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An improved distribution network reconfiguration method based on minimum spanning tree algorithm and heuristic rules

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ABSTRACT

This paper presents an improved distribution network reconfiguration method with the goal to minimize active power loss. The proposed method combines the minimum spanning tree (MST) algorithm and improved heuristic rules. It consists of three procedures. The first procedure calculates the branch (edge) weights with bus (vertex) voltages, and then carries out preliminary optimization with MST algorithm to get a local optimal solution. The second procedure gets alternative optimal solution based on the improved heuristic rules. Then during the third procedure, the optimal solution can generally be obtained through correcting the results. The algorithm does not rely on the initial network topology. The local optimal solution, solved by MST algorithm, provides a favorable initial condition for the subsequent optimization procedures. Further with the improved heuristic rules, the amount of the candidate switches can be significantly reduced. Two typical test systems, 33-bus system and 69-bus system, and a real 210-bus MV utility distribution system verified the feasibility and effectiveness of the proposed method. The method has higher efficiency and can be used to the large distribution systems.

Introduction

Distribution network reconfiguration is an important tool for distribution network planning and online management. The main objectives of distribution network reconfiguration are to reduce the active power loss and achieve the rapid power restoration when system fails [1–4]. In order to get the optimal operation state of distribution network, it requires to decide the opened or closed status of all system switches. The distribution network reconfiguration is a combination optimization problem [5] and the candidate switches are more large, so it has a heavy computational burden and the optimal solution is difficult to find.

Currently, the common methods [4,5] to handle the distribution reconfiguration problems can be roughly divided into three categories,

(1) Optimal Flow Pattern Methods [6,7]. The basic idea is to find the optimal power flow according to the optimal conditions, and then to determine the opened or closed status of all switches. Because only one switch can be judged with twice weakly-meshed power flow calculations, those methods have more computational time and are difficult to get the optimal solution.
(2) Branches Exchange Method [8–11]. Those methods use the power loss changes with the branches exchange to find the switches need to be closed or opened. However, the results are heavily dependent on the network's initial structure. Moreover, the amount of switches which need to be evaluated may be great. So the searching efficiency is lower and it is not easy to find the optimal solution.
(3) Intelligent Optimization Algorithms, such as Particle Swarm Optimization algorithms [12,13], Genetic algorithms [14,15], Ant Colony algorithm [16], Tabu Search algorithms [17] and Harmony Search algorithms [18]. Generally speaking, this kind of methods can obtain the optimal solution. But those methods are more easily influenced by some factors. For example, network scale may lead to some parameters becomes more difficult to determine. Moreover, most of those methods are computational demanding, particularly for large-scale systems.

In such a great variety of solution techniques, the vast majority of the work presented in the literature was devoted to distribution system loss reduction and voltage profile improvement. In recent years, other significant objectives such as reliability, security

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enhancement and service restoration of in-service consumers have got more attention in the literature [19,20]. Moreover, since the smart grid philosophy has been a reality now, and besides the network reconfiguration, other methods, such as capacitor and distributed generator placement, can also reduce the loss [21–23].

Graph theory is a branch of mathematics. Graphs are commonly used to specify the specific relationships among objects. It can be described with sets of points and lines. Points are called vertices and the lines are called edges. The vertices represent objects and each edge represents the relationships between two objects. The distribution network can be seen as a graph, so it can use the graph theory algorithms to solve the distribution network planning and reconfiguration problems. Ref. [24] presented a fast determination method of topological radial property of distribution network based on the basic-tree and distribution network reconfiguration. By using an improved minimum cost spanning tree algorithm, Ref. [25] presented an optimal planning of distribution networks with multi-way power supply. The minimal spanning tree (MST) algorithm has been used to solve configuration problem in the distribution networks [26,27], where an assignment of the weighting coefficient to all branches are used to construct the minimal spanning tree. MST is an appropriate strategy to reconfigure the radial topology with less losses without using any optimization techniques. But they may not get the optimal solution.

In this paper, the loss reduction is selected as the objective for such methods can still be further improved. Next step, the reliability and the distributed generation can be taken into account in the application. The proposed reconfiguration method combines the minimum spanning tree (MST) algorithm and improved heuristic strategies. It involves three procedures. The first procedure carries out preliminary optimization with MST to get the local optimal solution. The second procedure can obtain alternative optimal solution based on the improved heuristic rules. And then the optimal solution can be generally obtained by the third procedure, correction. The method significantly reduces the amount of the switches which need to be evaluated. It makes reconfiguration much more efficient and saves computational time greatly. Moreover, the graph theory based reconfiguration method does not rely on the initial network topology. The test feeders verified the feasibility and effectiveness of the proposed method.

Objective function and constraints

Here, the objective is minimizing the active power loss. It can be expressed as follows [8],

$$\min P_{\text{loss}} = \sum_{k=1}^{n_b} R_k \frac{P_k^2 + Q_k^2}{V_k^2} \quad (1)$$

where n_b is the total amount of branches, R_k, P_k, Q_k and V_k refer to the resistance, active power, reactive power and the sending end bus voltage at the k-th branch.

The following constraints need to be met,

(1) Network topology constraints

$$g_k \in \boldsymbol{G} \quad (2)$$

where g_k represents the network topology after reconfiguration, $\boldsymbol{G}$ is the set of all feasible radial network topologies.

(2) Operation constraints of distribution system

$$\begin{cases} V_{k\min} \leqslant V_k \leqslant V_{k\max} \\ I_k \leqslant I_{k\max} \end{cases} \quad (3)$$

where $V_{k\min}$ and $V_{k\max}$ are the lower limit and upper limit of the sending end bus voltage at the kth branch, V_k and I_k are the operating voltage and current at the k-th branch respectively, $I_{k\max}$ is the current upper limit at that branch.

(3) Conservation of power flow

$$\sum_{\{(j,i)\in\boldsymbol{B}\}} S_{ji} - \sum_{\{(i,j)\in\boldsymbol{B}\}} S_{ij} = L_i, \quad \forall i \in N \quad (4)$$

where N is the total amount of buses, L_i is the load on bus i, $\boldsymbol{B}$ is the set of all branches, $S_{ji}(S_{ij})$ is the power injection from bus j (i) to bus i (j).

Minimum spanning tree (MST) algorithm

Principle of MST

Distribution network can be described with an undirected graph $\boldsymbol{G} \in (\boldsymbol{N}, \boldsymbol{B})$ [28]. Here, $\boldsymbol{N}$ is the set of vertices which represents power supply and buses, $\boldsymbol{B}$ is set of edges which indicates the branches including tie-branches. The $C(e)$ is the weight of edge, $e \in \boldsymbol{B}$. A simple distribution network is shown in Fig. 1(a) and its corresponding undirected graph is depicted as Fig. 1(b).

Distribution network is usually designed with meshed structure but operated with radial structure. The reconfiguration problem is actually to look for a tree to meet the given constraints and the optimization goals with main source as the root. Thus, the graph theory can be considered. According to the requirements of reconfiguration, the appropriate weights will be set firstly. Then the graph theory algorithm can be used to find one satisfactory spanning tree, a better initial optimal solution.

The sum of each edge weight is called the weight of the spanning tree of a graph. The spanning tree with minimum weight is called the minimum spanning tree (MST). Kruskal algorithm and Prim algorithm are commonly used to construct MST [28]. The basic principles of two algorithms are much similar. The main difference is that the former is dominated by edges but the latter is dominated by vertices during constructing MST. Considering the weakly-meshed characteristics of distribution network, Kruskal algorithm is adopted in this paper. With the Kruskal algorithm, the weights of N edges in $\boldsymbol{G}$ are sorted in ascending order firstly. Then, the edge with the minimum weight is selected first. After that, from rest of the edges, the edge with the smaller weight and which does not form a loop with the selected edges will be selected. The process is repeated one after another until the $N-1$ edges have been selected. For example, Fig. 2(a) and (b) shows the process of constructing the minimum spanning tree based on Kruskal algorithm.

Where in Fig. 2(a), the numerals above the edges are the weights of edges. In Fig. 2(b), the roman numerals indicate the order to select the edges during generating the minimum spanning tree with Kruskal algorithm.

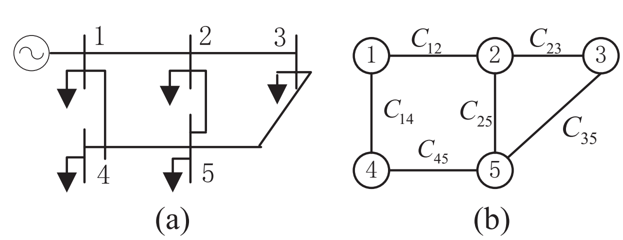

Fig. 1. (a) A simple distribution network; and (b) the corresponding undirected graph $\boldsymbol{G}$.