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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.*

Streszczenie. *W artykule przedstawiono propozycję algorytmu rekonfiguracji sieci dystrybucji energii. W metodzie zastosowano projektowanie ortogonalnego eksperymentu. Wykonanie operacji polega na przełączaniu (łączeniu) odpowiednich łączników w pierścieniu sieci, która zapisana jest w tablicy ortogonalnej. (**Algorytm projektowania ortogonalnego eksperymentu w rekonfiguracji elektroenergetycznej sieci dystrybucyjnej**).*

Key words: power distribution network, orthogonal experiment design, reconfiguration.
Słowa kluczowe: energetyczna sieć dystrybucyjna, projektowanie ortogonalnego eksperymentu, rekonfiguracja

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 [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 monocyclic 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_{Lsys} (the index of system balance). B_{Li} can be described as follows:

$$(1)\quad B_{Li}=\frac{S_i}{S_{i\max}}$$

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_{Lsys} can be described as follows:

$$(2)\quad B_{Lsys}=\frac{1}{n_b}\sum_{i=1}^{n_b}\frac{S_i}{S_{i\max}},$$

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_{Lsys}, which requires the following:

$$\frac{S_1}{S_{1\max}} \approx \frac{S_2}{S_{2\max}} \approx \cdots \frac{S_n}{S_{n\max}} \approx \frac{1}{n_b}\sum_{i=1}^{n_b}\frac{S_i}{S_{i\max}} \quad (3)$$

This equation is the same as the following:

$$\max[\frac{S_i}{S_{i\max}} - \frac{S_j}{S_{j\max}}] < \varepsilon \, . \quad (4)$$

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

The mathematical model of a complete distribution network reconfiguration with balanced load is as follows:

$$\min \sum_{i=1}^{n_b} r_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (5)$$

s.t.

a. $V_{i\min} \leq V_i \leq V_{i\max}$

b. $S_i \leq S_{i\max}$

c. $\max[\frac{S_i}{S_{i\max}} - \frac{S_j}{S_{j\max}}] < \varepsilon$

d. power flow constraint

e. tree-like constraint

In this equation, r_i is the resistance of branch i; P_i, and Q_i are the active power and the reactive power of branch i, respectively; V_i is the voltage on the node at the end of branch i; and V_{imin} and V_{imax} are the least voltage restriction and most voltage restriction on the node at the end of branch i, respectively.

3. Algorithm of Distribution Network Reconfiguration based on Orthogonal Experiment Design

3.1 Basic Principle of the Orthogonal Experiment Design

The orthogonal experiment design is a method suitable for an experiment involving many factors through the selection of some representative points from a comprehensive experiment. Although this method conducts only a partial experiment (part of a comprehensive experiment), for any two factors, it is an experiment of even distribution and order. The orthogonal table, a basic tool in the orthogonal experiment design, is based on the balanced distribution idea and is made using the combinatorial mathematics theory based on the Latin square and orthogonal Latin square.

3.2 Steps of the Algorithm

The following are the methods and steps of the orthogonal experiment design:

1).Clarify the experiment purpose, and set the experiment index.

Experiment purpose: To minimize the total active power loss in the network by choosing different supply channels

Experiment index: Active power loss in the network

2) Choose the factors, and select the levels.

If the action switches could be used directly as the factors in orthogonal experiment, and the state of the switches could be used as the levels of various factors, then the majority of this all-factor combination is not the connected graph combination, which will greatly weaken the advantage of the orthogonal experiment. According to the tree structure of the power distribution network and using the node with branch lines as boundary, the network can be divided into different blocks used as factors to ensure the connectivity of network reconfiguration. On each block, only a switch is open, so the number of its level is the total number of switches plus 1. For example, in Fig. 1(a), nodes 7 and 13 have node branch lines, and thus they are used as the boundary to make switches 11, 16, and 15 and nodes 11 and node 16 as a block (a factor) whose level number is 4.

3) Choose a suitable orthogonal table.

The conventional orthogonal table is $L^A(p^q)$. "L" is the orthogonal table, and "A" indicates the number of rows, i.e., the times of experiments. The "q" in brackets denotes the number of columns, i.e., the permitted number of factors. "p" indicates p kind of numbers exists in the main part of the table, i.e., the levels of factors are p. 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 arrays can be used when the experiment time is shorter, cost is lower, and the method is easier. Otherwise, the table with fewer arrays is used. When high precision and accuracy are required, the table with more arrays is used.

4) Arrange the experiment with the orthogonal table.

According to the code in the factor level table, the experimental frame can be obtained by providing the data in the orthogonal table chosen. In the table, each transverse line stands for a group of conditions. During the experiment, except the factors to be tested, other conditions should be kept unchanged to facilitate the comparison between results.

Considering the characteristics of the power distribution network, the combination of switches is fixed in the orthogonal table as follows. Each tie switch corresponds to a loop. According to these loops, the factors are divided into different groups. One switch in each loop must be open. In this paper, the switch farthest from the power source point is selected.

5). Conduct experiment according to experimental plan.

6). Conduct a direct analysis on the experimental results.

7). Verify the experiment.

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, 7-8, 8-9, 5-9}, {branch 7-10, 12-15, 10-15}, and {branch 2-3, 3-4, 4-14, 12-13, 13-14}. The orthogonal table of L36 (63×33) is selected for reconstruction.

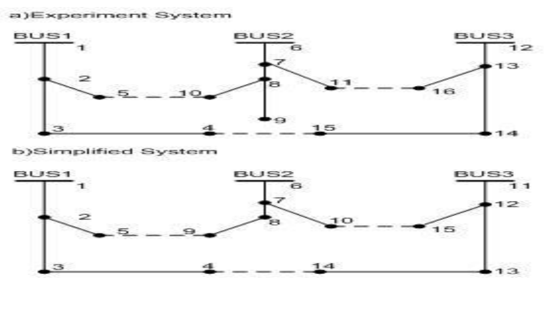

Fig. 1.IEEE Typical Three-feeder System

4.2 Experiment results

The summary of the test run is presented in Table 1.

Table 1. Experiment results

	Open switches	Network loss (MW)	Minimum voltage (p.u.)
Before reconstruction	4-14/5-9/10-15	521.36	0.9702
After reconstruction	4-14/8-9/7-10	471.62	0.9751

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.

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