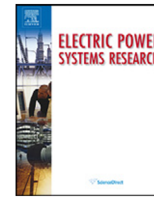
Electric Power Systems Research 97 (2013) 19–33

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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



A practical codification and its analysis for the generalized reconfiguration problem

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ARTICLE INFO

Article history:
Received 20 May 2012
Received in revised form 6 October 2012
Accepted 3 December 2012
Available online 16 January 2013

Keywords:
Radial distribution networks
Multi-objective
Constrained optimization problem
Graph theory

ABSTRACT

Distribution network reconfiguration problem is simply aimed at finding the best set of radial configurations among a huge number of possibilities. Each solution of this set ensures optimal operation of the system without violating any prescribed constraint. To solve such problem, it is important to count on efficient procedure to enforce radiality. In this paper, we propose a reliable approach to deal properly with topology constraint enabling algorithm convergence toward optimal or quasi-optimal solutions. A simple and practical codification of individuals used in evolutionary algorithms to solve the generalized reconfiguration problem is detailed in this paper. Mathematical formulation, algorithm, and simulation results are presented for the distribution reconfiguration problem, incorporating a new representation scheme which is immune to topologically unfeasible possibilities. The individual interpretation procedure is straight and it demands no additional data structure or graph preprocessing. Comparisons are made for five well-known distribution systems to demonstrate the efficacy of the proposed methodology. It is also demonstrated that optimal configurations are properly surveyed when single or multiple sources are dealt.

1. Introduction

Reconfiguration is often employed in distribution networks to improve their operating conditions which are guided by common theoretical indexes such as power loss and voltage deviation. As a matter of concern, reconfiguration of such networks can be done only if system security is preserved. The distribution feeder reconfiguration, known as the DFR problem in short, is understood as altering the interconnections between busses by means of switching on and off the connecting lines. As stated by Zhu [1], DFR optimization problem consists in finding feasible configurations over a meshed structure which may be able to improve objectives as much as possible while operating constraints are satisfied [1]. In this sense, the radial topology is preferred over others due to the coordination of protective devices at lower financial costs and lesser vulnerability against overcurrent. The DFR problem is highly combinatorial since the number of possible configurations increases exponentially according to the number of N_W maneuverable switches (sectionalizing and tie-switches included) in the distribution network [2,3]. Due to it, feasible configurations set belong to a small fraction of the space delimited by topological and electrical constraints which is a challenge for most of the searching methods.

The DFR problem is characterized as being a multimodal and combinatorial optimization problem, generally described by a set of nonlinear and non-differentiable functions. Being a NP-complete problem [4,5], there is no known method able to provide exact solution within a reasonable time. Its complexity weakens the effectiveness of any pre-established guideline unless the approach is restricted to particular network structure, as expert systems are. Exact solution (or optima set) is obtained by sweeping the entire search space to find every feasible configuration. This exhaustive procedure requires intensive computing to evaluate 2^{N_W} combinations. In real-world distribution networks, maneuverable switches are numerous and the computational effort spent to find the pareto-optimal solutions (PoS) becomes prohibitive as we will demonstrate in this paper. Despite of problem dimensionality, larger search spaces implicate on more opportunities for greater losses reduction and better system operating conditions probed by means of reconfiguration [6].

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http://dx.doi.org/10.1016/j.epsr.2012.12.002

One of the main challenges closely related to the discrete and combinatorial nature of DFR problem is the representation of solutions. In this article, codification is our main concern and a complete scheme to represent, interpret and recombine solutions is described. As stated in [7,8], the individual representation determines the success or failure of the optimization procedure tackled by any evolutionary algorithm. This paper keeps its focus on a novel, simple and generic, but not less efficient, individual codification that needs no additional computation to repair individuals or special genetic operator customization. Our strategy works for single and multiple sources as well as for networks where some of the lines have no switches. From the experiments, we have clear evidence that our scheme does not disturb the convergence of the evolutionary algorithm. It trusts on a proper individual interpretation which is done gradually to avoid topology violation such as bus islanding or loop. The way the individual is built and modified satisfies many properties required for encoding techniques reported by Raidl [9], such as feasibility and bias. The decoding procedure has lower complexity keeping the search space coverage at a reasonable level. Although we have applied our codification scheme to an NSGA-II [10] implementation, it is also adaptable to any other population-based meta-heuristic search technique.

This paper is organized as follows. In Section 2, related works are discussed and their main drawbacks and specialties are commented. The restricted multi-objective formulation to the feeder reconfiguration problem is given in Section 3. In Section 4, details about our codification scheme and associated stochastic operators are provided justifying the usefulness of the proposed methodology. Finally, experimental results are shown in Section 5 while concluding remarks of this work are summarized in Section 6.

2. Previous works

In the last three decades, much work has been dedicated to improve methodologies and adapt the algorithms which deal with DFR optimization problem, making them proper, faster and more robust in searching for global optima, especially when large-sized distribution networks are dealt. Initially, heuristic techniques were thought to be the best option due to the combinatorial nature of DFR problem. Many proposals as the methods reviewed by Sarfi [11] range from pure heuristics [6,12–14] to blended methods [15–17]. They were widely employed in the past to solve DFR problem and they are still being used [18–21]. Nonetheless, those methods are susceptible to landscape entrapments and regions of attraction created by local optima. To overcome such drawbacks, evolutionary algorithms have been a promising class of techniques in solving combinatorial problems satisfactorily. Although these techniques were first introduced to the DFR problem by Nara using classical genetic algorithms in the 1980s [22], the performance of such algorithms has been hardly affected by the chromosome representation ever since [23,24]. Since then, several skillful codification schemes have already been proposed by researchers in order to properly deal with topology check which is considered the main hurdle of the DFR problem [25]. On binary coding, bit 0 (1) conventionally denotes an open (closed) switch of the distribution network [22,26]. From technical viewpoint, codification schemes have been classified in two main types: node encoding and branch encoding. Of course, secondary encoding strategies conceived as a combination of the two previous codifications have also been proposed like path-to-node [27], matroid theory, [28] and network random key [7].

This brief review focused on the main contributions of codification applied to meta-heuristic techniques found in the specialized literature. Particularly, our codification scheme is derived from Carreno's proposal [29]. In that work, he presented a branch encoding approach which aimed on better application of stochastic operators. Its chromosome contained N_L genes which were grouped into two parts to represent active and inactive lines. A time-consuming local search was employed in place of mutation operator. This local improvement step worked as a limited brute force trying all possible combination derived from the best solution known hitherto. To efficiently implement it, knowledge about loops and paths to substation were required in advance at the expense of additional processing. Carreno's strategy may degrade diversity on the current population leading to local optima. His integer codification has followed previous schemes based on strings, presented by Hsiao [23], Shin [30], Huang [31], and Kumar [32]. Although being easy to implement, those strings (characterisc vectors) are longer as the network size increases. Aiming at more concise representations, Zhu [1] coded only the open switches of a distribution network. The suggestions came from Zhu brought some efficiency to the representation proposed by Nara [22] to the landscape searching and to the algorithm itself with the shortening of chromosome length. Other simpler node encoding representations adopted integer codification focusing more on the content of the individual than on the stochastic operator functionalities. To cite a few works, predecessor node [33] and predecessor node with restricted alphabet [34] could be pointed out. Thus, those strategies soften the individual interpretation but feasibility assessment becomes burdened. Milani [35] also employed a chromosome structure dividing genes into groups of substrings to represent, in a binary form, the set of branches pertaining to the same loop. To improve the search throughout the viable space, he adopted a scattered crossover and mutation with variable rate as genetic operators. Adopting a variable length differential vector, Lin [36] coded only switches whose status were modified. As an alternative, Lin also proposed a partial non-random initial population and a probability rate shared by both crossover and mutation operators to enable balance between exploration and exploitation fed back by the actual performance of the algorithm. Following a quite different strategy, Mendoza [37] also used an integer codification to enumerate open switches in the network. His work was primarily based on graph/topological analysis. As a consequence, his strategy demanded preprocessing to generate a lookup table of fundamental loops. Any further description about repair mechanism was not provided which could be probably based on hit and trial. Swarnkar [25] conceived an individual encoding, as Mendoza did, whose application was guided by a set of rules along with concepts on graph theory. In that work, the optimization process should start up from an initial solution found by a branch-exchange heuristic [13]. As in [37], this strategy demanded supplemental information about the system under analysis. It is noteworthy that this preprocessing stage is much costly for meshed and larger structures. Furthermore, the rate of successful crossovers decreases with the number of loops in the network [28]. Even adopting a similar chromosome structure to Carreno's proposal, our representation scheme is submitted to a different interpretation which is the key to ensure immunity to unfeasible solutions that would be produced by an evolutionary algorithm (EA). In our proposition, there is no effort applied to avoid or repair unfeasible offspring, since we simply circumvent these obstacles by means of a flexible interpretation. Avoiding most of the drawbacks seen in the references above is our main concern.

3. DFR mathematical model

Once DFR optimization problem is closely related to configuration, optimization variables should reflect somehow the interconnections among busses. Commonly, any configuration c can be described by on/off statuses of the N_W switches. A binary vector $\boldsymbol{sw^c}$ ($\boldsymbol{sw^c} = [sw_1^c \ldots sw_q^c \ldots sw_{N_W}^c]$) is a possible representation