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A reliability assessment based graph theoretical approach for feeder routing in power distribution networks including distributed generations

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ABSTRACT

Feeder routing becomes more challenging as Distributed Generations (DGs) are increasingly embedded into the power distribution network. This paper presents a graph theoretic based feeder routing (a mixed non-linear integer optimization problem) in power distribution network including DGs. Graph theory is found to be much simpler and effective technique that significantly reduces the complexities of the search algorithms and provides the optimal radial path while minimizing the cost. The proposed technique has been extensively tested for different topologies of power distribution networks considering DGs and the results obtained for feeder routing is highly encouraging compared to the existing techniques. Also the reliability assessment is carried out to evaluate the reliability of the optimal radial networks including DGs.

1. Introduction

Planning of power distribution network is highly complex as it has to consider various important issues including technical and environmental constraints while meeting the customer needs [1,2]. Thus, the objective of the optimization function is to obtain optimal network configuration while satisfying all the system requirements and constraints with minimum cost. In general, the planning problem of distribution networks may be stated as an optimization problem for a given geographical area or region with a set of load demands including the location of the transformation centers required for the load supply while minimizing the total installation and operation costs [3–16]. Moreover, the distribution system planning addresses numbers of issues such as to determine number of feeders and their routes, the substation location, size and its service area. The problem is nonlinear, non-differentiable, and combinatorial in nature with a large number of discrete and continuous variables. Among the aforementioned issues, feeder routing is one of the critical tasks in distribution planning and needs to be focused for obtaining improved solution.

The most commonly used classical solution for feeder routing problem is mixed integer linear programming [4,5] and are multi-stage solutions where the nonlinear problem is transformed into linear problem without any integer restriction and is solved by employing linear programming techniques. These models are difficult to solve and computational burden becomes very high as the distribution system planning considers a large number of discrete variables. Recently, random search algorithms such as Genetic Algorithm (GA), Ant Colony System (ACS), Simulated Annealing (SA), Adaptive particle swarm optimization (AMPSO), and BFO etc. have been applied for distribution planning reconfiguration problem [7–25]. Even if GA [9] is found to be better compared to the classical techniques, however, the binary string for the integer variable becomes larger leading to computational complexities.

Simulated annealing [10] is another technique applied to improve the status of the optimal feeder routing which uses steepest descent method for initial solution and network is iterated by selecting a new branch randomly. Subsequently, the newly formed mesh is opened by removing a branch selected by a random selection process again. However, the load flow has to be performed at each step to check the effect of including new branch in the network. An attempt has been made to apply ant colony for the distribution planning [11], however, it requires number of parameters to be fine-tuned and the algorithm needs to run more generations to fine tune the parameters. Recently, other approaches for distribution planning [14,15] have been explored for providing a simple and reliable solution for feeder routing. However, the accuracy of the optimization techniques cannot improve further after certain limit.

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Recently, the distribution feeder reconfiguration planning proposed by Niknam et al. [16] presented a new method based on adaptive modified PSO for considering load and wind uncertainty. Furthermore, operational and economical aspects of the distribution systems including active power losses, voltage deviations and the total cost, are considered for problem formulation. However, the reliability assessment has not been done in the proposed work. Further, Niknam et al. [17] proposed a new method that combines the Self-Adaptive Modified Particle Swarm Optimization (SAMPSO) with Modified Shuffled Frog Leaping Algorithm (MSFLA) for optimal solution. However, the proposed work considered only the power loss as an objective function without taking system operational and investment cost into account and also reliability assessment has not been considered. In addition, reliability oriented distribution network reconfiguration [18] considers investment cost, operational cost and, expected energy not served (EENS) as an objective function. Similarly in our proposed GTA based approach, the cost associated with the system interruption has also been considered into account (in the objective function) along with the reliability assessment. Moreover, most of the aforementioned approaches have not considered DG units in the power distribution network and also their effect on reliability assessment while performing feeder routing task. Thus, there is a strong motivation for developing a new methodology for optimal feeder routing with DG units in power distribution network. Several recent research works have shown the impact of distributed generations on electrical energy losses in distribution lines, voltage profile, Var control and set of pollutants produced by the grid etc. [26–30]. Thus, a new approach based on graph theory [31–33] is considered for optimal feeder routing of power distribution network including DGs, providing improved performance.

In this paper we have proposed a graph-theoretic based feeder routing of the given power distribution system and observed the impact of DG integration on the feeder routing. To show the efficacy of this novel approach, comparisons have been made with existing techniques. This paper deals with following issues: (i) feeder routing without DG interface [8–15], (ii) feeder routing with and without DG interface considering reliability assessment. Thus, a comprehensive scheme for optimal feeder routing in power distribution network is developed for feeder routing including reliability assessment. The following sections deal with Problem Formulation, Graph Theory for Optimization, Computational results and analysis, Reliability assessment and Conclusions.

2. Problem formulation

The distribution planning problem may be defined as an optimization problem considering all the investment cost as well as the operational cost as objective function subject to the constraints.

In mathematical terms, the problem statement may be defined as

$$\text{Minimize, } C_{total} = C_{inv} + C_{opt} \tag{1}$$

where C_{total} is the total cost, C_{inv} refers to investment costs and C_{opt} denotes operational costs. An investment cost refers to the cost of a substation, feeder length cost, etc., whereas the cost against losses and interruption costs falls under operational cost. The details of the various cost functions are defined as follows [14]:

(i) *Investment costs*:

The capital yearly recovery cost is defined as:

$$C_f = g * \sum_{b \in K} C_b \tag{2}$$

where g is the capital recovery rate of the fixed cost; C_b the cost of the branch b of the main feeder; K is the total number of branches.

Costs of branches emanating from the source substation include both the lines and the corresponding source cost. K denotes set of branches of a network structure taken under consideration.

(ii) *Operational costs*:

The second component is interruption cost and as there are no alternative supply routes available to energize the load nodes in a radial network, thus an outage of a branch interrupts the delivery to all consumers supplied through this branch. Thus, the cost of supply interruption can be expressed as

$$C_i = ci\alpha d \sum_{b \in K} \lambda_b \sqrt{3}\mathrm{Re}\{I_b\} U_r \tag{3}$$

where ci is the cost per unit of energy not delivered; α the load factor; d the repair duration; λ_b the branch failure rate; U_r the network rated voltage; I_b is the branch current at peak load.

The third component is the cost of energy losses 'C_l' and is expressed as

$$C_l = 8760cl\beta \sum_{b \in K} r_b \mathrm{Re}\{I_b\}^2 \tag{4}$$

and,

$$\beta = 0.15\alpha + 0.85\alpha^2 \tag{5}$$

where cl is the cost per unit of energy lost; β the loss factor; r_b the branch resistance; I_b the branch current at peak load; α is the load factor.

The total annual cost that should be minimized is

$$C = C_f + C_i + C_l \tag{6}$$

Subjected to the following constraints:

(i) *Thermal capacity limit constraint*:

The power flow through a branch 'i' (P_{Li}) of a network should be within its thermal capacity limit.

$$PL_i \leqslant PL_{i\max} \quad \forall i \subset K \tag{7}$$

where PL_i is the thermal capacity limit of ith branch; $PL_{i\max}$ is the upper bound of PL_i respectively.

(ii) *Voltage drop constraint*:

$$U_{i\min} \leqslant U_i \leqslant U_{i\max} \quad \forall i \subset \mathit{\Delta}_n \tag{8}$$

where U_i is the voltage of ith bus (p.u.); $U_{i\max}$, $U_{i\min}$ the upper and lower bounds of U_i respectively; $\mathit{\Delta}_n$ is the set of nodes.

(iii) *Substation capacity limit constraint*:

$$S_{j\min} \leqslant S_{capj} \leqslant S_{j\max} \tag{9}$$

where $S_{j\max}$ is the maximum capacity of the jth substation; $S_{j\min}$ the minimum capacity of the jth substation; S_{capj} is the capacity of the jth substation.

(iv) *Conservation of power flow*:

$$\sum_{(ji) \in K} P_{ji} - \sum_{(ij) \in K} P_{ij} + h_i = d_i \qquad \forall i \in \Delta_n \tag{10}$$

where P_{ji} is the active power flow between nodes j and i; h_i the active power supplied by the substation i; d_i is the active power demand at node i.

(v) *Radiality limit constraint* [14].

3. Modified load flow method

Load flow algorithm is developed by Das et al. [5], is modified in this present work to incorporate different load models such as constant power load, constant current load, constant impedance and exponential load. The convergence criterion is such that if the difference of voltage at every successive iteration is less than 0.00001 p.u., the algorithm converges. The modified load flow