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Path-set based optimal planning of new urban distribution networks

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ABSTRACT

This paper presents a method for optimal planning of new urban distribution networks based upon the selection of the best subset of paths providing back feed from the entire path set generated for the available cable routes. The optimal solution is the path subset providing minimum total annual cost including capital recovery, loss and undelivered energy costs while satisfying all technical constraints. The impacts of distributed generator units, if available, can be also taken into account in the optimization flow. The reliability requirements are additionally assured by introducing SAIFI and SAIDI constraints. The method allows for common trenches for cables and different sizes of feeders depending on their loads. The planner is allowed to choose the concept of back feed, through only feeders interconnecting source nodes, ring feeders or by the best combination of these two structures. During the optimization process the optimal distribution system trees are generated providing minimum loss operation. The search for the optimal network is conducted using the simulated annealing algorithm.

1. Introduction

The planning of new distribution networks is a very important and complex task implying various technical and cost issues as well as environmental constraints and customer requirements concerning the quality of energy delivery [1–3]. The possible network configurations depend on the available routes, sizes and locations of source substations and distributed generator (DG) units, if available, load point locations and on the adopted general concept of their structure. Urban networks are usually formed as a set of radially operating feeders with back feed options. Most commonly applied configurations are the interconnecting and/or ring feeders that can be supplied from both ends by different sources or by the same source, respectively. In normal conditions the feeders operate partitioned in two sections supplied from one end only. The feeder partition is performed to minimize the power losses. Technical constraints that have to be satisfied for each feeder are the maximum allowable voltage drops and the maximum load capacity of cables that must not be violated in the worst emergency circumstances when all feeder loads are supplied from one end. In many systems the requirements concerning reliability indices and energy not delivered due to network failures have an important impact on the economy of distribution operation and must be seriously taken into account.

In order to find the optimal network configuration various discrete search approaches were used in the past. A genetic algorithm was successfully used for determining the optimal network configuration for urban distribution systems providing back feeds of customers in emergency situations with minimum investment and loss costs [4]. The optimization of radial distribution networks was also conducted using ant colony system algorithm providing the minimum investment and loss cost solution [5]. The potential solutions are conceived based on system experts' suggestions. A constructive heuristic algorithm has been developed to find the optimal distribution tree structure complying with the available installed capacity of source substations [6]. The optimization of radial distribution networks with no back feed facilities was also conducted by applying the dynamic programming technique and geographical information systems [7]. Some possible solutions for minimizing the capital and operational costs of radial distribution networks including the optimal sizing and location of DG units for deferring the new investments have been investigated and compared [8,9]. Multi-stage methods for reinforcing, replacing or adding new resources to meet the growing demands in radial distribution systems during the planning period are suggested in [10,11] by taking into account the associated investment and loss costs. A method for distribution system planning using discrete particle swarm optimization algorithm has been used for selecting new supply routes and locations and sizes of DG units to mitigate

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the load growth for a distribution system of moderate size [12]. In [13] the Tabu search approach has been applied for planning of distribution systems with fuzzy data for economical cost, reliability performance and technical constraints. The best solution is searched for from the set of non-dominated Pareto solutions using the professional judgment or max–min approach. A sorting genetic and Pareto evolutionary algorithms have been applied for optimizing the distribution networks by selecting the minimum investment and loss cost configuration from a set of available supply routes [14]. The proposed approach can generate the best radial or mesh solution, depending on planners' choice. Very detailed and systemized overviews of the models and methods of power distribution systems planning including the impacts of distributed generation are presented in papers [15,16].

The approach applied in this paper is based upon the selection of the set of minimum cost supply paths with back feed abilities that can be formed along the available routes. The planner can in advance select the preferable feeder options among the following: feeders interconnecting source nodes, ring feeders, solutions with single cables only or with cables sharing the same trenches, any combination of these options. The proposed approach takes into account the capital, construction, loss and undelivered energy costs while satisfying all technical requirements. The optimal radial operating structures are determined for all network solutions generated during the optimization flow in order to find their minimum loss costs. The impacts of the DG units with given locations and sizes, if available, can be adequately accounted for in the optimization procedure. The reliability aspects can be additionally taken care of by introducing constraints on SAIFI and SAIDI indices for the network. It is important to stress that the optimization procedure generates both the optimal network configuration and its optimal radial operating structure ("distribution tree"). As known, the determination of this optimal structure is alone the subject of serious investigations [17,18].

To find the best solution a combined heuristic and simulated annealing search approach is used.

2. Optimization method

2.1. Generation of the set of possible supply paths

The conventional security principle in supplying urban distribution networks is to provide back feed for each feeder. For networks that operate as radial this condition is most commonly realized using open ring feeders the both ends of which are supplied by the same source substation and/or inter-tie feeders with ends supplied by two different source substations. The ring and inter-ties should be opened in such a way to achieve minimum power loss in normal operation. The potential supply paths having the above mentioned structure can be generated using the graph connection matrix [19,20]. Consider the elementary example in Fig. 1. The figure displays the graph of possible cable routes connecting source points 1 and 2 and load points 3, 4 and 5. The connection matrix of the sample graph is

$$[c] = \begin{bmatrix} 0 & 0 & 2 & 1 & 0 \\ 0 & 0 & 4 & 0 & 6 \\ 2 & 4 & 0 & 3 & 0 \\ 1 & 0 & 3 & 0 & 5 \\ 0 & 6 & 0 & 5 & 0 \end{bmatrix} \tag{1}$$

Element in row i and column k of matrix $[c]$ is the network branch connecting nodes i and k. Zero element implies that there is no single branch connection between the nodes associated with the row and the column to which this element belongs. Matrix $[c]$ gives the first order paths among network nodes i.e. paths consisting of single branches. We are interested in paths associated with source nodes only as they indicate potential inter-ties between these nodes as well as ring paths originating and terminating at the same source node. The second order paths associated with source nodes are obtainable by symbolical multiplication of matrix $[c]$ from left by its two first rows. The elements of the first two rows of the matrix obtained after this multiplication are

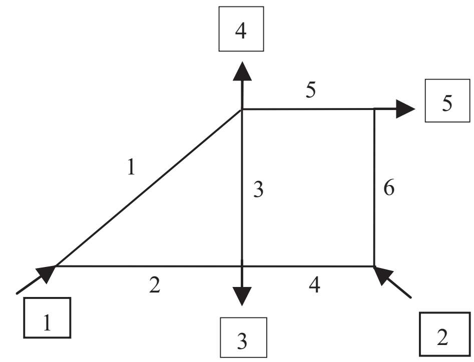

Fig. 1. Graph of available cable routes.

$$\begin{aligned}
&c_2(1,1) = 2\cdot 2 + 1\cdot 1, \quad c_2(1,2) = 2\cdot 4, \quad c_2(1,3) = 1\cdot 3,\\
&c_2(1,4) = 2\cdot 3, \quad c_2(1,5) = 1\cdot 5,\\
&c_2(2,1) = 2\cdot 4, \quad c_2(2,2) = 4\cdot 4 + 6\cdot 6, \quad c_2(2,3) = 0,\\
&c_2(2,4) = 4\cdot 3 + 6\cdot 5, \quad c_2(2,5) = 0.
\end{aligned} \tag{2}$$

Multiplication symbol between branch numbers implies that the corresponding branches form the path. Symbol "+" means "and". Element $c_2(i,k)$ in (2) gives the second order paths between nodes i and k. Elements $c_2(i,i)$ are rings associated with node i. As can be seen, there are two elementary rings at both source nodes implying two cables in the same trench, one going to the adjacent load node and the second, returning from this node to the source node. To determine the third order paths associated with source nodes matrix $[c]$ should be symbolically multiplied from left by the two row matrix formed by the elements in (2). This operation yields

$$\begin{aligned}
&c_3(1,1) = 1\cdot 3\cdot 2 + 1\cdot 2\cdot 3, \quad c_3(1,2) = 1\cdot 3\cdot 4 + 1\cdot 5\cdot 6,\\
&c_3(1,3) = 2\cdot 2\cdot 2 + 1\cdot 1\cdot 2 + 2\cdot 4\cdot 4 + 1\cdot 3\cdot 3,\\
&c_3(1,4) = 2\cdot 2\cdot 1 + 1\cdot 1\cdot 1 + 1\cdot 3\cdot 3 + 1\cdot 5\cdot 5,\\
&c_3(1,5) = 2\cdot 4\cdot 6 + 2\cdot 3\cdot 5,\\
&c_3(2,1) = 1\cdot 3\cdot 4 + 1\cdot 5\cdot 6, \quad c_3(2,2) = 0,\\
&c_3(2,3) = 4\cdot 2\cdot 2 + 4\cdot 4\cdot 4 + 6\cdot 6\cdot 4 + 4\cdot 3\cdot 3 + 6\cdot 5\cdot 3,\\
&c_3(2,4) = 4\cdot 2\cdot 1,\\
&c_3(2,5) = 4\cdot 4\cdot 6 + 6\cdot 6\cdot 6 + 6\cdot 5\cdot 6
\end{aligned} \tag{3}$$

The paths containing more than two same branches should be discarded in further analysis as they have no practical sense. Furthermore, if several identical paths for a source node or for a source node pair are generated, such paths are stored only once for further calculations. As can be seen from (3), two identical ring paths associated with node 1 have been generated. To deduce the fourth order paths, matrix $[c]$ should be symbolically multiplied from the left by the two row matrix with elements given by (3). The described procedure of generating paths of higher order from the paths of lower order can be continued till the previously selected path maximum order is reached or, if no such limit was introduced, till all generated paths contain multiples of same branches of higher order than two. The maximum path order should be selected in such a way to ensure that all load points will be covered