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Adapted ant colony optimization for efficient reconfiguration of balanced and unbalanced distribution systems for loss minimization

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ABSTRACT

This paper presents an efficient method for the reconfiguration of radial distribution systems for minimization of real power loss using adapted ant colony optimization. The conventional ant colony optimization is adapted by the graph theory to always create feasible radial topologies during the whole evolutionary process. This avoids tedious mesh check and hence reduces the computational burden. The initial population is created randomly and a heuristic spark is introduced to enhance the pace of the search process. The effectiveness of the proposed method is demonstrated on balanced and unbalanced test distribution systems. The simulation results show that the proposed method is efficient and promising for reconfiguration problem of radial distribution systems.

1. Introduction

Distribution networks are generally structured in a mesh but operated in the 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 the feeder topological structure by managing the open/close status of sectionalizing and tie-switches in the system under contingencies or under normal operating conditions. Reconfiguration of the radial distribution system is a very effective and efficient means to reduce distribution network losses, improve voltage profile, manage load congestion and enhance system reliability. 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).

A lot of research work has been carried out to solve distribution network reconfiguration problems. These research efforts can be broadly classified into traditional approaches and artificial intelligence (AI) based approaches. The traditional approaches include heuristic optimization techniques and classical optimization techniques. Merlin and Back [1] were first to report a method for distribution network reconfiguration to minimize feeder loss. They formulated the problem as a mixed integer nonlinear optimization problem and solved it through a discrete branch-and-bound technique. Later, [2–7] also suggested different branch exchange heuristic algorithms. The complexity of reconfiguration problem increases with the exponential growth in the size of modern distribution networks and the heuristic techniques fail to provide a quality solution. Therefore, the researchers diverted toward various stochastic-based search techniques. Nara et al. [8] introduced genetic algorithm (GA) for reconfiguration of distribution networks for loss minimization. Later, several GA based methods [9–14] have been used for the reconfiguration of distribution networks. Mendoza et al. [13] proposed a new methodology for minimal loss reconfiguration using GA with the help of fundamental loops. They restricted the search space of GA by modifying the genetic operators. Enacheanu et al. [14] presented a method based on GA for loss minimization in the distribution networks using matroid theory and graph theory. Some other population-based meta-heuristic techniques, e.g., immune algorithm [15], evolutionary algorithm [16], simulated annealing [17,18], tabu search [19–21], particle swarm optimization [22] also attempted the reconfiguration problem.

The ant colony optimization (ACO) is a population-based meta-heuristic technique, has emerged as a powerful tool for solving combinatorial optimization problems, initially proposed by Marco Dorigo in 1992 in his Ph.D. thesis [23]. The search technique is inspired by the behavior of ants in finding paths from the nest to food and back to the nest. It was implemented to solve the traveling salesman problem (TSP) by Dorigo and Gambardella [24]. Later, Stutzle and Hoos [25] developed the max–min ant system (MMAS) to solve TSP and quadratic assignment problem. Then the basic ACO was further improved and a model-based search (MBS) algorithm was introduced by Blum and Dorigo [26]. Das et al. [27] attempted ant colony

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approach to compute minimum Steiner tree. The original idea of ACO has been diversified to solve a wider class of problems. Recently, the ant algorithm also has been applied to various optimization problems of the power systems, such as short-term generation scheduling problem [28], unit commitment [29], hydroelectric generation scheduling [30], distribution system planning [31,32], joint optimization for capacitor placement and reconfiguration of the distribution systems [33]. Su et al. [34] proposed state transition rule, local and global updating rules to make the ACO computationally efficient to minimize real power loss in the distribution networks. Ahuja et al. [35] introduced the inherent feature of hyper-mutation of Artificial Immune System (AIS) into the ACO algorithm for multi-objective optimization reconfiguration problem to avoid local minima. Carpaneto and Chicco [36] employed restricted branch exchange to improve the computation efficiency of the conventional ACO.

The reconfiguration of the distribution system for loss minimization is a complex, combinatorial optimization problem. The application of these population-based search techniques to solve the reconfiguration problem of the distribution networks faces an additional difficulty of maintaining the radiality constraint throughout the evolutionary process. The methods available in the literature provide different ways of maintaining radiality constraint, but, they are incomplete in the sense that they may generate infeasible individuals during initialization as well as during the evolutionary process. These infeasible individuals are either rejected or corrected using some mechanism and the process is repeated till feasible individuals are obtained, which may be time consuming.

The main contribution of this paper is to propose a new codification to generate only feasible radial topologies of distribution system while solving the reconfiguration problem using the ACO. For this purpose, some rules are framed with the help of the graph theory and the conventional ACO is adapted by these rules, hence named Adaptive Ant Colony Optimization (AACO). The other contributions of this work are: initial feasible population is created randomly to maintain the diversity, a heuristic spark (HS) is introduced to make AACO computationally efficient, and the desirability is defined on the basis of node voltages to guide the ant search.

In this paper, the reconfiguration problem of the balanced and unbalanced distribution networks to minimize real power loss is solved using AACO. The organization of the paper is as follows. The formulation of the loss minimization problem is discussed in Section 2. The conventional ACO is explained in Section 3. The modifications proposed in the conventional ACO are discussed in Section 4, in Section 5 the proposed codification for AACO is illustrated with the help of an example. In Section 6, the application results of the proposed method on balanced and unbalanced distribution systems are presented and finally concluded in Section 7.

2. Problem formulation for minimal power loss

The distribution networks are reconfigured frequently to optimize operational efficiency and maintain power quality. The principal objective of distribution network reconfiguration is to find the radial operating structure having minimum real power loss while satisfying various operating constraints. All the loads are assumed of the nature of constant power. The reconfiguration problem of distribution networks for loss minimization is formulated as below:

$$\text{Minimize} \quad \sum_{n=1}^{E} R_n \frac{P_n^2 + Q_n^2}{|V_n|^2} \tag{1}$$

$$\text{Subject to} \quad I_n \le I_{\max}^n \tag{2}$$

$$V_{\min} \le V_n \le V_{\max} \tag{3}$$

$$\Phi(i) = 0 \tag{4}$$

where, V_n, P_n and Q_n are voltage, real power and reactive power at the sending end of the nth branch respectively, R_n is the resistance of the nth branch and E is the total number of branches in the system.

Eq. (1) corresponds to the objective function to be optimized and represent total real power loss of the distribution system. Eq. (2) corresponds to limit branch current and substation current capacities within the permissible limits. Eq. (3) considers voltage constraints for each node of the system. Eq. (4), represents the radial topology constraint, it ensures radial structure of the ith candidate topology.

3. Ant colony optimization

The ant communication is accomplished primarily through the chemicals called pheromones. While moving, the ants deposit the pheromone trail on the ground. Other ants perceive the presence of the pheromone and tend to follow paths where the pheromone concentration is higher. The probability with which the kth ant will move from node i to node j can be determined by the random-proportional state transition rule [25] as given below:

$$P_{i,j}^k = \frac{(\tau_{i,j})^\alpha (\eta_{i,j})^\beta}{\sum (\tau_{i,j})^\alpha (\eta_{i,j})^\beta} \tag{5}$$

where $\tau_{i,j}$ is the amount of the pheromone on the edge $i - j$, α is the parameter to control the influence of $\tau_{i,j}$, $\eta_{i,j}$ is the desirability of the edge $i - j$ (a priori knowledge, typically $1/d_{i,j}$, where d_{ij} is the distance between node i and node j) and β is the parameter to control the influence of $\eta_{i,j}$

While moving from node i to node j, the kth ant updates the pheromone on the edge $i - j$. To escape local minima, the pheromone evaporation is used. A minimum pheromone concentration of small positive number may be considered to avoid zero or negative value. The evaporation is applied uniformly to all the edges with a simple decay coefficient ρ. The pheromone update is given by

$$\tau_{i,j} = (1 - \rho)\tau_{i,j} + \Delta\tau_{i,j}^k \tag{6}$$

where $\tau_{i,j}$ is the amount of pheromone on a given edge $i - j$, ρ is the rate of pheromone evaporation and $\Delta\tau_{i,j}^k$ is the amount of pheromone deposited by the kth ant, typically given by

$$\Delta\tau_{i,j}^k = \begin{cases} 1/C_k, & \text{if and } k \text{ travels on the edge } i - j \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where C_k is the cost of the kth ant's tour (typically length).

4. Proposed adaptive ant colony optimization (AACO)

When the conventional ACO is employed to solve the reconfiguration problem of distribution networks, the radiality constraint imposes the main hurdle since a large number of infeasible individuals appear during initialization as well as at intermediate stages of the evolutionary process. These infeasible individuals may be transformed into feasible ones using some engineering knowledge base. The proposed methodology creates feasible individuals all times by encoding the individual ant with the help of the graph theory [37] and the terms are redefined in the context of distribution network reconfiguration, as described in the next sub-sections.

4.1. Ant encoding using graph theory

The graph of the given distribution network can be obtained by closing all the tie-switches. The radial configuration in which the distribution networks must operate should not possess any closed path with all nodes energized. These radial configurations