guaranteed.

Merlin and Back [1] introduced the concept of distribution system reconfiguration for system loss reduction. Later, several reconfiguration techniques for power loss reduction have been proposed, which can be grouped into different categories: blend optimization and heuristic techniques [2–5], purely heuristic techniques [6–8] and finally, techniques based on artificial intelligence [9,10].

Unlike Merlin and Back, Civanlar et al. [6] were the first to suggest a purely heuristic algorithm, based on a branch exchange, using a simple formula to determine if a particular switching operation would increase or reduce system losses.

A different method has been proposed by Baran and Wu [7] to identify the branches to be exchanged using a heuristic approach, which searches over relevant spanning trees systematically.

Based on the methods described above, several improved works have been suggested [11–14], which use either branch exchange [11,12] or sequential switch opening [13,14]. However, McDermott et al. [8] proposed a heuristic constructive algorithm that starts

---

* Corresponding author. Tel.: +34 956 028 015; fax: +34 956 028 001.
E-mail addresses: juanandres.martin@uca.es (J.A. Martín), antonio.gil@uca.es (A.J. Gil).

[1] Tel.: +34 956 028 167; fax: +34 956 028 001.

0378-7796/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2008.04.001

with all manoeuvrable switches opened, and at each step a switch is closed.

Recent works on distribution systems reconfiguration for loss minimization, using heuristic algorithms are described in [15,16]. Heuristics are applied in most cases to reduce the number of switching-options considered. Even so, approximate loss formulas, linearized costs, and other simplifying assumptions are typically used to avoid repetitive solution of system load flows.

In this paper, an efficient method for solving the reconfiguration problem in distribution systems under normal operation to reduce active losses is developed. This new heuristic approach is based on the direction of power flows through the branches of the network, that is, it takes into account the direction of the real and reactive power flowing in each line. Throughout this paper, the discussion will be focussed on feeder reconfiguration by closing a single tie switch and opening a single sectionalizing switch to preserve radiality of the two feeders that are under consideration. As only one loop at a time is considered, the switch to be opened (for opening the loop) can be selected properly every time because it corresponds to the actual operating condition. At each step, the heuristic procedure establishes the switching-options significantly reducing (in most cases) the number of candidate branches to be opened within the loop. The choice of the most effective switching-option for loss minimization is obtained from the calculation of a few power flows, however, it does not ensure that the total number of power flow computations are minimized. The effectiveness of the method is demonstrated by several test systems used by others authors in the technical literature, which provide strict test conditions.

The contents of this paper are briefly outlined below. Section 2 presents the proposed heuristic technique. In Section 3, the algorithm used to solve the reconfiguration problem is developed. Numerical examples are discussed in Section 4. Finally, the conclusions are exposed in Section 5.

2. Proposed heuristic technique

Considering a direct current (DC) network with a loop, this one can be represented by a directed graph based on the direction of the branch power flows, as it is shown in Fig. 1a. It can be seen that only one load is supplied by two feeders, that is, only one node of the directed graph has in degree equal to two (the number of edges entering in this node is two). The goal is to find the radial configuration that will cause minimum resistive line losses.

An equivalent radial network to the meshed can be obtained by dividing the doubly fed load, as it is represented in Fig. 1b.

The above configuration is not allowed, although it is the radial configuration that causes minimal losses. Note that is necessary to break the node (breakpoint) into two end nodes, one for each feeder, for obtaining that configuration. A switch must be opened to restore the radial configuration. For this reason, as there is only one load in the loop which is fed by the two feeders, and it cannot be partitioned, then it is clear that the breakpoint must be the end node of one feeder. In this way, the direction of the branch power flows is the same both in the optimal radial network and in the initial meshed network. This significantly reduces the number of relevant candidate branches for realistic networks, because only two candidates for each loop must be considered and they are the branches entering in the breakpoint.

The decision about whether the load is transferred to one or another feeder is made depending upon the obtained results from the two radial network's power flow solutions.

An alternating current network (AC) with a loop is considered now for generalizing the considerations previously exposed for a DC network. The main difference with regard to a DC network is that in an AC network there are an active power flow and a reactive power flow. To deal with this drawback, the branch power flows of the AC network are represented by two directed graphs, one based on the direction of the branch active power flows (*P*-directed graph), and another one based on the direction of the branch reactive power flows (*Q*-directed graph), as it is shown in Fig. 2a and b, respectively.

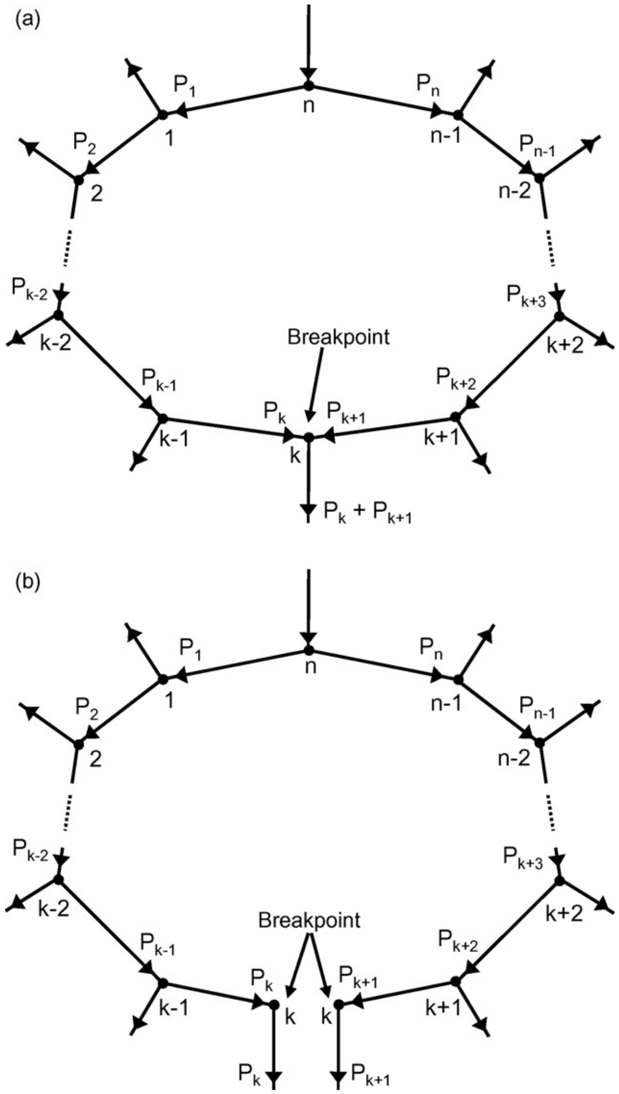

Fig. 1. Directed graph of a DC network. (a) Single loop network and (b) equivalent radial network.

It can be appreciated that two breakpoints appear: the *P*-breakpoint (the node of the *P*-directed graph which has in degree equal to two) in Fig. 2a and the *Q*-breakpoint (the node of the *Q*-directed graph which has in degree equal to two) in Fig. 2b.

According to DC problem, the two branches entering in the *P*-breakpoint will be the candidate branches to consider, and one of them will be the branch that minimizes the resistive line losses due to active line currents. Just the same way, one of the two branches entering in the *Q*-breakpoint will be the branch that minimizes the resistive line losses due to reactive line currents. Taking into account that the total resistive line losses in a network is equal to the sum of the resistive line losses due to both active and reactive line currents, three different cases can be addressed.

2.1. *Case I: P-breakpoint and Q-breakpoint are the same node*

In this case, only two candidates for the loop must be considered and they are the branches entering in the breakpoint as it is shown in Fig. 3. This is the most favourable case and it usually happens when realistic networks are considered.

2.2. *Case II: P-breakpoint and Q-breakpoint are different nodes*

Now, the candidate branches are the collection of the following branches, as it is shown in Fig. 4: the branches entering in the *P*-breakpoint, $\{k-2, k-1\}$; the branches entering in the *Q*-breakpoint, $\{k+1, k+2\}$ and the branches of the path between the two breakpoints, $\{k-1, k, k+1\}$. So, in this case the set of candidate branches are $\{k-2, k-1, k, k+1, k+2\}$. Note that the path which has not the root node has been chosen, because in the branches of that path the power flows have the opposite direction.

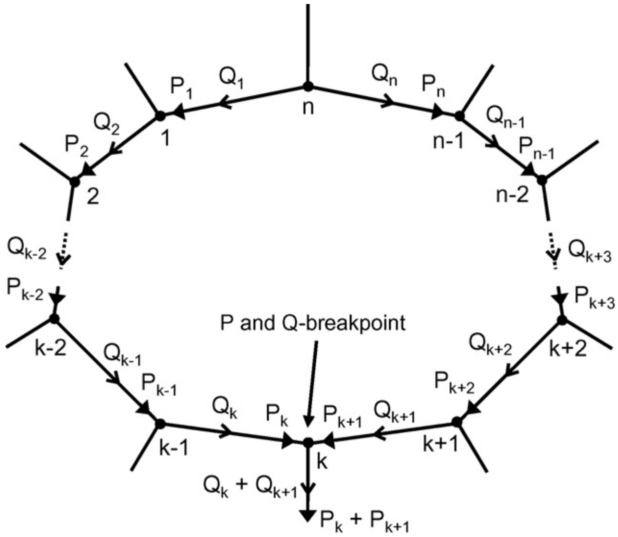

Fig. 3. *P*-breakpoint and *Q*-breakpoint are the same node.

2.3. *Case III: multiple Q-breakpoints*

In this particular case, the candidate branches are all those between the two extreme breakpoints in the path (which has not the root node of the single loop), $\{k-1, k, k+1\}$ and the branches entering in the extreme breakpoints $\{k-2, k+2\}$. So, in this case the set of candidate branches are $\{k-2, k-1, k, k+1, k+2\}$, as it is shown in Fig. 5. This case takes place when capacitor banks are connected to the system.

The following comments about the algorithm can be noted:

- In cases I and II, it is not necessary to look for any loop in the network, because only branches entering and between breakpoints are considered. In these cases, it is only necessary to look for the breakpoint, and this task is implemented using the branch-node incidence matrix of the directed graph of the electrical network, once the power flow has been solved. However, when the effects of the shunt capacitors have not been neglected (case III) it is necessary to look for the single loop in the system, in order to identify the extreme breakpoints.
- The 'radiality' and connectivity are always ensured, because the candidate branches are in the loop.

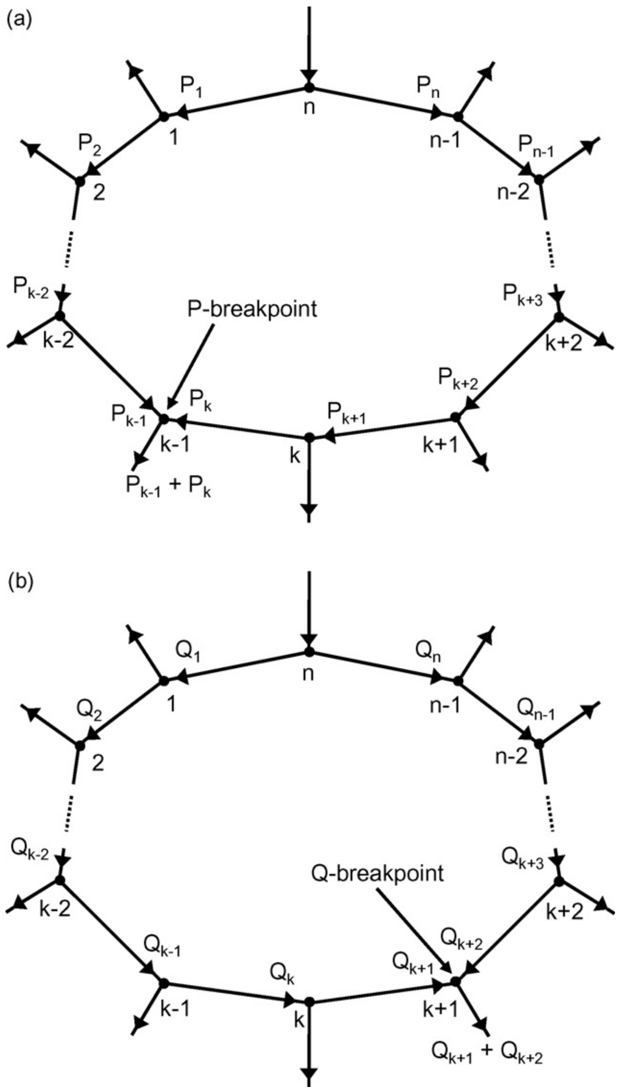

Fig. 2. Directed graphs of an AC network. (a) *P*-directed graph and (b) *Q*-directed graph.

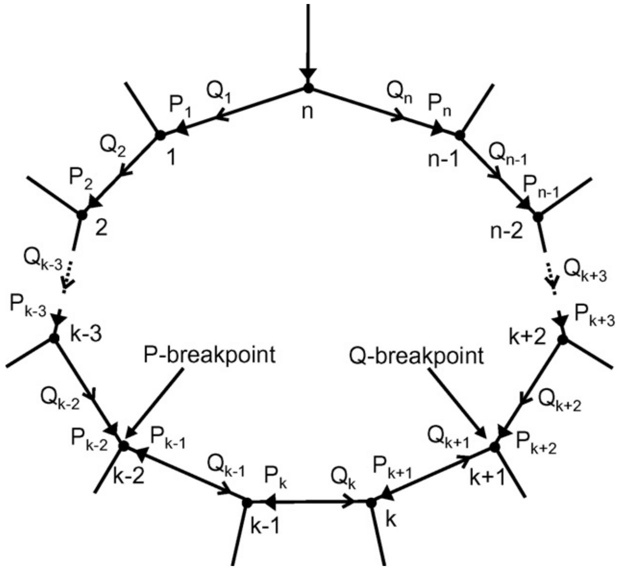

Fig. 4. *P*-breakpoint and *Q*-breakpoint are different nodes.

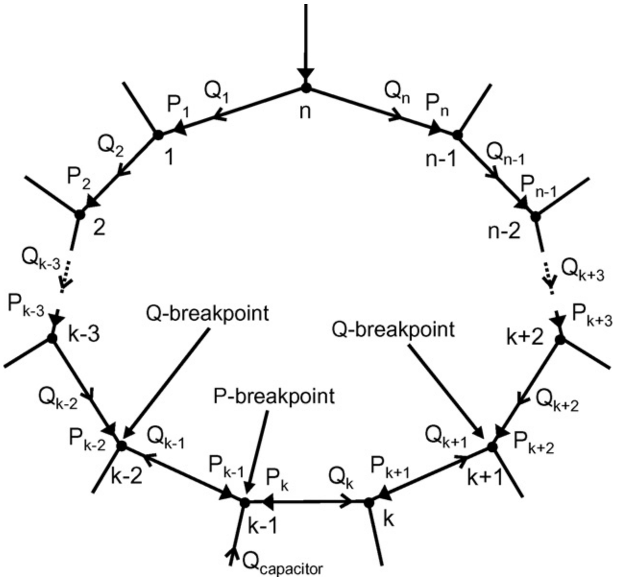

Fig. 5. Multiple *Q*-breakpoints.

- In cases II and III, the number of radial power flows calculations is greater than in case I, because the number of candidate branches is larger.

3. Algorithm description and example system

The proposed algorithm starts from a radial network with *k* tie-lines initially opened, it closes only one switch at a time to introduce a mesh in the system and it comes back to the radial configuration by opening the same or a different switch of the loop depending upon the results obtained.

The complete algorithm constitutes simply in making exchanges among each of the open switches and the corresponding candidate branches in the loop, which were identified in the above section.

An exchange operation is defined as the action to close an open switch and to open a closed switch in the loop formed. For each loop, the number of operations performed is equal to the number of candidate branches. For each configuration thus obtained, the total losses are determined. The configuration that has resulted in the smallest losses is chosen. This iterative procedure is repeated until the radial configuration obtained is the same *k*-times consecutively.

The steps of the algorithm are the following.

Step 1 Generate a LIST of *k* tie-lines initially opened and set REPETITIONS equal to zero.
Step 2 Close next switch *i* of the LIST.
Step 3 Calculate a power flow, taking into account that all the loops that are not being analysed remain radial, but are included in the load flow solution. Obtain the *P*-breakpoint and *Q*-breakpoint. If it is necessary (case III), look for the loop to identify the extreme breakpoints. Finally, select the candidate branches.
Step 4 For each switch *j* of the candidate branches
- open switch *j*,
- calculate a radial power flow,
- determine and save the total losses in the network,
- close switch *j*.

Step 5 Open the switch *m* that has resulted in the smallest losses.
Step 6 If switch *i* is the same than switch *m* then REPETITIONS is increased by one; if not, REPETITIONS is set to zero and the LIST is updated (switch *i* = switch *m*).
Step 7 If REPETITIONS is less than the length of the LIST (*k*) then the algorithm returns to Step 2; if not, the process ends.

Consider the small distribution network of Fig. 6 found in the literature [4], consisting of three radial feeders connected at the root node, with 13 sectionalizing switches and three tie switches. Initially, open switches are represented by dotted lines, and closed switches by straight lines. It can be seen from Fig. 6 that the network is initially configured radial with all tie switches open, which, if all closed, can form three independent loops.

Now, the example distribution system in Fig. 6 is used to illustrate how the algorithm works.

Step 1 Initially, the open switches are s14, s15 and s16. So LIST = {s14, s15, s16} and REPETITIONS is set to zero.
Step 2 The next switch, s14, is closed.
Step 3 A power flow and the breakpoints are calculated. In this case, node 7 is the *P*-breakpoint and nodes 6 and 7 are the *Q*-breakpoints. Thus, the candidate branches are: s5, s6 and s8.
Step 4 A radial power flow and the total power losses are calculated for each network configuration. If s5 is opened the losses are 1.346886 MW. On the other hand, for s6 and s8 the losses are 0.707749 and 0.493154, respectively.
Step 5 Switch s8 is chosen to be opened because is the one that provides the smallest losses in the system.
Step 6 REPETITIONS is set to zero because switch s8 is not the switch that was closed in Step 2 and LIST is updated.
Step 7 As REPETITIONS = 0, then the procedure is repeated, starting from Step 2 and with the updated LIST = {s8, s15, s16}.

In Table 1, the results obtained when the algorithm is executed are shown. Results for each iteration of the algorithm appear in rows, while in columns the information corresponding to each step of the algorithm is represented. The radial configuration obtained from the previous iteration is shown in the second column. Initially, it corresponds with all open tie-switches. In the following columns, the branch to be closed so as to create a loop, the breakpoints obtained when closing the branch, candidate branches and their corresponding losses are shown, respectively. Finally, the number of consecutive times that the selected branch like the best solution coincides with the branch that was closed to form the loop (value of variable REPETITIONS), is shown in the seventh column. When REPETITIONS is equal to 3 the algorithm stops as it is seen in Table 1.

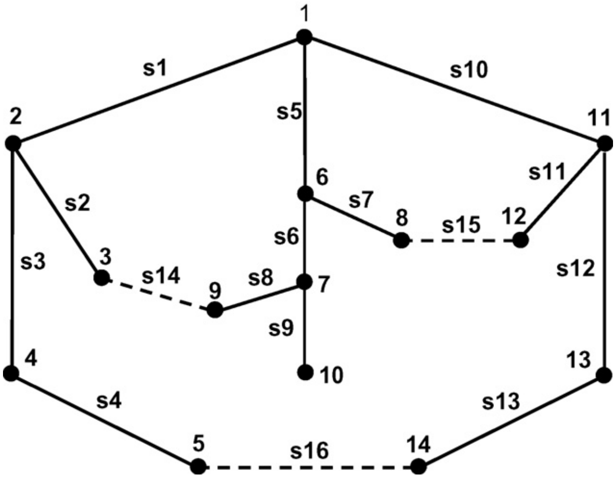

Fig. 6. 14-Bus test system.

Table 1
Results of the iterative procedure for the network of Fig. 6

Iter.	LIST	Branch to close	Breakpoint		Candidate branches	Losses (MW)	Rep.
			P	Q			
1	s14, s15, s16	s14	7	6, 7	s8 s6 s5	0.493154 0.707749 1.346886	0
2	s8, s15, s16	s15	6	6	s7 s5	0.466127 1.334326	0
3	s8, s7, s16	s16	5	2, 5, 11, 13	s16 s4 s13 s12 s3 s10 s1	0.466127 0.479291 0.492832 0.524912 0.531118 0.697460 0.975079	1
4	s8, s7, s16	s8	7	6, 7	s8 s6 s5	0.466127 0.705026 1.180735	2
5	s8, s7, s16	s7	6	6	s7 s5	0.466127 1.334326	3

Iter.: iteration, Rep.: REPETITIONS.

In this example, the final radial configuration has already been reached by the third iteration. The reason why more iterations are necessary is because a change in a loop alters the flow pattern in the network.

The number of iterations that are necessary to get the result is influenced by the order with which the meshes are considered. The attained solution also is influenced by this matter. In this aspect, simulations with different systems have been performed, changing the order of execution of the closing operations. For each investigated system (considering different initial orders) different final solutions have been reached. The power loss reductions corresponding to these solutions are identical or very similar. In this particular example, it has been found that the final configuration obtained is the same in all possible different initial orders.

4. Test results and discussion

In this section, four test cases are discussed using the networks presented by Baran and Wu [7], Chiang and Jean-Jumeau [3], Das [10] and Su and Lee [17] and Su et al. [9]. The numbering of branches and nodes coincides with the numbering used in the aforementioned references. The proposed method was implemented using MATLAB v 6.5. The CPU timings were obtained using an AMD Turion 64, 1.6 GHz computer with 1024 Mb of RAM.

For these test cases, the initial order chosen to form the loops has been based upon the following criteria: switch having “minimum branch index” is closed first. In all test cases, it has been found that the final configuration obtained is the same in all possible different initial orders.

4.1. *Baran and Wu test system [7]*

This system has 33 buses, 37 branches and 5 tie-lines. The normally open switches are s33, s34, s35, s36 and s37. For this case, the initial losses are 202.68 kW. The proposed heuristic procedure opens branches s7, s9, s14, s32 and s37. With this configuration the losses are 139.55 kW. This solution is identical to those obtained by a number of approaches available in the technical literature. Table 2 shows the results obtained using the proposed method. Table 3 shows that the time taken by the procedure is only 0.41 s and it requires 38 load flow solutions. Of these solutions, 29 radial power flow solutions are required and it is only necessary to find the power flow solution of 9 meshed networks with only one loop.

4.2. *Chiang and Jean-Jumeau test system [3]*

This test system has 69 buses, 73 branches and 5 tie-lines. The normally open switches are s69, s70, s71, s72 and s73. For this case, the initial losses are 20.88 kW using the system data given in [3,18]. The proposed heuristic procedure opens branches s14, s58, s61, s69 and s70. With this configuration the losses are 9.43 kW. This solution has also produced the same efficient configuration when compared with a number of approaches available in the technical literature. Table 2 shows the results obtained using the proposed method. In this case, the time taken by the procedure is only 0.69 s and it requires 58 load flow calculations, as it is shown in Table 3.

4.3. *Das test system [10]*

This network is taken from Ref. [10]; it has 69 buses, 79 branches and 11 tie-lines. In the initial configuration the branches s69 to s79

Table 2
Results provided by the proposed algorithm for the test systems

Test system	Initial losses (kW)	Final losses (kW)	Saving (%)	Open switches
Baran and Wu [7]	202.68	139.55	31.1	s7, s9, s14, s32, s37
Chiang and Jean-Jumeau [3]	20.88	9.43	54.8	s14, s58, s61, s69, s70
Das [10]	227.53	203.86	10.4	s13, s28, s45, s51, s67, s70, s73, s75, s76, s78, s79
Sue and Lee [17]	711.73	624.81	12.0	s7, s13, s34, s39, s42, s55, s62, s72, s83, s86, s89, s90, s92

Table 3
Test systems characteristics, load flows and CPU times

Test system	Buses/loops	No. of load flows		CPU time (s)
		Meshed	Radial	
Baran and Wu [7]	33/5	9	29	0.41
Chiang and Jean-Jumeau [3]	69/5	15	43	0.69
Das [10]	69/11	25	58	0.98
Sue and Lee [17]	84/13	39	94	1.73

are opened. For this test, the initial losses are 227.53 kW. The configuration obtained by the proposed heuristic method has branches s13, s28, s45, s51, s67, s70, s73, s75, s76, s78 and s79 opened. With this configuration the losses are 203.86 kW. This solution has produced a better configuration when compared with the configuration suggested by Das [10] (branches s14, s28, s39, s46, s51, s67, s70, s71, s73, s76 and s79 opened) whose losses are 205.07 kW. Table 2 shows the results obtained using the proposed method. It can be seen from Table 3 that in this case, the time taken by the procedure is only 0.98 s and it requires 83 load flow calculations.

4.4. Su and Lee test system [17] Su et al. [9]

This system is a practical distribution network of the Taiwan Power Company (TPC). It is taken from Refs. [9,17], and it consists of 11 feeders, 83 normally closed switches, and 13 normally open switches (84 buses, 96 branches and 13 tie-lines). The original configuration has branches s84 to s96 opened. For this case, the initial losses are 711.73 kW. The configuration obtained by the proposed heuristic method has branches s7, s13, s34, s39, s42, s55, s62, s72, s83, s86, s89, s90 and s92 opened. With this configuration the losses are 624.81 kW. This solution has produced a better configuration when compared with the configuration suggested in Refs. [9,17] (branches s7, s13, s34, s39, s41, s55, s62, s72, s83, s86, s89, s90 and s92) whose losses are 626.45 kW. Table 2 shows the results obtained using the proposed method. In this case, the time taken by the procedure is only 1.73 s and it requires 133 load flow calculations, as it is shown in Table 3.

5. Conclusion

A new heuristic algorithm has been presented in this paper in order to minimize the total power losses in distribution systems. The proposed algorithm is based on the direction of the branch power flows. Several tests have been performed, and the results have shown that global or very close to global optimum solutions for the system losses have been attained. These solutions have produced equal or more efficient configurations when compared with a number of approaches available in the technical literature.

The simulations on several small size systems have proved the feasibility of the proposed approach. The obtained results are quite good and they encourage the implementation of the strategy on large size networks.

Acknowledgements

The authors thank Ms. M. Molina Gutiérrez for her improvement of the English text. Finally, the authors are very grateful for the useful comments and suggestions offered by reviewers.

References

[1] A. Merlin, H. Back, Search for a minimal-loss operation spanning tree configuration in an urban power distribution system, in: Proceedings of the Fifth Power Systems Computation Conference, Cambridge, UK, 1975, pp. 1–18.
[2] D. Shirmohammadi, H.W. Hong, Reconfiguration of electric distribution networks for resistive line loss reduction, IEEE Trans. Power Deliv. 4 (4) (1989) 1492–1498.
[3] H.D. Chiang, R.M. Jean-Jumeau, Optimal network reconfiguration in distribution systems. Part 2. Solution algorithms and numerical results, IEEE Trans. Power Deliv. 5 (1990) 1568–1574.
[4] S.K. Goswami, S.K. Basu, A new algorithm for the reconfiguration of distribution feeders for loss minimization, IEEE Trans. Power Deliv. 7 (3) (1992) 1484–1491.
[5] F.V. Gomes, S. Carneiro Jr., J.L.R. Pereira, M.P. Vinagre, P.A.N. Garcia, L.R. De Araujo, A new distribution system reconfiguration approach using optimum power flow and sensitivity analysis for loss reduction, IEEE Trans. Power Syst. 21 (4) (2006) 1616–1623.
[6] S. Civanlar, J.J. Grainger, S.S.H. Le, Distribution feeder reconfiguration for loss reduction, IEEE Trans. Power Deliv. 3 (1988) 1217–1223.
[7] M.E. Baran, F.F. Wu, Network reconfiguration in distribution systems for loss reduction and load balancing, IEEE Trans. Power Deliv. 4 (2) (1989) 1401–1407.
[8] T.E. McDermott, I. Drezga, R.P. Broadwater, A heuristic nonlinear constructive method for distribution system reconfiguration, IEEE Trans. Power Syst. 14 (2) (1999) 478–483.
[9] C.T. Su, C.F. Chang, J.P. Chiou, Distribution network reconfiguration for loss reduction by ant colony search algorithm, Electr. Power Syst. Res. 75 (2–3) (2005) 190–199.
[10] D. Das, A fuzzy multi objective approach for network reconfiguration of distribution systems, IEEE Trans. Power Deliv. 21 (1) (2006) 202–209.
[11] C.A. Castro Jr., A.A. Watanabe, An efficient reconfiguration algorithm for loss reduction of distribution systems, Electr. Power Syst. Res. 19 (2) (1990) 137–144.
[12] G.B. Jasmon, L.H. Callistus, C. Lee, A modified technique for minimization of distribution system losses, Electr. Power Syst. Res. 20 (2) (1991) 81–88.
[13] A. Augugliaro, L. Dusonchet, S. Mangione, An efficient greedy approach for minimum loss reconfiguration of distribution networks, Electr. Power Syst. Res. 35 (3) (1995) 167–176.
[14] W.M. Lin, H.C. Chin, A new approach for distribution feeder reconfiguration for loss reduction and service restoration, IEEE Trans. Power Deliv. 13 (3) (1998) 870–875.
[15] V.N. Gohokar, M.K. Khedkar, G.M. Dhole, Formulation of distribution reconfiguration problem using network topology: a generalized approach, Electr. Power Syst. Res. 69 (2–3) (2004) 304–310.
[16] F.V. Gomes, S. Carneiro Jr., J.L.R. Pereira, M.P. Vinagre, P.A.N. Garcia, L.R. Araujo, A new heuristic reconfiguration algorithm for large distribution systems, IEEE Trans. Power Syst. 20 (3) (2005) 1373–1378.
[17] C.T. Su, C.S. Lee, Network reconfiguration of distribution systems using improved mixed-integer hybrid differential evolution, IEEE Trans. Power Deliv. 18 (3) (2003) 1022–1027.
[18] H.C. Chang, C.C. Kuo, Network reconfiguration in distribution systems using simulated annealing, Electr. Power Syst. Res. 29 (3) (1994) 227–238.