G Model
ASOC 2355 1–11
ARTICLE IN PRESS

Applied Soft Computing xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Soft Computing

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

Differential evolution using ancestor tree for service restoration in power distribution systems

Q1 Ricardo S. Prado [a], Rodrigo C. Pedrosa Silva [b,c], Oriane M. Neto [b], Frederico G. Guimarães [b,*], Danilo Sipoli Sanches [d], João Bosco A. London [e], Alexandre C.B. Delbem [f]

[a] Area of Automation and Control, Instituto Federal de Minas Gerais, IFMG, Ouro Preto, Brazil
[b] Department of Electrical Engineering, Universidade Federal de Minas Gerais, UFMG, Belo Horizonte, Brazil
[c] Electrical and Computer Engineering Department, McGill University, Montreal, Canada
[d] Federal Technological University of Paraná, UTFPR, Cornélio Procópio, Brazil
[e] São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil
[f] Institute of Mathematical and Computing Sciences, University of São Paulo, São Carlos, Brazil

ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form 6 May 2014
Accepted 5 June 2014
Available online xxx

Keywords:
Differential evolution
Node-depth encoding
Large-scale distribution system
Service restoration

ABSTRACT

Problems in power distribution system reconfiguration (PDSR), such as service restoration, power loss reduction, and expansion planning, are usually formulated as complex multi-objective and multi-constrained optimization problems. Several evolutionary algorithms (EAs) have been developed to deal with PDSR problems, but the majority of EAs still demand high running time when applied to large-scale distribution systems (thousands of buses and switches). This paper presents a new approach for service restoration in large scale distribution systems that employs a discrete differential evolution with ancestor tree (DE-Tree). We combine the node-depth encoding (NDE) to represent computationally the electrical topology of the system and the ancestor tree presented here to implement differential evolution for service restoration problems. The ancestor tree is used to build a list of elementary movements that maps one solution in the search space into another, thus capturing the "difference" between forests encoded with the NDE, which is essential in the search engine of differential evolution. The use of an ancestor tree is not only central to implement differential mutation in our algorithm but also can track the sequence of switching operations in the restoration of the system after the optimization process is finished. The proposed approach makes differential evolution suitable for treating combinatorial optimization problems related to PDSR. Results presented on distribution system reconfiguration problems suggest the benefits and fast convergence of the proposed approach.

1. Introduction

Power distribution networks are responsible for delivering electricity from the high-voltage transmission systems to the consumers. They are very complex networks with many challenges from the operational and control points of view. Problems in power distribution system reconfiguration (PDSR), such as service restoration, power loss reduction, and expansion planning, are usually formulated as multi-objective and multi-constrained optimization problems.

In the last decades, several evolutionary algorithms (EAs) have been developed to deal with PDSR problems [10,29,3,34,1], including some methods based on Ant Colony Optimization [33,14] in service restoration. However, the majority of EAs still demand high running time when applied to large-scale distribution systems (thousands of buses and switches) [6]. Furthermore, the performance obtained by EAs for large-scale distribution systems is dramatically affected by the data structures used to represent computationally the electrical topology of the system: inadequate data structures may reduce drastically the performance of EAs [6,26,2,27]. Other critical aspects when designing EAs for this application is the design of the genetic operators that are used to promote the search and evolution. Generally these operators do not generate radial configurations [2], thus requiring additional repair operations.

In order to improve the EA performance in PDSR problems, the approach proposed by Santos et al. [26,27] and Mansour et al. [16] used a new tree encoding, named node-depth encoding (NDE) and

Q2 * Corresponding author. Tel.: +55 3134093419.
E-mail addresses: ricardo.prado@ifmg.edu.br (R.S. Prado), rodrigo.silva@mail.mcgill.ca (R.C. Pedrosa Silva), oriane@dee.ufmg.br (O.M. Neto), fredericoguimaraes@ufmg.br, frederico.g.guimaraes@gmail.com (F.G. Guimarães), danilosanches@utfpr.edu.br (D.S. Sanches), jbali@sc.usp.br (J.B.A. London), acbd@icmc.usp.br (A.C.B. Delbem).

http://dx.doi.org/10.1016/j.asoc.2014.06.005
1568-4946/© 2014 Published by Elsevier B.V.

its corresponding genetic operators [7]. The NDE can improve the performance obtained by EAs in PDSR problems because of the following properties:

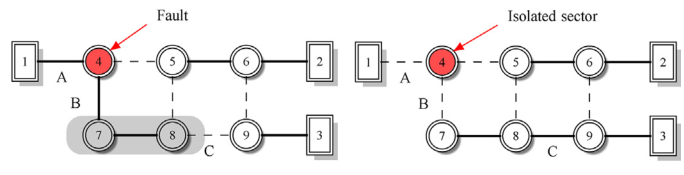
- This encoding and its genetic operators produce exclusively feasible configurations, that is, radial networks able to supply energy for the whole re-connectible system.[1]
- It can significantly generate more feasible configurations (potential solutions) than other encodings in the same running time since its average time complexity is $O(\sqrt{n})$, where n is the number of graph nodes.
- The NDE-based formulation also enables a more efficient forward-backward sweep load flow algorithm (SLFA) for PDSR. 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 [31,30,4]. Fortunately, each configuration represented by the NDE has the buses naturally arranged in the TSO. Thus, the SLFA can be significantly improved by the NDE-based formulation.

The approach proposed in Santos et al. [26] uses the NDE together with a conventional EA. The algorithm optimizes one combined objective function that weights the multiple objectives and penalizes the violation of constraints. The approach proposed in Mansour et al. [16,17] uses the NDE and a modified version of the non-dominated sorting genetic algorithm-II (NSGA-II) [5]. Later, Santos et al. [27] combined the NDE with a technique of multi-Objective evolutionary algorithm (MOEA) based on sub-population tables, where each sub-population stores those solutions that better satisfy an objective or a constraint of the PDSR problem. The authors say that the MOEA with sub-population tables can more easily escape from local minima towards global optima. Simulation results presented in Santos et al. [27] show evidence that the MOEA with NDE (MEAT) is an efficient alternative to deal with PDSR problems in large-scale distribution systems.

In this paper we present a novel method for solving PDSR problems, which is the result of an ongoing collaboration between two research groups in Brazil, one at UFMG, Minas Gerais, and another at USP, São Paulo. The approach is based on a discrete version of the differential evolution (DE) algorithm, initially presented in Prado et al. [22,23] and Guimarães et al. [11] for permutation-based combinatorial optimization problems. We extend the ideas and general framework presented in Prado et al. [22,23], by using the NDE presented in Santos et al. [26] and a new ancestor tree presented here to implement DE for service restoration problems. The use of an ancestor tree is not only central to implement differential mutation in our algorithm but also can track the sequence of switching operations in the restoration of the system when the optimization process is finished. In Section 3.3 we describe in detail through an illustrative example how the ancestor tree is built based on the NDE for PDSR problems.

In summary, the main contributions of this work are:

- The proposition of an ancestor tree that links individuals in the population to its ancestors in the evolutionary process.
- The use of this ancestor tree to build a list of elementary movements that maps one solution in the search space into another, thus capturing the "difference" between forests encoded with the NDE, which is essential in the search engine of DE.
- The combination of the NDE presented in Santos et al. [26] and the ancestor tree to implement a DE algorithm that is suitable for PDSR problems, particularly returning high quality solutions quickly for service restoration.
- The possibility of obtaining the sequence of switching operations for service restoration from the ancestor tree, hence tracking the operations from the initial configuration to the best solution found. The utility company can use this information to analyze the effects of the switching operations after the optimization is completed.



(a) Sector in fault (b) New configuration

Fig. 1. Service restoration.

The goal in this work is to evaluate the proposed algorithm for solving the problem of service restoration in large distribution systems. We adopt a single objective formulation, combining objectives and constraints into one function to be minimized. Although multi-objective approaches have been used in network reconfiguration problems and have been justified and attractive in some reconfiguration and planning applications, obtaining high quality solutions in a short time is a requirement in service restoration problems, since utilities are evaluated by the regulatory agencies also in terms of the duration of service interruptions. Therefore the additional step of selecting one solution among the trade-off solutions returned by a multi-objective approach might introduce unwanted delay in the process. For this practical reason, the several objectives and constraints in the PDSR problem are addressed through a mono-objective formulation that uses an aggregation function weighting objectives and constraints.

The paper is organized as follows: Section 2 describes the reconfiguration problem and its mathematical formulation; Section 3 presents the differential evolution for the problem; Section 4 shows the test results obtained with the method.

2. Reconfiguration problem

2.1. Service restoration

After the occurrence of a fault in a distribution system (DS), the area near the fault has to be identified and isolated, leading to some out-of-service areas. Service restoration (SR) consists in connecting the out-of-service areas to other feeders by opening and/or closing switches. An example of SR in a DS with three feeders is shown in Fig. 1, where rectangles indicate power sources in a feeder, solid lines are normally closed (NC) switches, dashed lines are normally open (NO) switches, and circles indicate sectors[2] [27]. In Fig. 1(a), a fault happens in sector 4 hence it must be isolated from the system by opening switches A and B. In this case, sectors 7 and 8 will become an out-of-service area (shaded region in Fig. 1(a)). One way to restore energy for these sectors is closing switch C, as shown in Fig. 1(b).

However, in typical distribution systems, there is a high number of possible combinations of these switching operations that could restore the energy to the out-of-service areas or at least to the majority of them. Optimizing this process means reconnecting the system in an optimal (or near optimal) way, satisfying the following constraints [27]: (i) a radial network structure should be

[1] The term "re-connectible 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 DS sector is a set of buses connected by lines without switches.

Please cite this article in press as: R.S. Prado, et al., Differential evolution using ancestor tree for service restoration in power distribution systems, Appl. Soft Comput. J. (2014), http://dx.doi.org/10.1016/j.asoc.2014.06.005