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A genetic algorithm based on the edge window decoder technique to optimize power distribution systems reconfiguration

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ABSTRACT

This paper describes a genetic algorithm developed for power distribution system reconfiguration with minimal losses. The reconfiguration problem consists in identifying a new network topology with minimal power losses, while all the electrical system constraints are satisfied like radial topology, lines and substations power flow below capacity limits, node voltage magnitude within limits and all nodes connected. This is a combinatorial optimization problem where the aim is to determine the final status, open/closed, of all switches in a large scale distribution system. The genetic algorithm developed uses the edge window decoder encoding technique for network representation and building up spanning trees, as well as efficient genetic operators in order to explore the search space. Using two representative distribution system configurations, the results obtained with the developed methodology are compared with those obtained with other heuristic and metaheuristic techniques. The numerical results presented show the usefulness and effectiveness of the proposed algorithm.

1. Introduction

Distribution systems are planned and designed not only to reduce the investment cost but also the system operational cost. During unexpected forced outages of transformers and feeders or during overloads and maintenance, the system operators need to reconfigure the system by controlling the status of the different switches in order to improve the system efficiency, reliability and operational cost for the new operating conditions.

According to the operating conditions, distribution systems are reconfigured for three purposes: (1) reconfiguration for loss reduction, (2) reconfiguration for load balancing, and (3) reconfiguration for service restoration. In this sense, the efficient operation of distribution systems can be achieved by modifying the open/closed status of the different switches in order to transfer load from heavily loaded feeders and substation transformers to relatively less heavily loaded feeders and transformers. By reducing the level of loads on feeders and substation transformers the power losses are reduced and the voltage profile along the feeders is improved. Therefore, the distribution system reconfiguration (DSR) problem can be conceptualized like the task of identify a new configuration with minimal power losses, while all the system constraints are satisfied. This is a combinatorial optimization problem where the aim is to determine the open/closed status of all switches in order to obtain an optimum configuration in a large scale distribution system.

Several methods for solving the DSR problem have been proposed in the literature. Merlin and Back were the first to use a heuristic approach aimed to obtain a "global minimum" of losses [1]. In 1989, this method was improved by Shirmohammadi and Hong [2], obtaining the optimal system configuration by opening the switches with the lowest current determined by the optimal flow pattern in the distribution system. Later, Glamocamin [3] and Sarfi et al. [4] used quadratic programming and network partitioning techniques, respectively, in order to solve the DSR problem. In 1999, McDermott et al. [5] proposed a heuristic nonlinear constructive method. Different approaches to the DSR problem in these initial stages were also made in [6–8]. However, in general "these algorithms find excellent solutions in medium size systems, but for large systems the quality of the solutions is not satisfactory" [9].

In recent years, new heuristic algorithms have been proposed in the literature with good results. They are aimed to deal with the problem of system size [10], fast execution time [11], the use of an optimal power flow algorithm [12], variability of the demand [13] and large scale distribution system reconfiguration [14].

Nara et al. were the first to propose the use of genetic algorithms (GAs) to solve the DSR problem with minimal losses [15]. Since then, a great number of publications based on evolutionary algorithms (EAs) have been proposed in the literature, some of them can be found in [9,16–20]. Recently, GA has also been used to solve the DSR problem with distributed generation [21] and capacitor allocation [22]. It should be mentioned that each technique has its own approach to the problem, with significant contributions at the time of publication. Also, there have been important

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contributions to the DSR problem by using other metaheuristics techniques like plant growth [23], particle swarm optimization [24], tabu search [25] and ant colony search [26,27], among others.

One of the main difficulties for solving the DSR problem using evolutionary algorithms is the radiality constraint. This constraint not only creates difficulties in the formation of the initial population but also during intermediate stages of the evolutionary process. Also, a proper selection of the encoding strategy and genetic operators is a key factor for solving efficiently the DSR problem. In this sense, new encoding strategies and genetic operators for evolutionary techniques have been proposed by researchers in the EA community. In general, these techniques have attempted to find a way to reach a balance between the encoding properties of locality, heritability and diversity.

The locality property is defined as how well neighboring genotypes correspond to neighboring phenotypes. Therefore, the locality of an EA is high if small changes in the genotype result in small changes in the corresponding phenotype. Mutation operators are usually responsible for small changes in a phenotype space. The heritability property means how many structures belonging to parent solutions are transferred to new offspring. This property is determined by the crossover operator and it is desirable that key features can be propagated from one generation to the next one. Equally important is a population with high diversity in order to avoid a premature convergence and local optima. In sum, all these properties are strongly dependent on the encoding strategy and the genetic operators used.

In Ref. [28] it is presented an assessment of several encoding strategies and genetic operators representative of the state of the art. In several tests using the Optimum Communication Spanning Tree (OCST) problem as a base case, eight encoding strategies and their genetic operators were compared. According to [28], the results shown that the edge window decoder (EWD) [29] and the edge set (ES) [30] encoding strategies seems to have a good performance for solving the OCST problem, and potentially other spanning tree based problems. Since a power distribution system in operation is basically a spanning tree, the DSR problem can be solved by using a minimum spanning tree formulation where evolutionary algorithms search efficiently for the optimal reconfiguration.

The approach used in this paper for representing the distribution system is based on the EWD technique which ensures radiality and facilitates the use of efficient genetic operators for crossing and mutation. The EWD technique is modified and embedded in a genetic algorithm specially designed to deal with the DSR problem.

2. Problem formulation

In this paper, the DSR problem is solved for minimum real power losses while satisfying several system operating constraints like radial topology, lines and substations power flow below capacity limits, node voltage magnitude within limits, and all nodes connected. The three phase distribution system is considered to be balanced and all the loads are assumed of the nature of constant power. The objective function for the problem is [23]:

$$\text{Min } P_{\text{LOSSES}} = \sum_{i \in Ni} 3 I_i^2 R_i \tag{1}$$

Subject to:

$$S_i \leqslant S_{i\ \max} \tag{2}$$

$$V_{i\min} \leqslant V_i \leqslant V_{i\max} \tag{3}$$

$$S_{Ai} \leqslant S_{Ai\max} \tag{4}$$

Eq. (1) corresponds to the objective function to be optimized and represents the sum of power losses of all line sections in the distribution system N_i. I_i and R_i are the electrical current and resistance of line section i, respectively. S_i and $S_{i\ \max}$ are the apparent power and maximum capacity limit of line section i. V_i is the voltage magnitude of bus i; and $V_{i\ \min}$ and $V_{i\ \max}$ are the minimum and maximum voltage limits of bus i. S_{Ai} and $S_{Ai\ \max}$ are the apparent power and maximum capacity limit of substations i. Finally, the radial structure of the network must be maintained, and all loads must be supplied.

3. The proposed genetic algorithm

A genetic algorithm based on the EWD encoding strategy was developed in order to solve the DSR problem. The general structure of the proposed EWD-Reconfig algorithm is shown in Fig. 1.

Fig. 1, where *best* is the value of the solution with the best fitness (minimum energy losses), *average* is the average fitness of population $P(t)$, τ is a predetermined tolerance value, Pc is the crossing rate and Pm is the mutation rate. A binary tournament selection was used in the GA. The binary tournament consists in selecting randomly two individuals from the current population and the individual with the best fitness is selected for the crossover operation. This procedure is repeated until $Q(t)$ is completed.

3.1. The encoding strategy in the EWD-Reconfig algorithm

The EWD encoding strategy for spanning trees was used to codify each solution in the DSR problem. In order to describe the encoding strategy, Fig. 2 shows a power distribution network with three feeders, 13 line sections with normally closed switches, three line sections with normally open switches and 13 power demand nodes. In order to manipulate the system in Fig. 2 as a spanning tree, the nodes (1), (2) and (3) can be consider as a single node.

Now, by visiting every node in the system without leaving the paper, the following string of visited nodes are obtained (1,4,5,4,6,7,16,15,13,14,13,3,2,8,10,8,9,12,9,11). At this stage the switch status open/closed is not relevant, since the main purpose is visiting all nodes. Now, imagine a window of length two moving along the string, one place at a time. The moving window first sees “1,4”, so this edge is added to the edge set ES{(1,4)}. Next, the moving window sees “4,5”, “5,4” and so on. Only the edges indicated by the moving window are considered as long as the second node in the window has not been already included in ES{}, otherwise the edge is skipped. For example, when the window sees “5,4”, the edge (5,4) is skipped because node 4 has already been considered when the windows was “4,5” in the previous step. In this paper, only undirected graphs are considered, so (4,5) is equivalent to (5,4). Also, any window containing copies of the same node identifier is ignored, for example when “3,2” in the string is

```
Procedure: EWD-Reconfig Algorithm
Begin
      t = 0
      Generate an initial population P(t)
      Evaluate P(t)
      While ((best-average) > τ ) do
      begin
        Select P(t)*Pc parents from P(t) to build Q(t)
        Recombine Q(t) to yield the offspring population R(t)
                                                    (CROSSOVER)
        Modify R(t)*Pm offspring in R(t)     (MUTATION)
        Evaluate R(t)
        Select P(t+1) from P(t) and R(t)
        t = t + 1
      end
end
```

Fig. 1. The proposed EWD-Reconfig algorithm.