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A novel codification for meta-heuristic techniques used in distribution network reconfiguration

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ABSTRACT

In this paper, a new codification is proposed for various meta-heuristic techniques to solve the reconfiguration problem of distribution networks. The full potential of meta-heuristic algorithms can be exploited by their efficient codification using some engineering knowledge base. The distribution system reconfiguration problems are non-differentiable, mixed integer and highly complex combinatorial in nature. In addition, the radiality constraint typically increases the intricacy of the meta-heuristic evolutionary algorithms. The proposed codification is based upon the fundamentals of graph theory which not only restricts the search space but also avoids tedious mesh checks. The proposed codification is computationally efficient and guarantees to generate only feasible radial topologies all times. The proposed method has been tested on three different test distribution systems and the results are promising.

1. Introduction

Distribution networks are generally structured in mesh but operated in radial configuration for effective co-ordination of their protective schemes and to reduce the fault level. The reconfiguration of a distribution system is a process that alters feeder topological structure by managing the open/close status of sectionalizing and tie-switches in the system under contingencies or under normal operating conditions. The aim of distribution network reconfiguration is to find a radial operating configuration that optimizes certain objectives while satisfying all the operational constraints without islanding of any node(s). The problem of distribution network reconfiguration is highly complex, combinatorial, nondifferentiable optimization problem due to the large number of discrete switching elements. In addition, the radiality constraint typically introduces additional complexity in the reconfiguration problem of large-sized distribution networks.

In the literature, several meta-heuristic techniques were proposed to solve the reconfiguration problem for loss minimization. To mention some of the publications [1–11], applied genetic or evolutionary algorithms for loss minimization. Recently some other stochastic based techniques like simulated annealing [12,13], tabu search algorithm [14,15], ant colony optimization [16–19], particle swarm optimization [20,21] etc. also attempted the distribution network reconfiguration problem. These meta-heuristic techniques are stochastic based search techniques which are initiated by initial population composed of definite number of individuals, i.e., tentative solutions. When the network reconfiguration problem is solved by these techniques, one of the principal difficulties is the radiality constraint, which ensures the radial network topology with all nodes energized. The radiality constraint not only creates difficulties in the formation of the initial population but also during intermediate stages of the evolutionary process. An efficient codification of these meta-heuristic techniques has remained without perfect solution for many years.

Morton and Mareels [22] proposed brute force solution to list and evaluate all feasible radial configurations for a distribution network. The optimal solution was guaranteed, but the method cannot be used for a real distribution network because the number of feasible radial configurations increases exponentially with the increase in the number of distribution feeders. To solve the reconfiguration problem of large-sized or real distribution systems, many researchers have proposed different codification for meta-heuristic techniques to maintain the radiality constraint. Delbem et al. [5] developed an integral proposal using concepts of graph theory by introducing specialized operators to deal with the problem of generating radial topologies efficiently. However in this approach, only the mutation operator was used and the recombination operator was discarded as it usually generates infeasible individuals. The Prufer number representation suggested by Hong

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and Ho [6] suffered from the drawback that infeasible radial configurations could appear after operations of crossover or mutation [10,11]. Mendoza et al. [7] have used loop vectors to ensure the generation of feasible individuals. However, this approach fails to search the isolation of principal interior nodes of the distribution networks and therefore requires mesh checks. Romero et al. [8], proposed a method to generate radial topologies based on the concept called path-to-node. The proposal consists of identifying paths linking each bus to the substation, which is an exhaustive approach. Enacheanu et al. [9] combined the Kruskal algorithm with the matroid theory to find spanning trees. The algorithm generates a chain of spanning trees using branch exchange mechanism. Carreno et al. [10] suggested a method of codification to generate only radial topologies by subsequent branch addition technique in an exhaustive manner therefore it increases computational burden until or unless supplemented by the knowledge of previously obtained heuristic solutions and by the general intelligence about topology of the given distribution network, but this may result in the loss of diversity. Abdelaziz et al. [21] presented an algorithm to differentiate between feasible and infeasible individuals with the help of bus incidence matrix 'A'. They suggested that the value of the 'determinant of A' is either 0 or ±1 for unfeasible and feasible radial topologies respectively. If the individual is infeasible the correction algorithm is very exhaustive as it replaces each switch subsequently with all the switches of the network. This algorithm looks very handy but since the combinations ${}_EC^s \gg N_t$, it increases CPU time in particular for medium and large-sized distribution networks. Moreover, the correction algorithm will not generate feasible individual if two or more switches require simultaneous correction.

Medoza et al. [7] used fundamental loop vectors to act as 'the cross mask' to ensure radial topologies throughout the genetic evolution. This drastically reduces the search space. However, it will produce infeasible individuals especially while solving the reconfiguration problem of large-sized real distribution networks. However, the action of 'the cross mask' is not clearly defined to correct infeasible individuals. In addition, the correction mechanism employed after crossover is based on hit and trial. In order to extract full potential of these meta-heuristic techniques, their codification must be deterministic, efficient and should not loose diversity. This work presents a new efficient codification for population based meta-heuristic techniques used to solve the reconfiguration problems of distribution networks. It always generates only feasible radial topologies during initialization as well as at each intermediate evolutionary stage under the guidance of rules framed without applying tedious mesh checks. In this way the shortcomings of the [7] are removed. Although these rules are applicable to any population based meta-heuristic search technique, however in this paper the proposed codification is demonstrated using Genetic Algorithm (GA) to solve the distribution reconfiguration problem for real power loss minimization.

2. Proposed codification

The radial configuration, in which the distribution network operates, should not posses any closed path with all loads energized. Such radial configurations are called trees of the distribution network graph (DNG) [23]. In the proposed codification the concepts of the graph theory [23] are incorporated and some rules are framed to correct infeasible individuals whenever generated in the evolutionary process without using tedious mesh checks. The application of the graph theory suggests total number of trees, N_t, which is given by the determinant of $A.A^T$, i.e.,

$$N_t = \det(A.A^T) \tag{1}$$

The square matrix A can be obtained from the matrix $\hat{A}$ by deleting the column corresponding to the reference node. The matrix $\hat{A}$ describes the incidence of nodes to the elements of a DNG and is of the order $E \times N$. The element a_{ij} of the matrix $\hat{A}$ can be +1, -1 or 0 as defined below

$$a_{ij} = \begin{cases} 1; & \text{if the } i\text{th element is incident to and oriented away from the } j\text{th node.} \\ -1; & \text{if the } i\text{th element is incident to and oriented toward the } j\text{th node.} \\ 0; & \text{if the } i\text{th element is not incident to the } j\text{th node.} \end{cases}$$

Any tree of a DNG is composed of $(N-1)$ twigs (i.e., tree branches). The set of links constitutes co-tree and it is the complement of the tree. The number of links of a DNG is unique and is given by

$$s = E - (N-1) \tag{2}$$

For distribution networks, the number of links is usually much less than the twigs. Therefore, co-tree can be used for the codification of the individual of meta-heuristic techniques as in [3,7].

While exploring the solution of distribution network reconfiguration problem using some meta-heuristic technique, the initial population may be obtained through the random selection of s number of candidate switches out of all E number of switches of the distribution network. Most of the time, it generates infeasible individuals, particularly in case of medium or large-sized distribution networks. This certainly leads to increased computational burden to create initial population. Moreover, there occur definite possibilities of the transformation of the feasible individuals into infeasible ones, during intermediate stages of the search techniques and thus mesh checks becomes mandatory. This is sufficient to slow down the pace of the meta-heuristic techniques. The problem of distribution network reconfiguration thus may be described as to explore that particular co-tree, whose corresponding tree optimizes its objectives while satisfying all the constraints.

In the proposed algorithm, to create feasible individuals and to correct the infeasible individuals, some graph theory based rules have been framed. Let us define the following terms before actually framing these rules.

Principal node: the junction of three or more elements of the DNG.
Exterior node: the node located at the perimeter of the DNG.
Interior node: the node located inside the perimeter of the DNG.
Loop vector: it is the set of elements constituting closed path in a DNG.
Common branch vector: it is the set of elements which are common between any two *loop vectors* of a DNG.
Prohibited group vector: it is the set of the *common branch vectors*, from each of them if one element is opened then one or more interior nodes of the DNG will be islanded. The size of *prohibited group vector* cannot be greater than *s*.

Let, $L_j; j \in \{1, 2, \ldots, s\}$, $C_k; k \in \{1, 2, \ldots, c\}$ and $P_h; h \in \{1, 2, \ldots, g\}$ denotes loop vectors, common branch vectors and the prohibited group vectors respectively for the given topology of a distribution network. Consider the qth individual I_q^t produced at tth iteration of the evolutionary process and is constituted as a set of s number of discrete switches, then it can be represented as

$$I_q^t = \{S_2^q, S_2^q, \ldots, S_m^q, \ldots, S_s^q\}; q \in \{1, 2 \ldots, s\} \text{ and } t \in \{1, 2 \ldots, N_o\}$$

For this individual I_q^t to be feasible, i.e., provides radial topology without islanding of any node or a group of nodes of the distribution network, the following rules have been framed to select its mth candidate switch S_m^q

Rule 1: each candidate switch must belong to its corresponding *loop vector*.

$$S_m^q \in L_m; m \in \{1, 2 \ldots, s\}; q \in \{1, 2, \ldots, p\}$$