MULTIOBJECTIVE HEURISTIC SEARCH FOR SERVICE RESTORATION IN ELECTRIC DISTRIBUTION NETWORKS

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Abstract: Power system distribution networks can face emergency situations, defined by the interruption of the power supply in certain regions. As certain quality of service limits must be maintained, especially those related to interruption frequency and duration, efforts should be made to reduce or eliminate the lack of services in any region. The main objective of service restoration is to minimize the number of consumers affected by the fault, transferring them to distribution support feeders to restore power while maintaining electrical and operational conditions, such as radial network configuration, equipment and voltage drop limits. This paper proposes a multiobjective heuristic search method that considers two criteria: the maximization of the restored load and the minimization of the number of switching operations. *Copyright© 2005 IFAC*

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1. INTRODUCTION

Power distribution systems incur, with certain frequency, in contingency situations caused by climatic or electromagnetic storms. They affect a portion of the network and conduce it to a blackout state, defined by the absence of power supply. Even if such a fault is restricted and correctly isolated, neighboring regions will be affected, thus reducing the indices that measure the quality of service and causing financial loss for utility companies. These aspects have lead them to concern with all the issues relating to the delivery of reliable power to customers. Technical considerations suggest that reliability performance is closely related to frequency and duration of service interruption. It is precisely these two aspects can be significantly improved via effective service restoration procedures.

The main objective of the service restoration problem is to minimize the number of customers faced with the interruption of power delivery by transferring them to support feeders via network reconfiguration, which respects all operational and electrical constraints. Another factor to be considered is the reaction time: outage areas should be restored as quickly as possible, to avoid an impact on the interruption duration indices.

Distribution utilities tend to use emergency procedures in a step-by-step way, following pre-established guidelines and operational procedures to handle contingencies and restore as many loads as possible. However, the simplicity of these approaches may limit their effectiveness, because the Service Restoration Problem (SRP) is in fact a combinatorial, nonlinear and hard constrained optimization problem that requires fast and effective solution techniques.

Since the late 80s, important work have been developed addressing the SRP. The first contributions attempted to reproduce system operator knowledge, dealing with heuristics closely related to guidelines and operational procedures. Such approaches can be purely heuristic (Morelato and Monticelli, 1989) or based on artificial intelligence techniques (expert systems) (Liu *et al.*, 1988). In the following decade, heuristic approaches were still used to solve the problem (Shirmohammadi, 1992). This work has been summarized in the survey of Curcic *et al.* (1996).

Recent papers have addressed the inherently multiobjective nature of the SRP. Lee *et al.* (1998) emphasized the relevance of a variety of factors in a multiobjective methodology using fuzzy decision making. In the same year, Miu *et al.* (1998) proposed a multiobjective heuristic method making use of certain indices in order to guide the search towards a solution. These indices made it possible to distinguish systematically between network switches on the basis of analytically determined criteria. Matos and Melo (1999) introduced the well-known *Simulated Annealing* method for network reconfiguration and service restoration based on minimizing the number of switching operations and maximizing the load supplied. Later, Augugliaro *et al.* (2001) suggested a method that combines fuzzy sets with genetic algorithms considering two criteria: maximization of loads supplied and minimization of power losses. Ciric and Popovic (2000) developed a heuristic approach using mixed integer programming based on a single objective function that includes five criteria.

The present paper proposes the combination of a new constructive and local search method in the solution of the SRP for radial networks using a multiobjective heuristic search methodology. The problem is defined in Section 2, and the method described in Section 3. Finally, computational experiments and conclusions are presented in Sections 4 and 5, respectively.

2. PROBLEM DEFINITION

When one observes a real distribution network, it is possible to identify three well defined states (Murphy and Wu, 1990): the normal state, the emergency state and the restoration state. In the first, all loads are supplied within current and voltage limits. The emergency state is characterized by the activation of protective devices which leave some areas with no power supply. Restoration is that state characterized by attempting to find support feeders to reestablish the power supply to as many load as possible.

The SRP arises with the occurrence of a fault, switching the system from the normal to an emergency state in an attempt to identify support feeders which will be able to reduce the size of the out-of-service area, while respecting the constraints related to current and voltage limits.

The network reconfiguration proposed by a restoration plan should be minimal, since the emergency state is transitory existing only until the fault is eliminated. The SRP should thus be considered as a multiobjective optimization problem, since it must minimize both the load not supplied and the number of switching operations. The solution for this problem is a trade-off between these two criteria. Other aspects such as power losses and feeder load balance could be included, but are normally better left for consideration after normal operating conditions, whereas other constraints such as the line, power source, and voltage drop limits are included in the calculations to avoid the activation of protective devices.

In the following mathematical formulation based on Ciric and Popovic (2000) we define the SRP to minimize the number of switching operations and the load not restored in a scenario which considers limits on current, voltage and substation power, power balance constraints and the maintenance of a radial structure.

$$Min \quad \sum_{k \in F_{cs}} (1 - X_k) + \sum_{k \in F_{os}} X_k \tag{1}$$

$$Min \quad \sum_{k \in B} (1 - Z_k) L_k \tag{2}$$

subject to:

$$|I_k| X_k \leq |I_{max}^{F_k}|, \ \forall k \in F \tag{3}$$

$$|V_k^{min}| \leq |V_k| \leq |V_k^{max}|, \ \forall k \in B \tag{4}$$

$$\text{substation power limits} \tag{5}$$

$$\text{power balance constraints} \tag{6}$$

$$\text{radial configuration} \tag{7}$$

where on this problem:

- Z_k is an integer variable denoting energizing of load k (1) or its lack (0);
- X_k is an integer variable denoting use of branch k (1) or its lack (0);
- B is the set of all buses;
- F is the set of all branches;
- F_{os} is the set of all switches which are normally open;
- F_{cs} is the set of all switches which are normally closed;
- L_k is the load of bus k;
- I_k is the current in the branch k;
- V_k is the voltage at bus k;

- $I_{max}^{F_k}$ is the maximum current at the branch k;
- V_k^{min}/V_k^{max} is the minimum/maximum acceptable voltage drop.

A feasible solution for the SRP must maintain all network switch status so that the configuration implemented not violate any of these constraints. In fact, it is possible that there will be no restoration plan capable of energizing any of the out-of-service areas. When this happens the network configuration implemented by the activation of protective devices will be maintained until the fault is eliminated.

3. THE HEURISTIC SEARCH METHOD

In this paper a multiobjective heuristic search method is proposed for the exploration of the search space of the SRP, denoted by all post-fault network configurations. This is a neighborhood-based method which systematically generates solutions from the transformation of others. The solutions generated, called neighbor solutions, are derived by a specific solution-generation mechanism.

Multiobjective optimization problems involve the simultaneous minimization (or maximization) of a set of conflicting criteria, satisfying a set of constraints (Steuer, 1986). There is no simple solution that is optimal for all criteria for such problems but rather a set of solutions which, as long as all criteria are simultaneously met, are equally efficient. This leads to the establishment of dominance relation which applies to the objective space Z: a point z^1 dominates z^2 if $z_j^1 \leq z_j^2$ for all of j objectives. When a point is not dominated by any other point in Z, it is called *non-dominated* and the set of all non-dominated points is called a *Pareto set* or an *efficient solution set*. At the end of the execution, the decision maker will choose one or more solutions of the Pareto set which best apply to his personal subjective aspirations.

The method developed here makes the following assumptions: (1) the distribution system is radial; (2) the pre-fault system state is known; and (3) the faults have been isolated.

Under these circumstances, the SRP is characterized by the occurrence of loads without a power supply, leading to their disconnection from the energized network. In a graph representation (Ahuja *et al.*, 1993) there is a *light area*, composed of all the loads where the power supply has been maintained, and a *black area*, including loads without power supply. Therefore, an SRP instance corresponds to a forest graph, with one tree for the light area and at least one other for the black area. The best case solution is to reestablish power supply for all loads in the black area.

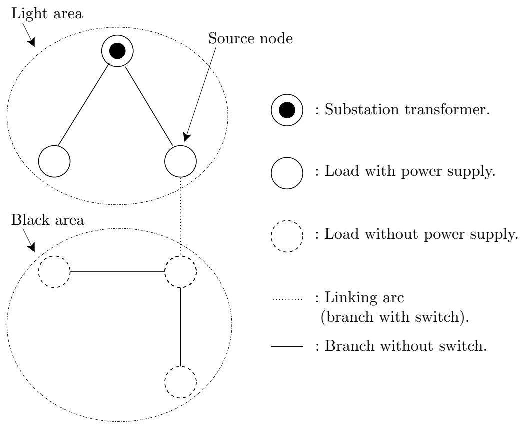

Fig. 1. SRP graph representation for an hypothetical network.

MOHeuristicSearch$(IT_1, IT_2, N_{sol}, opNet)$
1. PS = **Constructive**$(IT_1, opNet)$;
2. PS = **LocalSearch**(IT_2, N_{sol}, PS);
3. **return**(PS)

Fig. 2. Multiobjective heuristic search procedure.

The proposed method makes use of an other very important concept (Toune *et al.*, 2002): *source nodes*. These belong to the light area, with each one having at least one switch to connect it to the black area. These switches, or *linking arcs*, are included in the graph representation. Figure 1 shows the light and black areas, the source nodes and the linkings arc for an hypothetical network obtained after fault isolation.

This method of resolution is based on the appropriate use of source nodes to connect loads to the light area, always respecting the problem constraints. The feasibility of the solutions is maintained for every load connected by using a *backward-forward sweep* power flow method (Baran and Wu, 1989). The algorithm illustrated in Figure 2 shows how the constructive and improvement phases are managed in the search process.

The algorithm considers three parameters, as well as the pre-fault configuration($opNet$): the first two parameters correspond to the maximum number of iterations of the constructive phase (IT_1) and of the local search phase (IT_2), respectively; the third (N_{sol}) refers to the number of solutions for which the search will be conducted in parallel in the local search phase.

The first two steps refer to the phases in the solution of the problem, both requiring a specific solution representation. Step 1 involves the creation of initial solutions, whereas the Step 2 involves their improvement. These two steps will be discussed in the following sections, as well as the solution representation adopted.

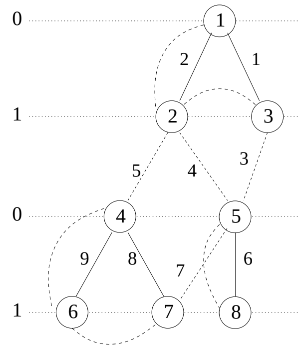

Fig. 3. Sample Network.

Table 1. Representation for the sample network.

	Nodes									Trees		
	1	2	3	4	5	6	7	8		1	2	3
$N(i)$	2	3	0	6	8	7	0	0	$R(a)$	1	4	5
$P(i)$	0	1	1	0	0	4	4	5				
$D(i)$	0	1	1	0	0	1	1	1				
$T(i)$	1	1	1	2	3	2	2	3				

3.1 Solution representation

Since the size of the search space is determined by the representation of the solution and the manner in which it is manipulated (Michalewicz and Fogel, 2000), this aspect becomes highly important when heuristic algorithms are applied in solving an optimization problem.

As previously stated, the solution for an SRP is a forest graph and any solution representation must be able to handle and update it. This means the method must be able to retrieve and explore a specific tree, as well as identifying how many trees exist and the boundaries between them. Table 1 shows the solution representation for the sample network given by Figure 3.

Figure 1 furnishes the four lists used to manage the forest graph: list $N(i)$ providing the next node for node i when the graph is traversal in preorder (Ahuja *et al.*, 1993); list $P(i)$ indicating the predecessor node of node i; list $D(i)$ furnishing the depth of node i; and list $T(i)$ determining the tree to which node i belongs. Another list, $R(a)$ is needed to indicate the root of the trees, with the number 1 conventionally referring to the light area.

3.2 Constructive phase

The constructive phase is carried out by a random version of the well-known *Prim* algorithm (Ahuja *et al.*, 1993). Two versions were originally developed, one for minimizing the load not supplied and the other for minimizing the number of switching operations, with the first consisting of a breadth-first search and the latter a depth-first search. These two search algorithms attempt to produce solutions topologically different from each other.

Constructive$(MAX_{iter}, opNet)$
1. $PS = \emptyset$;
2. $it = 0$;
3. **while**$(it < MAX_{iter})$ **do**
4. $SNL =$ **CreateSourceNodes**$(opNet)$;
5. **ConstructMinLoad**$(SNL, opNet, PS)$;
6. **ConstructMinSwitch**$(SNL, opNet, PS)$;
7. $it = it + 1$;
8. **return**(PS);

Fig. 4. Constructive algorithm developed.

For both of these algorithms, randomness is guaranteed by defining a uniform probability distribution according to the objective function value of adjacent nodes. For each execution, it is thus possible to get different solutions. As illustrated in Figure 4, the source node list (SNL) is defined as the starting nodes from which both algorithms (Steps 5 and 6) will try to enlarge the light area by transferring nodes from the black area. The algorithm finishes when the maximum number of iterations (MAX_{iter}) has been reached.
The constructive algorithms can be understood better by considering Figure 3. The black area includes nodes 4-8, while nodes 2 and 3 are the source nodes. Suppose that neither of the switches associated with arcs 3, 4 and 5 can support the power load for the entire black area (nodes 4-8), and further that $L(4) > L(6) > L(7) > L(5) > L(8)$, where $L(i)$ corresponds to the load of node i. Therefore, the only way to restore nodes 4-8 is to connect some of the nodes to the source node 2 and the others to node 3. When executing the constructive algorithm for minimizing the load not supplied, suppose that the source node 2 is the first chosen. Its adjacent nodes are nodes 4 and 5. Since $L(4) > L(5)$, node 4 is first included in the light area and its adjacent nodes will only be considered after the evaluation of node 5. Given the power flow limits on the arcs 4 and 5, the final configuration will involve the inclusion of nodes 4, 5 and 6 in the light area, by closing switches 4, 5 and 9.

The second algorithm follows the same basic procedure, except that it uses a depth-first search and selects the nodes according to the number of switching operations involved when current status is compared to the pre-fault configuration.

3.3 Local search phase

The local search phase tries to improve on the initial solutions by using a multiobjective search procedure, which generates neighbor solutions by changing the source node for each node in the black area. In order to find well distributed solutions in the objective space, a subset of them is explored in parallel, employing Pareto dominance as the optimization criterion.

Figure 5 explains how the multiobjective local search is conducted.

LocalSearch(MAX_{iter}, N_{sol}, PS)
1. it = 0; $\quad PS_i = PS$;
2. **while**($it < MAX_{iter}$) **do**
3. $\quad$ **if**($|PS| > N_{sol}$) **then**
4. $\quad\quad PS_r =$ **Reduce**(PS, N_{sol});
5. $\quad PS_n = \emptyset$;
6. $\quad$ **for each** $s_i \in PS_r$ **do**
7. $\quad\quad$ **Neighbors**(s_i, PS_n);
8. $\quad$ **Update**(PS_i, PS_n);
9. $\quad$ **Update**(PS, PS_n);
10. $\quad PS = PS_n$;
11. $\quad it = it + 1$;
12. **return**(PS_i);

Fig. 5. Multiobjective local search procedure.

The parameters include the maximum number of iterations (MAX_{iter}), the number of solutions to be explored in parallel (N_{sol}), and the approximate Pareto set (PS). Three other sets are also used during the procedure: the first containing all non-dominated solutions found (PS_i); the second containing the non-dominated solutions generated during the current iteration (PS_n); and the last containing the representative solutions chosen for exploration (PS_r).

The loop between Steps 2 and 11 is repeated for all the iterations (MAX_{iter}). Steps 3 and 4 attempt to reduce the PS by using a *clustering* procedure (Morse, 1980), which extracts the N_{sol} most representative solutions from PS and stores them in PS_r, while the remaining solutions stay in PS. For each solution of the set PS_r a neighborhood is generated by changing the source node for each black area node (Steps 6 and 7). The non-dominated solutions generated by all neighborhoods of PS_r are included in PS_n and are used to update the set PS_i in Step 8 and the set PS in Step 9. This new PS set is them used for the next iteration for the selection of further representative solutions.

For example, consider Figure 3 and suppose that node 6 is chosen by the local search. From this configuration, this node can be connected to the light area through source nodes 2 and 3. Since only one will be chosen at a time by the procedure on Step 7 of the local search algorithm (Figure 5), assume that source node 2 will be used to make the connection to node 6. Because node 4 is on this path it will also be included in the light area besides node 6. The same procedure will be conducted to all other nodes in the black area.

4. TEST RESULTS

The proposed multiobjective heuristic search method was applied to the 92-bus distribution system of Augugliaro *et al.* (2001), given in Figure 7. It has 115 branches (all sectionalizable in at least one point), 81 load nodes and 18 capacitor banks; it is supplied by six HV/MV substations. The programming language used was C++, on a Pentium

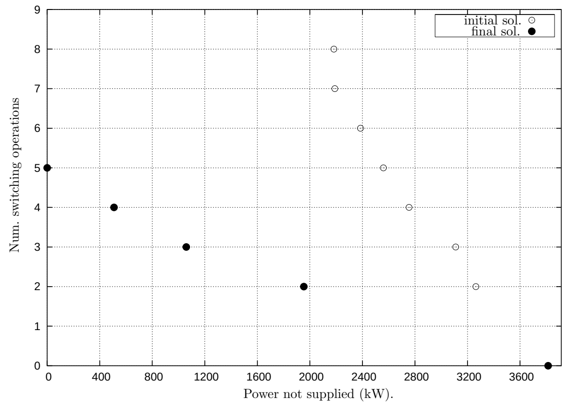

Fig. 6. Initial and final Pareto fronts obtained.

4 PC with 2.8 GHz. The computational time was less than 0.5 seconds.

The SRP involves the permanent fault of the transformer at node 90, leaving nodes 19, 29, 37-41, 52-54 without power. The load model used considers constant power with the required power flow calculations made using the *backward-forward sweep method* (Baran and Wu, 1989). Capacity limits on the substations were considered so that all the black area nodes could not be connected to a single one of them.

Figure 6 shows the non-dominated fronts before (initial solutions) and after the local search phase (final solutions), with all being feasible in relation to the problem constraints. The parameter settings were as follows: 200 iterations for the constructive and local search phases, with 4 solutions explored in parallel in this last phase.

The contribution of the second phase is clear, since it tries to approximate the front obtained to the optimal Pareto front. In fact, the advantage of the heuristic is the obtainment of complementary algorithms so that more points can be explored. The two original criteria are contradictory: as the load not supplied decreases, the number of switching operations increases. It is the system operator who will decide which of the possible solutions suggested by the Pareto set obtained will be adopted.

Let us consider, for example, solution (3; 1059). That it is more important to involve fewer switches than to restore the total load. He can thus close only the switches 26-29, 29-37, 37-38, 38-39, 39-40, 40-41, 41-54 and 54-53, even though this will leave nodes 19 and 52 in the black area. On the other hand he may opt for the establishment of the complete load, but in this case he would have to close 2 more switches.

5. CONCLUSIONS

This paper has presented a multiobjective heuristic search method to solve the Service Restoration Problem (SRP) in electrical distribution systems.

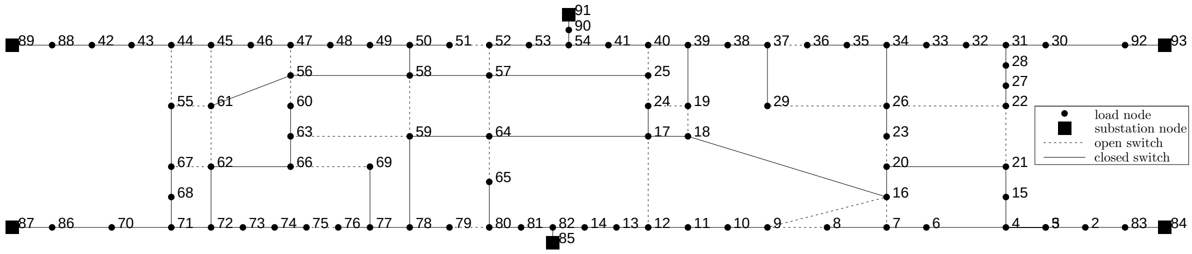

Fig. 7. Test system before fault.

The mathematical formulation presented considers the minimization of the load not supplied and of the number of switching operations, while respecting voltage, current and feeder capacity constraints.

The methodology has proved suitable for the SRP, due to the interaction of constructive and local search algorithms in the selection of source nodes. Moreover, the method has proved its flexibility in arriving at a variety of possible well distributed solutions throughout the Pareto front, while requiring minimal computational time.

Further studies should investigate the inclusion of more objective functions and the testing with larger distribution networks.

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