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Multiobjective evolutionary algorithm with a discrete differential mutation operator developed for service restoration in distribution systems

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ABSTRACT

Network reconfiguration for service restoration in distribution systems is a combinatorial complex optimization problem that usually involves multiple non-linear constraints and objective functions. For large scale distribution systems no exact algorithm has found adequate restoration plans in real-time. On the other hand, the combination of Multi-Objective Evolutionary Algorithms (MOEAs) with the Node-Depth Encoding (NDE) has been able to efficiently generate adequate restoration plans for relatively large distribution systems (with thousands of buses and switches). The approach called MEAN results from the combination of NDE with a technique of MOEA based on subpopulation tables. In order to improve the capacity of MEAN to explore both the search and objective spaces, this paper proposes a new approach that results from the combination of MEAN with characteristics from the mutation operator of the Differential Evolution (DE) algorithm. Simulation results have shown that the proposed approach, called MEAN-DE, is able to find adequate restoration plans for distribution systems from 3860 to 30,880 switches. Comparisons have been performed using the Hypervolume metric and the Wilcoxon rank-sum test. In addition, a MOEA using subproblem Decomposition and NDE (MOEA/D-NDE) was investigated. MEAN-DE has shown the best average results in relation to MEAN and MOEA/D-NDE.

Introduction

Distribution system problems, such as service restoration (SR) [1], power loss reduction [2], and expansion planning [3], usually involve network reconfiguration procedures [4–7]. As a consequence, they can be considered Distribution System Reconfiguration (DSR) problems, which are usually formulated as multiobjective and multiconstrained optimization problems [8,9,5,10,1,11–13,6,14].

Several Evolutionary Algorithms (EAs) have been developed to deal with DSR problems [8,4,9,5,10,14]. The results obtained by such approaches have surpassed those obtained through both Mathematical Programming and traditional Artificial Intelligence [9]. However the majority of EAs still demands high running time when applied to Large-Scale Distribution Systems (DSs) [9], that is, DSs with thousands of buses and switches.

The performance obtained by EAs for large-scale DSs is dramatically affected by the data structure used to represent computationally the electrical topology of the DSs. Inadequate data structure may reduce drastically the EA performance [9,15,13,14,10]. Other critical aspects of EAs are the genetic operators that are used. Generally these operators do not generate radial configurations [13].

In order to improve the EAs performance in DSR problems, the approach proposed in [5] uses a vertex encoding based on the Prufer number to encode the chromosomes. The Prufer number encoding ensures system radiality avoiding the tedious "mesh check" algorithms, which are required to identify the existence of loops

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(meshes) in the temporary solutions (DSs configurations). On the other hand, in [16] it was proposed an innovative and effective heuristic graph-based approach to SR problem. The idea is to minimize the switch operations in the de-energized areas. The approach is based on the Prim algorithm [17].

In this context, the approaches proposed in [15,18,14] use a new tree encoding, called Node-Depth Encoding (NDE), and its corresponding genetic operators [19]. As it was shown in those references, the NDE can improve the performance obtained by EAs in DSR problems because of the following NDE properties: (i) The NDE and its genetics operators produce exclusively feasible configurations, that is, radial configurations able to supply energy for the whole re-connectable system[1]; (ii) The NDE can generate significantly more feasible configurations (potential solutions) in relation to other encoding in the same running time since its average time complexity is $O(\sqrt{n})$, where n is the number of graph nodes (each graph node corresponds to a DS sector[2]); (iii) The NDE-based formulation also enables a more efficient forward–backward Sweep Load Flow Algorithm (SLFA) for DSs. Typically this kind of load flow applied to radial networks requires a routine to sort network buses into the Terminal-Substation Order (TSO) before calculating the bus voltages [20–22]. Fortunately, each configuration generated by the NDE has the buses naturally arranged in the TSO. Thus, the SLFA can be significantly improved by the NDE-based formulation. Observe that, once a feasible configuration is guaranteed, the objective function and the network operational constraints of a DSR problem can be analyzed solving a radial load-flow.

The approach proposed in [15] uses NDE together with a conventional EA, that is, an EA based on just one objective function that weights the multiple objectives and penalizes the violation of constraints. According to [11,23] this strategy for treating problems with multiple objectives and constraints suffers from various disadvantages. In this sense, in [14] NDE was combined with a technique of Multi-Objective Evolutionary Algorithm (MOEA) based on subpopulation tables, where each subpopulation stores the found solutions that better satisfy an objective or a constraint of a DSR problem. The MOEA with subpopulation tables can more easily leave the local toward global optima. Simulation results presented in [14] demonstrate that the Multi-Objective EA with NDE (MEAN) is an efficient alternative to deal with DSR problems in large-scale DSs. Also simulations results obtained by MEAN to treat the SR problem in large-scale DSs have surpassed those obtained by the NSGA-II, the SPEA-2 and the integration of MEAN with both NSGA-II and SPEA-2 [24,25].

Beyond the scopes of multiobjective and data structures for DSR problems, new relevant EAs have been investigated in the literature. The Differential Evolution (DE) [26] has received increased interest from the Evolutionary Computation community, since DE has shown better performance over other well-known metaheuristics like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) [27]. The DE can identify promising regions of the search space by a relatively simple operator (called differential mutation) that generates new solutions (called individuals) from random calculation of pairs of differences between individuals.

Nevertheless, there are few proposals of implementation of this operator in the space of discrete variables [28–30] and their performance has not been evaluated for a significant number of problems. Moreover, the available versions of DE for combinatorial optimization in the literature focus on permutation-based combinatorial problems, such as the job shop scheduling, flow shop scheduling and the travelling salesman problem, precluding their use for SRs in DSs.

The main contribution of this paper is to propose a differential mutation operator based on the NDE. The new operator can extract the essential difference between two DS feasible configurations and use it in order to compose new feasible configurations. Moreover, the average time complexity of the proposed operator is $O(\sqrt{n})$, enabling efficient manipulation of large-scale networks. In addition, the differential mutation operator based on the NDE is combined with MEAN, producing a new powerful MOEA (called MEAN-DE) to solve SR problems for large-scale DSs. Experimental results have indicated that MEAN-DE can find restoration plans with one-fourth less switching operations than MEAN plans for the largest DS used in the tests (30,880 buses and 5166 switches).

Although the majority of MOEA has successfully worked with combinatorial Multi-Objective Problems (MOPs) with at most two objectives, the MEAN have solved the SR problem formulated with more than two objectives [14]. Other MOEA that has obtained interesting results for MOPs with more than two objectives is the MOEA based on Decomposition (MOEA/D) [38]. As a consequence, we also proposed an extension of MOEA/D using NDE, called MOEA/D-NDE, adapted for the SR problem. However, the MEAN-DE also presented better results in relation to MOEA/D-NDE for the SR problem.

This paper is organized as follows: 'Service restoration problem' formalizes the SR problem; 'Addressing the SR problem for large-scale DSs' addresses the SR problem for large-scale DSs; 'Evolutionary Algorithms with NDE' summarizes the MEAN, proposes the extension of MOEA/D using NDE (MOEA/D-NDE) and describes the recombination operator for the NDE; 'Discrete DE with movements list' presents the Discrete Differential Evolution algorithm with list of movements proposed in [46]; 'Proposed approach' proposed the MEAN-DE; 'Experimental analyses' evaluates and compares MEAN-DE to the MEAN and MOEA/D-NDE approaches; finally, 'Conclusions' summarizes the main contributions and concludes the paper.

Service restoration problem

Next sections present the nomenclature and the general formulation for the SR problem.

Nomenclature

After the faulted areas have been identified and isolated, the out-of-service areas must be connected to other feeders by closing and/or opening switches. Fig. 1 shows an example of SR in a DS with three feeders. Nodes 1, 2 and 3 represent power sources in a feeder, solid lines are Normally Closed (NC) switches, dashed lines are Normally Open (NO) switches, and each circle represents sectors.[3] Suppose sector 4 is in fault (Fig. 1). Then, sector 4 must be isolated from the system by opening switches A and B. Sectors 7 and 8 are in an out-of-service area (gray box in Fig. 1). One way to restore energy for those sectors is by closing switch C.

Mathematical formulation

The SR problem emerges after the faulted areas have been identified and isolated. The desired solution is the minimal number of switching operations that results in a configuration with minimal number of out-of-service loads, without violating the operational and radial constraints of the DS. The minimization of the number

[1] The term "re-connectable system" means all areas having at least one switch linking them to energized areas. Some out-of-service areas may not have any switch to re-connect them to the remaining energized areas.

[2] A sector is a set of buses connected by lines without switches.

[3] Lines and buses without sectionalizing or tie-switches are inside a sector, thus, they are not shown in DS representations, similar to the one in Fig. 1.