Orthogonal Experiment Design Algorithm of a Distribution Network Reconfiguration

Abstract. According to the operation characteristics of the power distribution network with tree structure and the reconfiguration power distribution network, this paper proposes the orthogonal experiment design algorithm of power distribution network reconfiguration by mending the switch of the ring net presented by the orthogonal table.

1. Introduction

A distribution network is characterized by a closed loop in designing and open loop in operation. Many sectionalizing switches (which are always closed to the isolate fault) and several tie switches (which are always open to provide optional power supply channels) are installed. Therefore, the system structure can be modified by changing the state of switches (to open or closed) according to different loadings in the normal operation. Thus, network loss can be reduced, and the load in each line and in the transformers can be balanced [1].

Reconfiguration is an effective and significant way to improve the operation efficiency of a power distribution network and the quality and security of power supply. Distribution network reconfiguration problems are formulated as multi-objective, nonlinear, and complex optimization problems. Currently, the algorithms of power distribution network reconstruction method [2,3,4,5,6,7,8] are mainly the mathematical optimization method, the optimal flow pattern method, branch exchange algorithm, and artificial intelligence algorithm, to name a few [4]. Branch exchange algorithm [2] initially forms a radiation net and in turn opens and closes the switches. Each time a tie switch is closed, a monochromic loop is formed to produce the optimum conditions; when a switch is opened, the network maintains the shape of the radiation. Based on the optimization theory, this method can fix the node and inject current into the fixed node to change the switch operation from the combination mode into the heuristic single open mode, which can guide the practical switch operation process. Given this method, only the network loss caused by the branch exchange needs to be calculated roughly without having to calculate the flow once more, and so the calculation is less. The disadvantages of this method are the many calculation procedures, low efficiency, and the calculation results being related to the original network structure. Thus, it is more convergent to a locally optimal solution. The optimal flow pattern method [3] initially closes all switches in the network to form a multi-ring net-hole system. Current distribution in the loop net branch can be obtained with a pure resistance network, disconnecting the branch of the minimum current. Thus, a loop is unlocked, and the optimal power flow is calculated once again. This operation is repeated until the power distribution network changes into radiation nets. The calculation is very complex, as each time the switch is closed or opened, the power flow should be calculated. However, the reconfiguration is not related to the state of the original network, and it is easy to converge toward the optimal solution. The artificial intelligence algorithm [4] includes the genetic algorithm, artificial neural networks, and simulated annealing method, to name a few. The state of the branch switches can be shown directly by the chromosome code in the genetic algorithm. The optimal network structure can be determined by simulating the biological evolution breeding/cross/mutation to change the state of each switch, and to some extent it converges toward the optimal solution. However, the parameters, such as the crossover and mutation rate, are difficult to control, and producing a universal and effective algorithm is difficult. Tabu searching is adopted in the power distribution reconfiguration in the literature [7].

The combinatorial optimization can also be achieved using the orthogonal experiment design. The optimal combination can be obtained when all possible combinations are listed. However, the workload increases exponentially with the addition of more factors. Moreover, this kind of calculation is neither economical nor necessary. The orthogonal experiment design, a method suitable due to various factors, can be used to find a better or the best solution efficiently by choosing some representative points featured by “being even” and “being in order.”

2. Mathematical Model of Distribution Network Reconfiguration

Network reconfiguration in distribution systems is realized by changing the status of switches, i.e., choosing different supply channels to minimize the total active power loss in the system in the pre-condition of a secure power supply.

Definition 1: The index of load balance [2] $B_L$ is composed of $B_{Li}$ (the index of branch load balance) and $B_{sys}$ (the index of system balance). $B_{Li}$ can be described as follows:

\[
B_{Li} = \frac{S_i}{S_{i,max}}
\]

where $S_i$ is the complex power passing branch $i$, and $S_{i,max}$ is the minimum capacity of branch $i$.

The mathematical equation of $B_{sys}$ can be described as follows:

\[
B_{sys} = \frac{1}{n_b} \sum_{i=1}^{n_b} \frac{S_i}{S_{i,max}}
\]

where $n_b$ is the total number of branches in the system.

In terms of mathematics, the load balance indicates that $B_{Li}$ equals or is close to $B_{sys}$, which requires the following:
3.1 Basic Principle of the Orthogonal Experiment Design

Based on the orthogonal experiment design, the mathematical model of a complete distribution network reconfiguration with balanced load is as follows:

\[
\text{max} \left[ \frac{S_i}{S_{i_{\text{max}}}} - \frac{S_j}{S_{j_{\text{max}}}} \right] < \varepsilon
\]

In this equation, \( \varepsilon \) is an artificial figure set according to the requirement of the network structure and system operation.

3.2 Steps of the Algorithm

The orthogonal table of \( L(4^p) \) is selected for the orthogonal table design, and \( "L" \) is the orthogonal table, and \( "A" \) indicates the number of rows, i.e., the times of experiments. The \( "p" \) in brackets denotes the number of columns, i.e., the permitted number of factors. When choosing the orthogonal table, first, the number of levels must be the same as that of the factors tested. Second, the number of columns in the orthogonal table should be the same as or more than that of the factors tested. Moreover, the table with more columns can be used when the experiment time is longer, cost is lower, and the method is easier. Otherwise, the table with fewer columns is used. When high precision and accuracy are required, the table with more columns is used.

4. Case Study Analysis

4.1 Design and Implementation of Experiment

The distribution network is reconstructed with an IEEE typical three-feeder system [9]. This system is a distribution network with three tie switches. The supply to node 9 can be secured only when switch 8-9 is closed; thus, this switch is not considered. The network is simplified in Fig. 1 (b). This network is divided into six blocks: \{branch 1-2\}, \{branch 6-7\}, \{branch 11-12\}, \{branch 2-5\}, \{branch 8-9\}, \{branch 7-10\}, 12-15, 10-15\}, and \{branch 2-3\}, 3-4, 4-14, 12-13, 13-14\}. The orthogonal table of \( L_{36} (63 \times 33) \) is selected for reconstruction.
4.2 Experiment results
The summary of the test run is presented in Table 1.

Table 1. Experiment results

<table>
<thead>
<tr>
<th>Before reconstruction</th>
<th>Open switches</th>
<th>Network loss (MW)</th>
<th>Minimum voltage (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-14/5-9/10-15</td>
<td>521.36</td>
<td>0.9702</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After reconstruction</th>
<th>Open switches</th>
<th>Network loss (MW)</th>
<th>Minimum voltage (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-14/8-9/7-10</td>
<td>471.62</td>
<td>0.9751</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusions
Many algorithm methods of the power distribution network reconfiguration are available, but most of them are complicated. The most obvious advantages of the method proposed in this paper are its ease of operation and ease of understanding the model.

ACKNOWLEDGMENT
This research is supported by the Educational Commission of Anhui Province of China (KJ2012B047, KJ2011A013, KJ2011B046, 2012SQRL128ZD) and by the National Natural Science Foundation of China (60872163).

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