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A rule based comprehensive approach for reconfiguration of electrical distribution network

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ABSTRACT

This paper proposes a rule based comprehensive approach to study distribution network reconfiguration (DNRC). The DNRC model with line power constraints is set up, in which the objective is to minimize the system power loss. In order to get the precise branch current and system power loss, a power summation based radiation distribution network load flow (PSRDNLF) method is applied in the study. The rules that are used to select the optimal reconfiguration of distribution network are formed based on the system operation experiences. The proposed rule based comprehensive approach is implemented in distribution network in Guiyang South Power Supply Bureau. For the purpose of illustrating the proposed approach, two distribution network systems are tested and analyzed in the paper.

1. Introduction

The distribution networks are the most extensive part of electrical power system, and produce lots of power losses since the low voltage level of the distribution system. The goal of reconfiguration of distribution network is to find a radial operating structure that minimizes the power losses of distribution system under the normal operation conditions. Generally, distribution networks are built as interconnected meshed networks, while in the operation they are arranged into a radial tree structure. This means that distribution systems are divided into subsystems of radial feeders, which contain a number of normally closed switches and a number of normally open switches. According to the graph theory, a distribution network can be represented with a graph of G (N, B) that contains a set of nodes N and a set of branches B. Every node represents either a source node (supply transformer) or a sink node (customer load point), while a branch represents a feeder section that can either be loaded (switch closed) or unloaded (switch open). The network is radial, so that feeder sections form a set of trees where each sink node is supplied from exactly one source node. Therefore, the distribution network reconfiguration problem is to find a radial operating structure that minimizes the system power loss while satisfying operating constraints [1]. In fact, the distribution network reconfiguration can be viewed as a problem of determining an optimal tree of the given graph. Many algorithms have been used to solve the reconfiguration problem: heuristic methods [2–8], expert system, combinatorial optimization with discrete branch and bound methods [9–14], and genetic algorithm [1,15–17].

Merlin and Back first proposed the discrete branch and bound method to reduce losses in a distribution network [3]. Due to the combinatorial nature of the problem, it requires checking a great number of configurations for a real-sized system. Shirmohammadi and Hong [7] use the same heuristic procedure mentioned in [3]. Castro et al. [4] propose search heuristic techniques to restore the service and load balance of the feeders. Castro and Franca [6] propose modified heuristic algorithms to restore the service and load balance. The operation constraints are checked through a load flow solved by means of modified fast decoupled Newton–Raphson. Baran and Wu [5] present a heuristic reconfiguration methodology based on the method of branch exchange to reduce losses and balance loads in the feeders. To assist in the search, two approximated load flows for radial networks with different degrees of accuracy are used. Also they propose an algebraic expression that allows estimating the loss reduction for a given topological change. Liu et al. [12] propose an expert system to solve the problem of restoration and loss reduction in distribution systems. The model for the reconfiguration problem is a combinatorial non-linear optimiza-

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tion problem, because to find the optimal solution, it is necessary to consider all the possible trees generated due to the opening and closing of the switches existing in the network.

At present, new methods based on genetic algorithm (GA) have been used in distribution network reconfiguration (DNRC) [1,15–17]. GA based methods are better than traditional heuristic algorithms in the aspect of obtaining the global optima. However, GA is essentially unconstrained search procedures within the given represented space [15–17]. All information should be fully represented in the fitness function. Over-approximated fitness function would lead directly to unreliable solution.

This paper proposes a rule based comprehensive approach to study DNRC. The DNRC model with line power constraints is set up, in which the objective is to minimize the system power loss. Since the distribution network is a simple radial tree structure, in which the ratio of R/X is relatively big, even bigger than 1.0 for some transmission lines, neither P–Q decoupled method nor Newton–Raphson method is suited to compute the distribution network load flow. Therefore, a power summation based radiation distribution network load flow (PSRDNLF) method is applied in the study. The rules that are used to select the optimal reconfiguration of distribution network are formed based on the system operation experiences. The proposed rule based comprehensive approach is implemented in distribution network in Guiyang city. For the purpose of illustrating the proposed approach, two distribution network systems (14-bus and 33-bus system) are tested and analyzed in the paper.

2. Mathematical model of DNRC

The purpose of DNRC is to find a radial operating structure that minimizes the system power loss while satisfying operating constraints. Thus, the following model can represent the DNRC problem.

$$\mathrm{Min} f = \sum_{l=1}^{\mathrm{NL}} k_l P^2 R_l \quad l \in \mathrm{NL} \tag{1}$$

Such that

$$k_l |P_l| \le P_{l\,\max} \quad l \in \mathrm{NL} \tag{2}$$

$$k_l |Q_l| \le Q_{l\,\max} \quad l \in \mathrm{NL} \tag{3}$$

$$V_{i\,\min} \le V_i \le V_{i\,\max} \quad i \in N \tag{4}$$

$$g_i(P, k) = 0 \tag{5}$$

$$g_i(Q, k) = 0 \tag{6}$$

$$g_i(V, k) = 0 \tag{7}$$

$$\varphi(k) = 0 \tag{8}$$

where, P_l, the real power in branch l; Q_l, the reactive power in branch l; R_l, the resistance of branch l; V_i, the node voltage at node i; K_l, represents the topological status of the branches. $k_l = 1$ if the branch l is closed, and $k_l = 0$ if the branch l is open; N, the set of nodes; NL, the set of branches. Subscripts "*min*" and "*max*" represent the lower and upper bounds of the constraint.

In the above model, Eqs. (2) and (3) stand for the branch real power and reactive power constraints. Eq. (4) stands for the node voltage constraints. Eqs. (5) and (6) represent Kirchhoff's first and second laws. Eq. (8) stands for topological constraints which ensure radial structure of each candidate topology. It consists of two structural constraints:

(a) Feasibility: all nodes in network must be connected by some branches, i.e., there is no isolated node.
(b) Radiality: the number of branches in network must be smaller than the number of nodes by one unit ($k_l \times \mathrm{NL} = N - 1$).

Therefore, the final network configuration must be radial and all loads must remain connected.

3. Implementation

This paper uses a rule based comprehensive approach to study distribution network reconfiguration. The algorithm consists of a modified heuristic solution methodology and the rules base. It determines the switching actions based on a search by branch exchange to reduce the network's losses as well as to balance the load of the system.

In order to get the precise expression of system power loss, the branch power will be computed through a radiation distribution network load flow (RDNLF) method in the study. It is well known that in the distribution network, the ratio of R/X (resistance/reactance) is relatively big, even bigger than 1.0 for some transmission lines. In this case, P–Q decoupled load flow is invalid for distribution network load flow calculation. It will also be complicated and time-consuming to use the Newton–Raphson load flow because the distribution network is only a simple radial tree structure. Therefore, the PSRDNLF is presented in the paper. PSRDNLF calculation consists of three parts:

(1) Conduct optimal node order calculation for all redial network based on graph theory. Consequently, the branches are divided into different layers according to the distant between the ordered node and 'root of a tree' node.
(2) Calculate the branch real power and reactive power from the 'top of a tree' node to the 'root of a tree' node. That is from last layer to first layer.
(3) Compute the node voltage from the 'root of a tree' node to the 'top of a tree node, i.e., from first layer to last layer.

The initial conditions are the given voltage vectors at root nodes as well as real and reactive power at load nodes. In final, the deviation of injection power at all nodes can be computed. The iteration calculation will be ceased if the deviation is less than the given permissive error.

If there are multiple generation sources in the distribution network, one source will be selected as a reference/slack source and others can be handled as negative load.

Unlike the traditional branch exchange based heuristic method, this paper divides switching branches into three types.

(1) Type I: the switching branches are planned for maintenance in a short period according to the equipment maintenance schedule.
(2) Type II: the power flows of the switching branches almost reach their maximal power limits (e.g. 90%).
(3) Type III: the other switching branches that have enough available transfer capacity under the system operation conditions.

Thus, the following rules will be used for the modified heuristic approach according to the practical system operation experiences of the engineers.

(a) If the switching branches lead to system power losses increase, do not switch them.