Reconfiguration of Distribution Systems for Loss Reduction using Tabu Search

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Abstract - This work proposes a Tabu Search algorithm for the reconfiguration of distribution systems for minimizing the real power losses. A new characterization of the neighborhood structure avoids the exploration of an excessive number of configurations, thus reducing the computacional effort without reducing the quality of the generated configurations. Results are presented for realistic systems with 135 and 202 buses.

1 Introduction

IN most cases, distribution systems are operated radially, in order to avoid protection coordination problems and to reduce short-circuit currents. However, the radial structure itself can lead to other operating problems, such as the lack of alternative power supply paths in case of contingencies, where consumers may be deprived from the electric energy service after the fault identification and isolation. In practice, distribution systems are actually meshed, even though they are still operated radially. Therefore, it is possible to change the system topology by transferring load buses from one feeder to another by opening/closing appropriate switches, so that the radial structure is maintained. This bus transfer process is often referred to as *feeder reconfiguration*.

Feeder reconfiguration is carried out to meet many different objectives, as for example the service restoration to dark areas, the minimization of real power losses, or the load balancing among feeders. Therefore, performing a reconfiguration may provide solutions for emergency situations as well as conditions to increase reliability, quality, and security levels of operation. Usually, the feeder reconfiguration problem can be defined as an optimization problem, consisting of finding a configuration that maximizes/minimizes a certain objective function. Among the many possible objective functions are minimizing the real power losses and minimizing the feeder load imbalance. This is a very difficult problem to be solved, since the number of candidate configurations grows exponentially with the number of available tie switches, leading to a combinatorial explosion and an impractical computational effort to achieve the best configuration. The radiality constraint is of difficult mathematical representation. The problem can be classified as a nonlinear mixed integer programming problem with combinatorial explosion.

Several papers on network reconfiguration have been introduced in the last years. Civanlar *at al.* [6] developed a simple expression for the total real power losses variation in a radial network. Heuristic rules to reduce the number of switching options to be considered were used. In Shirmohammadi and Hong [4] the minimum real power losses for radial networks was obtained by a sensitivity index "Optimum Flow Pattern" (OFP). The OFP is computed on a purely resistive distribution network, neglecting the reactive components of the branch impedances, after closing all switches.

In Goswami and Basu algorithm [5] the concept of the OFP was also used, however switches are closed to form one loop at a time. Thus, one tie-line is closed and, with the information of the OFP vector, one switch of the loop is opened to restore the radial structure.

The reduction of real power losses for a three-phase distribution system using *simulated annealing* was proposed in [7]. Simulated annealing algorithms are based on the idea of the simulation of a metal solidification process. The slow cooling of a metal is simulated in such a way that the system goes to an equilibrium point characterized by a stable, ordered structure. The variables associated to the problem are disturbed randomly and the configuration corresponding to the best objective function after each disturbance is stored. The temperature is then reduced (*annealing*) and the process is repeated. This procedure continues until the variables scape from the attraction region of a local minimum . At the end of the process, it possible that a global minimum has been achieved [8].

In [12] a genetic algorithm was used in a reconfiguration method for the reduction of real power losses. The genetic algorithm consists of the simulation of alive beings' natural evolution, where only the strongest or more addapted to the environment survive. Therefore the proposed solutions (or configurations) of good quality have a larger probability of prevailing and generating offsprings.

In this work, feeder reconfiguration is considered as a way to minimize the real power losses of distribution systems. Also, the use of a Tabu Search (TS) algorithm to carry through the reconfiguration to minimize the real power loss is proposed. TS is a metaheuristic procedure, first proposed by Fred Glover [1]. Basically, it consists of managing a local search heuristic algorithm in order to avoid local optimum solutions using many different strategies. TS algorithms lead to a series of configuration transitions in the search space and the best neighbor solutions are stored.

A TS algorithm with short term memory and an aspiration criterion was implemented in this paper. A series of transitions in search space are determined. Also, the visited configurations remain forbidden for a certain number of iterations. Actually, the attributes associated to each visited solution are stored only, which results in significant memory gains and reduction of the computational effort. The attributes are stored in a tabu list, and the number of iterations for which the attribute remains forbidden must be set in the algorithm. The process of storing the attributes has many advantages, however it can also refuse a good quality configuration because it bears a forbidden attribute. The solution for this problem consists of eliminating the prohibition in case the visited configuration presents the desired characteristics through an aspiration criterion.

The output of the proposed algorithm consists of a set of good quality candidate configurations. A significant real power loss reduction was obtained for all simulated systems. Sometimes certain switching operations determined by the algorithm cannot be taken into effect, due to operational problems. Therefore, it seems interesting for the system operator to choose one out of a number of good quality configurations. Results for realistic systems with 135 [11] and 202 buses [10] are presented and discussed.

2 TABU SEARCH: BASIC CONCEPTS [2], [13]

Tabu Search as described by Fred Glover [1] is "a metaheuristic superimposed on another heuristic". The basic approach aims to avoiding being trapped in cycles by forbidding or penalizing moves which take the solution, in the next iteration, to points in the solution space which were previously visited .

The algorithm consists of moving from a current solution a next solution until a stopping condition is met. Each solution $x \in X$ is associated a neighboorhood $N(x) \subset X$, and each neighbor solution $x' \in N(x)$ is reached from x by an operation called *move*.

TS can be compared to a descent method, where the objetive is the minimization of an objetive function $f\,(x)$). The method only allows moves to neighbor solutions that improve the objective function, and stops when solutions that improve $f\,(x)$ are no longer found. The basic steps of a descent method is outlined below.

(1) Choose an initial solution $x \in X$

(2) Find $x' \in N(x)$ such that $f\,(x') < f\,(x)$

(3) If none of the neighbor solutions reduce $f\,(x)$, then x is a local optimum. Stop.

(4) Else, x' with the smallest $f\,(x)$ is set as a new initial solution. Go to step **(2)**.

Generally speaking, TS algorithms solve problems formulated as follows.

$$\begin{array}{ll} \min & f\,(x) \\ \text{s.t.} & x \in X \end{array} \qquad (1)$$

where x is a solution (or a decision variable), $f\,(x)$ is objective function and X is the search space.

There is a great variety of optimization problems that can be represented as a minimization problem involving an objetive function and constraints. In the case of the reconfiguration of distribution networks, for example, the maintenance of the radial topology is the most difficult constraint to be represented in mathematical form. The TS algorithm solves this problem with an appropriate codification of the solutions.

The TS algorithm solves problem (1) by carrying out a heuristic local search procedure, where, for an initial solution x a neighbor of x is defined as the set of all solutions $x' \in N(x)$ that can be reached by a transition mechanism applied to x. The conditions required for x' to be a neighbor of x is defined by the neighbor structure of x. In the local search algorithm, a move is taken from de current solution to the neighbor solution with the largest reduction in the objective function. The iterative procedure is interrupted when solutions that improve the objective function are no longer found. This means that a local optimum has been reached.

The TS algorithm is different from a local search algorithm regarding two fundamental aspects:

- The best neighbor solution may be of worse quality than the current solution, which means that a degradation in the quality of the objective function can be accepted.

- The set of neighbors of x is not characterized in a static way. Thus, the algorithm defines a new neighbor structure N^* that varies dynamically in structure and dimension along the optimization process. This strategy allows the TS algorithm to carry through an efficient and intelligent search, which can taken the following forms.

  - A tabu list is used to store the attributes of solutions considered tabu (forbidden). In this case $N^*(x) \subset N(x)$ since some neighbors defined for the neighborhood structure and whose attributes belong to tabu list are forbidden. This strategy avoids the return to solutions that were already visited, thus avoiding cycling situations.
  - The use of strategies to decrease the neighborhood or the candidate solutions list.
  - The use of elite solutions and *path relinking* to find new candidate solutions.
  - To define the set $N^*(x)$ during the optimization process.

3 Representation and codification of the problem

The distribution network reconfiguration problem will be analyzed in this Section. The systems studied in this work may present the following characteristics.

- It is assumed that there is a sectionalizing switch in each branch of the network, and

- The command for the opening of the switches is carried through vector ch. Vector ch indicates the switches are open, and consequently, all the others are closed.

Figure 1 shows an example of a radial distribution system widely known in the literature [6]. It can be observed that switches 14, 15 and 16 are tie switches, being initially open (dashed lines).

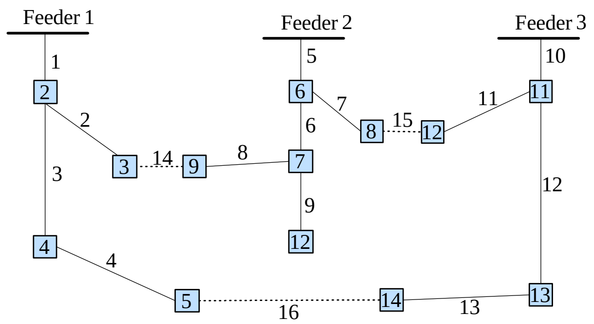

Figure 1: Three feeder distribution system [6].

The codification of the system can be made of the following form:

$sch =$

1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1

9	10	11	12	13	14	15	16
1	1	1	1	1	0	0	0

Vector sch is used to identify which switches are open and which are closed. This codification method is efficient because it is very easy to control the topology of the network. Thus, if a tie-line is closed, a loop will be formed, and the radial topology must be restored. It will be necessary to open a switch that belongs to this loop.

For instance, vector sch after tie-line 14 is closed is:

$sch =$

1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1

9	10	11	12	13	14	15	16
1	1	1	1	1	1	0	0

It is easy to see that a loop containing switches 1, 2, 5, 6, 8, and 14 is created. The radiality is restored if a switch that belongs to the loop is opened.

Rather than vector sch, which is a binary vector that represents the statuses of the switches and has a dimension equal to the number of switches, a vector of integer variables was adopted. This vector, defined as ch, contains the open switches only, and it is shown below, along with the corresponding vector sch.

$ch =$

1	2	3
7	8	16

$sch =$

1	2	3	4	5	6	7	8
1	1	1	1	1	1	0	0

9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	0

Vector ch contains the open switches of the network (7, 8 and 16). Its use in the proposed method has resulted in significant memory and computation speed gains, since the use of a vector with dimension proportional to the total number of switches is not necessary.

4 Generation of the neighbors of the current configuration

The TS algorithm consists of an exploration of the neighborhood of the current configuration. An appropriate definition of the neighbors of the current configuration and the quality of these neighbors, are crucial for the good performance of the algorithm. A neighbor of the current configuration is generated by applying a perturbation mechanism to this configuration. In [14] some perturbation mechanisms are considered in a reconfiguration algorithm based on simulated annealing. The add/subtract mechanism used in [14] and in this paper will be briefly described below.

Considering l_s switches and l_t tie-lines, the configuration space is defined as $\Omega := \Omega_1 \cup \Omega_2$, where $\Omega_1 = (s_1, s_2, \cdots, si_s)$ and $\Omega_2 = (t_1, t_2, \cdots, ti_s)$, being s_i (or t_i) the status of the switch (or tie-line) i. It is assumed that $s_i = 1$ if the switch is closed and $s_i = 0$ if it is open. The same assumption holds for the tie-lines. Thus, the add/subtract method can be described as:

(1) Close switch s_k (or tie-line t_k) chosen from set Ω, where k is obtained by using a random number generator. This switching operation will create a loop in the normally radial network, say L_k.

(2) Open switch s_j (or tie-line t_j) chosen from set L_k, where j is obtained by using a random number generator. This operation will restore the radial structure of the network.

According to the procedure described above, the perturbation mechanism is based on random operations, therefore there is no intelligence added to the process. In this paper an alternative for the perturbation mechanism is proposed, in order to take advantage of the knowledge of the problem. Sensitivity index OFP is used to guide the choice of the switching operations.

As mentioned before, this index was successfully used in [4] and [5] in heuristic algorithms for distribution systems reconfiguration. Basically, the OFP is the current flow calculated in the loop formed after the switching operation with the branch impedances replaced by the corresponding resistances only. In [4] all switches of the system are closed resulting in a meshed system. Then they are opened one at a time according to the OFP. The switch to be opened in a certain loop is the one located in the branch with the smallest current flow. The method provides good results for small systems but it seems not to be the ideal alternative in general, since the meshed system does not represent the real operation state of the network.

In [5] the OFP concept is used, but one loop is formed at a time. Thus, after a tie-line is closed, the OFP is computed for that particular loop and switch with the smallest current flow is opened, and radiality is restored. The method implemented in [5] provided better results than the ones presented in [4].

In this paper, the OFP concept was used in the add/subtract method to eliminate the random choice of switches to be opened/closed. The method used for the generation of neighbors of the current configuration using the ideas described above is shown in figure 2.

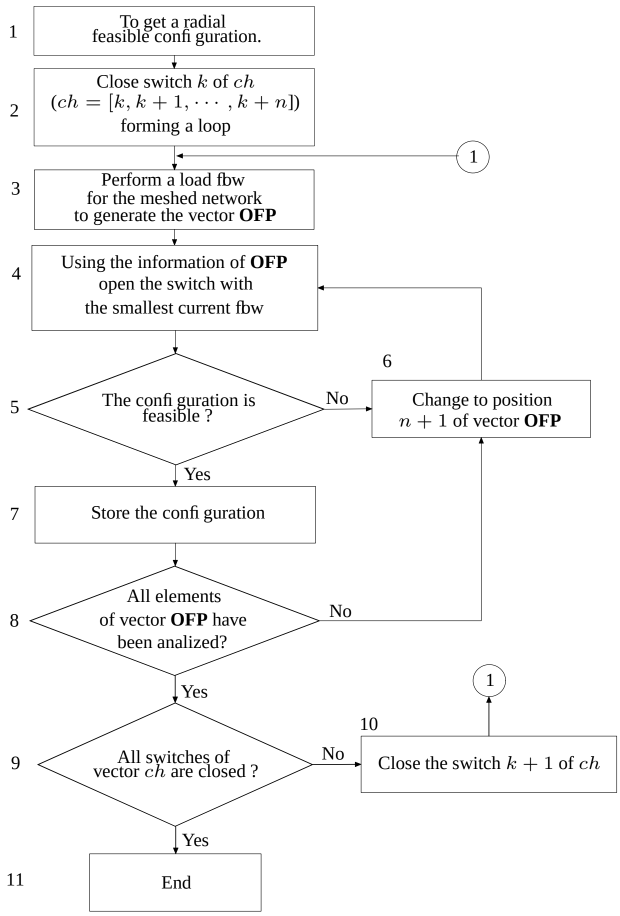

Figure 2: Proposed scheme for the generation of the neighbors.

The proposed method presents the following advantages.

1. The switching operations are no longer chosen randomly, but based on information provided by the OFP.

2. The OFP vector is stored in descending order, thus it is possible to limit the number of visited neighbors, decreasing the computational effort without, however to affect the quality of the configurations.

3. The TS algorithm converges quickly to solutions of good quality, since the generated neighbors present better characteristics than the randomly generated ones.

5 Implementation of the tabu list

One of the main characteristics of the TS algorithm is the use of memory, which can be of short term or long term. In the short term memory, the attributes of the solutions are stored such that solutions that contain the attribute *forbidden* are rejected. This strategy prevents the occurrence of ciclying. However, it can prevent a good quality solution from being accepted. This problem is overcome with the use of an *aspiration criterion*, which allows a configuration to be accepted even if it is forbidden provided that it meets some condition.

The long term memory is am improvement of the basic algorithm, and it allows new configurations of good quality be found using information stored during the optimization process. The attributes of the best configurations and the worst configurations can be stored in the memory. These information can be used in the processes of *intensification* and *diversification*.

The list of forbidden attributes (or tabu list) can be implemented in many ways as, for instance, by a matrix or vector where the forbidden attributes are stored. In this work the tabu list was implemented using vector tl shown below.

$tl =$

1	2	3	4	5	6	7	8
0	0	0	10	0	0	0	0
9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0	3	5	0	0	0	0	0

This type of storage is sufficient and convenient because it stores the position of the attribute (position of the vector tl), and the time during which the attribute will remain in the tabu list (value at the position of the vector). For instance, switch 4 (position 4 of the vector tl) cannot be operated for 10 iterations.

6 Implementation of the TS algorithm

The real power loss minimization problem can be formulated as:

$$\min \quad f = \sum_{i=1}^{nr} r_i \frac{P_i^2 + Q_i^2}{|V_i^2|} \tag{2}$$

$$\text{s.t.} \quad V_{min} \leq |V_i| \leq V_{max} \tag{3}$$

$$0 \leq |Ir_i| \leq Ir_{imax} \tag{4}$$

where P_i and Q_i are respectively the real and reactive power flows through branch i, V_i is the voltage magnitude at bus i, nr is the number of branches of the system, r_i is the resistance of branch i, Ir_i is the current flow through branch i, Ir_{imax} is the maximum current flow through branch i, and V_{min} and V_{max} are the voltage magnitude limits.

The additional constraints must also be met:

1. The topology of the network should always be radial, and
2. The reconfiguration process cannot result in islands.

A TS algorithm with short term memory and an aspiration criterion was implemented. A series of transitions in the search space are determined. Also, the visited configurations remain forbidden for a certain number of iterations. Actually, the attributes associated to each visited solution are stored only, which results in significant memory gains and reduction in the computational effort. The attributes are stored in a tabu list, and the number of iterations for which the attribute remain forbidden must be set in the algorithm.

The process of storing the attributes has many advantages, but good quality configurations can be discarded because they present a forbidden attribute. The solution for this problem is to eliminate the prohibition in case the visited configuration presents the desired characteristics through the aspiration criterion.

The proposed algorithm uses an aspiration criterion to toggle a configuration off the tabu condition in case the objective function is the best at that point in the iterative process. The basic steps of the proposed algorithm are shown below.

1. Initialize an empty tabu list.
2. Obtain a feasible initial solution $\mathbf{ch}$.
3. Consider $\mathbf{mch}$ as the current best solution $\rightarrow \mathbf{mch} = \mathbf{ch}$.
4. While the *stopping criterion* is not met do:
   (a) Generate the neighbor configurations $\mathbf{vch}_i$ from the initial configuration $\mathbf{ch}$.
   (b) Choose the best neighbor configuration $\mathbf{vch}^*$. This configuration cannot be tabu, or, in case it is tabu, it must satisfy the aspiration criterion.
   (c) Identify the movement that took $\mathbf{ch}$ to $\mathbf{vch}^*$.
   (d) Add the movement to the tabu list for the tabu time.
   (e) Do $\mathbf{ch} = \mathbf{vch}^*$.
   (f) If configuration $\mathbf{vch}^*$ is better than $\mathbf{mch}$, do $\mathbf{mch} = \mathbf{vch}^*$.
5. Show the best configurations.

Different stopping criteria can be used. The most popular ones are:

- Interrupt the iterative process after a certain number of iterations, or
- Interrupted the iterative process in case no significant improvement in the solution is obtained after a certain number of iterations.

The first criterion was adopted in this research work.

7 Simulation Results

The proposed algorithm was developed using Fortran, and tested with the realistic systems of 135 buses [9] and 202 buses [10]. The algorithm was able to find several good quality solutions.

Table 1 shows the results obtained with reducing the real power losses of the 135 bus system. The five best final configurations are shown.

Table 1: 135 bus system: real power losses reduction

Configuration	Open switches	Losses [kW]	Reduction [%]
1 - Initial	136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156	320.27	-
2	7 51 53 84 90 96 106 118 126 128 137 138 139 141 144 145 147 148 150 151 156	280.16	12.5
3	7 38 51 53 90 96 106 118 126 137 138 141 144 145 146 147 148 150 151 155 156	280.24	12.4
4	7 38 51 53 84 90 96 106 118 126 128 137 138 141 144 145 147 148 150 151 156	280.25	12.49
5	7 51 53 84 90 96 106 118 126 128 137 138 139 144 145 147 148 150 151 152 156	280.29	12.48
6	7 49 51 53 84 90 96 106 118 126 128 137 138 139 144 145 147 148 150 151 156	280.30	12.48

The solutions obtained with the proposed algorithm are compatible with the ones found in the literature, and the power losses are smaller than those found in [11] (real power losses reduction of 10.8%).

It seems interesting to provide the operator with a set of good quality solutions as shown in Table 1, since the best solution as far as power losses may not meet other criteria, related to power quality, reliability, etc. In this case, the operator would choose another good quality solution instead.

Table 2 shows the results obtained for the 202 bus system. The four best final configurations are shown.

Table 2: 202 bus system: real power losses reduction

Configuration	Open switches	Losses [kW]	Reduction [%]
1 - Initial	202 203 204 205 206 207 208 209 210 211 212 213 214 215 216	548.89	-
2	177 183 199 202 203 204 205 206 207 208 211 212 213 215 216	542.28	1.20
3	177 199 202 203 204 205 206 207 208 210 211 212 213 215 216	544.19	0.85
4	177 183 202 203 204 205 206 207 208 211 212 213 214 215 216	544.76	0.75
5	199 202 203 204 205 206 207 208 209 210 211 212 213 215 216	546.34	0.46

The power losses reduction in this case was smaller than the one in Table 1 because the number of switches available was small. The location of the switches was determined just for the sake of protection coordination.

Table 3 shows the results for the 202 bus system by assuming now that there is a switch associated to every branch in the system. Now a larger real power losses reduction was achieved.

Table 3: 202 bus system: real power losses reduction B

Configuration	Open switches	Losses [kW]	Reduction [%]
1 - Initial	202 203 204 205 206 207 208 209 210 211 212 213 214 215 216	548.89	-
2	29 66 74 83 111 118 125 131 135 136 140 177 199 202 208	511.50	6.80
3	29 66 74 83 11 118 125 131 136 137 140 177 199 202 208	511.56	6.80
4	29 66 74 83 111 118 125 131 135 137 137 140 177 199 202 208	511.62	6.79
5	28 66 74 83 111 118 125 131 135 136 140 177 199 202 208	511.65	6.78

Tables 2 and 3 show the importance of developing methods for the optimum location of switches regarding real power losses reduction.

Table 4 shows some computational times using a PC Athlon, 2.4 GHz, 512 MB RAM.

The CPU times for systems 202A e 202B correspond to tables 2 and 3, respectively.

Table 4: Tabu Search parameters

System	Number of iterations	Tabu time (iterations)	CPU time (seconds)
135 bus	35	6	46,78
202 bus - A	40	7	42,40
202 bus - B	40	7	49,98

8 Conclusion

The proposed algorithm showed to be efficient and good quality configurations were obtained for all tested systems, including the ones for the 135 and 202 bus systems, with acceptable computational effort.

The neighborhood limitation criterion adopted showed to be efficient, and good final results were obtained in spite of the small number of neighbor configurations.

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