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Study on Fundamental Principles and Methodologies of Distribution Network Reconfiguration

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Abstract

Distribution network reconfiguration is not only of great use in controlling and improving power distribution system's operation environment, but also an essential part of the distribution management system. Thus the research on fundamental principles and methodologies of distribution network reconfiguration is very important and meaningful. This article has suggested the principles of distribution network reconfiguration under circumstances of normal operation and service restoration after faults, and one step further focused on typical algorithms applied in the area including optimal power flow algorithm, branch exchange algorithm, simulated annealing algorithm, artificial neural network algorithm, genetic algorithm and tabu search algorithm. Based on specific comparison and analysis, this article summarized characters of different methodologies and pointed out that alterations still have to be made to derive better solution.

***Keywords**: distribution network, network reconfiguration, principle, algorithm*

1. Introduction

Distribution System is the final segment of power system, bridging the gap between power supply system and user facilities. The major responsibility of the distribution system would be proper electric power distribution and guaranteeing users' normal power consumption. Correspondingly, as a crucial part of the Distribution Management System, distribution network reconfiguration has great impact on the power quality. Frankly speaking, network reconfiguration means changing network structure through operations of sectionalizing and loop switches to minimize power loss and keep the balance of power supply and consumption, meanwhile on the premise of satisfying capacity and voltage restraints. Currently, the distribution power grid construction in our country still remains to be modified. Technology decline, equipment depreciation and inappropriate structure have led to low reliability and highly cost during the power transformation process. Considering the complicity of power distribution grid's mathematical model, the pursuit of optimal algorithm of network reconfiguration becomes inevitable and urgent [1, 2].

Theoretically, network reconfiguration is a complicated multi-objective nonlinear integral combinational optimization problem, which has characters of discontinuity, non-differentiability, multi-constraints and nonlinearity. Up to now the commonly proposed algorithms could be categorized as heuristic optimization algorithms and artificial intelligence algorithms. Based on these this article systematically analyzed principles of distribution network reconfiguration and core ideas of several typical algorithms.

2. Principles of Distribution Network Reconfiguration

Depending on the power system's running state, network reconfiguration could be classified as reconfiguration in normal operation and after faults. Even when the power system is in normal situation, network reconfiguration is still needed to reduce power loss, keep balance of power load and improve the quality of electricity power. To realize these switch operations must be implemented according to precise real time information on power network. After the reconfiguration process structure of the network would change. So is the power distribution. The

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other situation where network reconfiguration is needed is also called fault recovery. To realize the goal of isolating fault section and recovering power supply, switch operation schemes must be rapidly formulated and executed, meanwhile minimizing affected area and economic loss.

2.1. Network Reconfiguration in Normal Operating Situation

Network reconfiguration in normal operation situation is also known as network optimization. There are rules of power balance and capacity and voltage limits that must be obeyed and benefits of all kinds that should be maximized during the process of actual optimization. More specifically, the research mainly consists of following procedures.

Firstly, the reconfiguration should make distribution power system more stable and reliable. To realize this two methods are usually available. One would be improving performances of all equipment and the other would be increasing redundancy of the system. Unfortunately, both ways are not very practical because of high material cost. And this is where network reconfiguration excels. Reliability could be improved without additional investment.

The distribution network's reliability estimation usually depends on the analysis method and simulation method. The analysis method obtains system's reliability index by doing evaluation and calculation on predictable outage events. Because of simplicity of the method's principle and accuracy of the model, the analysis method has mainly been widely used in reliability estimation of radiant distribution power network. When the network structure is more complicated, the amount of calculation would increase tremendously. As one common analysis method, the minimum path method considers possible affection on network reliability caused by component failure both on and out of the minimum path, and finds out vulnerable area of the network, which makes it an effective method. Differently, the simulation method evaluates reliability index through simulation test and observation on component's life process. This method is applicable in calculation of complicated systems. Under certain circumstances, it might even be the only practical solution.

Secondly, the reconfiguration should balance the power load distribution to avoid energy overload and improve the quality of electricity power. The actual load of distribution network changes rapidly and leads to inappropriate energy distribution. Plus, the correspondent facility and construction could not catch up with the development of power network, which endangers the system's normal operation. The basic aim of network reconfiguration is transferring power load from heavy-loaded lines to light-loaded lines, eliminating overload and keeping voltage steady. It will not only reduce the possibility of usual faults, but also provide more economical benefits. In detail, the load balancing means include redefining boarders of power supply areas and reselecting power source among power transmission from one substation.

At last, the reconfiguration should reduce total power loss and improve economical efficiency. Up until now, power loss on transmission lines especially distribution network has been a heavy burden. It is of very little chance that the network has naturally been operating in profitable structure. Mostly load and power would be randomly distributed and not profitable. The operation mode of power network is of great significance and needed to be modified to achieve economical efficiency. Practically, the minimum power loss scheme chooses power load during a certain period of time as calculation parameter. Commonly the peak value of load could represent the system's general condition. The established reconfiguration scheme provides reference for switch operation schedules when distribution network is in normal operation.

2.2. Network Reconfiguration After Faults

The distribution power network is fragile to frequently happening faults. Due to characters of the distribution network's structure, when permanent faults cause power failure the clearance of faulty equipment would separate the non-faulted area into one part directly links to power source and the other that loses power. The former part could restore service through reclosing substation outgoing line's circuit breaker. The latter part has to operate relevant loop switches to regain power, which makes it the main research object of network reconfiguration after faults. Until now, there have been three modes that have been used.

a) Early artificial fault recovery mode

Early times of low automation level, fault recovery relies on fault indicators installed on distribution lines. Workers locate fault position according to signals from fault indicators and manually isolate fault area by opening pole mounted switches. Since the whole process needs people to be on sight and the time of fault treatment is rather long, this early method has its inevitable disadvantages.

b) Distribution automation (DA) fault recovery mode

The key of DA mode is to require that sectionalizers, reclosers and pole mounted switches in distribution network should be equipped with intelligent facilities. Through cooperation of switch operation with protection time, faults could be automatically diagnosed, isolated and recovered. This mode has great reliability on early design planning and structure of the network and automation level of power distribution equipment. So it is mostly used in simple structured network and not able to take real power load and network constraints into consideration.

c) Distribution management system (DMS) fault recovery mode

The DMS mode is unique because of the fault recovery software installed in distribution power control center. When faults have emerged, feeder terminal units collect and submit the information to distribution power control center. The real time data will be saved as reference for further logical analysis on happened faults. With the aid of SCADA and complete fault information, the software could locate fault position and determine procedures of isolating and recovery faults. The established operation scheme will be submitted to SCADA in form of operation sequence and then executed automatically or manually. This mode adapts to distribution network of all structures and special occasions like multiple faults. It has considered real power load and network constraints. However, performance of this mode concerns a lot about reliability and functions of equipment and software.

The DMS mode represents the future of fault recovery. It makes use of intelligent software and achieves a new height in planning and realizing fault recovery comprehensively. Some unpredictable conditions could be under control and dealt with properly. Its application also lies in all kinds of complicated distribution network.

3. Methodologies of Distribution Network Reconfiguration

Distribution network reconfiguration is a multi-objective combinational optimization problem. Present methods take all means to limit the size of solution space to derive solution faster. Heuristic optimization algorithms and artificial intelligence algorithms are two common species [3-5].

3.1. Heuristic Optimization Algorithms

a) Optimal flow pattern, OFP

The optimal flow pattern is proposed in 1989. Assuming that equivalent injecting current for each node's load is given, the OFP intends to obtain an ideal power flow path of minimum power loss in weakly meshed distribution network.

The objective function of OFP is based on reducing power loss. This method of reconfiguration firstly neglects the structure constraint of being radiant and closes all switches to build a multi-ring network. Then regardless of all constraints except power flow equation, calculation will be done to derive current distribution that costs minimum power loss, namely so called OFP. Ignoring the reactance part of all branch impedance, the obtained current distribution is the system's optimal flow pattern. At last, the switch operation principle is to open the switch with minimum current in optimal flow pattern. The opening of one switch is to open one loop. Repeat this procedure until no more loop exists and the network becomes radiant.

It needs to be concerned that the most important instruction is to open switches with minimum current because it has smallest affection on system power flow distribution. On the other hand, the power loss increase caused by network reconfiguration will be minimized.

b) Branch exchange method

The branch exchange method (BEM) is also known as switch exchange algorithm. It exchanges power load between feeders by opening and closing switches.

At first the initial power flow and power loss should be calculated. The results can be used to express the load with steady current. The formation of loop only needs to open one loop switch. Then select a sectionalizing switch within the loop and open it, changing the structure back to radiant network. So the load could be balanced and power loss reduced. To ensure the decline of power loss, the loop switch that has maximum voltage difference between two sides has to be closed. And power load must be transferred from the side with bigger voltage drop to the smaller side. Based on this there can be two heuristic principles of BEM. The load has to be transferred from the feeder with lower voltage to the feeder with higher voltage, which means after reconfiguration the voltage between feeder starting point and the load terminal should be lower. The other principle is only huge voltage difference between two sides of the switch can make the operation of closing the switch meaningful for reducing power loss.

The process of BEM could be listed as following. Use the second heuristic principle and check the voltage difference between two sides of each loop switch. For those switches with small voltages can be ignored. Others should be closed. Then use the first heuristic principle to determine which loop switch is to be opened. Apart from the rule already described, the efficiency of opening each sectionalizing switch must be estimated. After comparison of power loss the best option could be picked out. Then a load flow analysis subprogram is used to observe and guarantee no current overload or over voltage. The aforementioned procedures will be repeated until the repetition will not reduce power loss any longer. After that the network structure becomes optimal and costs minimum power loss. The obtained switch operation scheme could be implemented in real distribution network to fulfill the reconfiguration process.

The branch exchange method could obtain the ideal network structure with minimum power loss rapidly. The heuristic principles help save efforts of establishing the optimal switch operation scheme. Nonetheless, the final reconfiguration result is related to the switches' initial status. Although the power loss variation caused by each switch operation is calculated, there is still no guarantee for the reconfiguration process to be global optimal.

3.2. Artificial Intelligence Algorithms

The artificial intelligence algorithms emerged in modern times. Recently theories and methodologies of artificial intelligence have been applied in research and practice of power system. For the distribution power network, usual methods include simulated annealing algorithm, artificial neural network, genetic algorithm, tabu research algorithm, expert system and integration of the above [6-10].

a) Simulated annealing algorithm

Simulated annealing (SA) was firstly proposed in 1983 by Kirkpatrick to solve combinational optimization problems. Its core thought is seeking optimal solution through random search and iteration. As for the distribution power system in large scale, there could be numerous running states and complicated calculation of power loss in different operation conditions. In fact the random change of one or several feeders could mean new network structure. Assuming the voltage of power source keeps stable, this method only cares about feeders which happened changes and their active power loss. Considering the active power loss change equals to that of the whole distribution network, this method makes the decision of adopting or giving up the structure with the aid of the Metropolis rule.

The SA algorithm has no special requisition for the objective function. The final solution would be global optimal and has nothing to do with initial feasible solution. What's more, the SA algorithm elegantly avoided the curse of dimensionality. On the other hand, the key of SA algorithm is the annealing scheme. Inappropriate scheme could lead to complicated calculation and iteration. The final solution would also lose efficiency and accuracy.

b) Artificial neural network algorithm (ANN)

In the Sample training process of the artificial neural network algorithm, the load pattern is imported into the system and trained to export switch state. The nonlinear relationship between input and output is saved and kept in neurons' weight value, reflecting the nonlinearity between load pattern and structure of the distribution network.

The first step of using artificial neural network algorithm to realize distribution network reconfiguration is to carry out sample training and derive weight value. To make sure that the weight value is convincing, the iteration method is utilized here. Select certain initial load pattern and predict the ideal output. Then calculate and compare the newly trained load pattern with formerly predicted data while assuming the weight value is already known. Keep on updating the weight value and the calculation result to narrow the gap between real output and predicted data. This process shall proceed until the similarity degree is of acceptable satisfaction. So the ideal weight value is obtained and of use in training and improving present load pattern.

The artificial neural network algorithm has abandoned the power flow calculation of the distribution network. At the same time the power loss variation caused by switch operation is also neglected, which gives a great rise to the calculation speed. However, the accuracy of ANN has great reliance on sample training. And for a complicated network the derivation of load pattern requires lots of energy. In real system operation, structure of the network changes frequently and the weight value inevitably becomes inconstant. All but not limited to these are restrictions of the ANN algorithm.

c) Genetic algorithm (GA)

The genetic algorithm is based on natural selection and genetic mechanism. It is an adaptive iterative probability search algorithm. The genetic algorithm searches for the optimization scheme by means of simulating the random information exchange process between chromosomes and the survival of fittest theory rule. When used in distribution network reconfiguration, the genetic algorithm represents the status of sectionalizing and loop switches with bits in coding. The adaptability function is determined by system’s total power loss. If the objective function of distribution network reconfiguration is aiming at minimizing power loss, the adaptability function transformation is needed. The genetic algorithm generates new individuals through crossover and mutation. Natural selection will decide which structures are better to survive taking into account the probabilistic character. Finally the whole population evolves and the search process is shortened.

d) Tabu search algorithm (TS)

Tabu search algorithm was proposed in 1977. As a modern heuristic algorithm, it is fit for combinational optimization problems. The central thought of TS algorithm is a kind of memorizing technology. The optimization process is recorded in detail to guide the search direction and avoid encountering local optimization. Unfortunately, the technical problems still exist and restrict the TS algorithm’s application. Theoretically the global optimization is within reach on the premise of taboo length being sufficiently long enough, which requires full consideration of all conditions. This is contradictory to the principle of saving efforts and solving problems rapidly.

3.3. Summarization of the Reconfiguration Algorithms

The distribution network reconfiguration problem has to be thought over and solved from a global angle. By means of mathematical optimization the global optimal solution is available theoretically. But in real operation, the structure of the network and all kinds of constraints make it quite difficult to search for optimal solution. How to improve accuracy and calculation speed of the algorithms till remains to be further studied.

The simulated annealing algorithm obtains the optimal solution at the cost of reliance on parameters and large amount of calculation. The artificial neural network algorithm doesn’t need to do power flow calculation so the processing time is shortened. But the final result is quite related to the training sample, which is rather difficult to get. Plus the sample training takes lots of time. The genetic algorithm is fit for the distribution network. But it has to do research on algorithm convergence considering characters of the distribution network to accelerate calculation.

Up to now, the proposed algorithms still can’t satisfyingly solve the distribution network reconfiguration problem. Convergence, optimizing result and calculation speed could not be perfectly coordinated and combined. Modifications still remain to be found and carried out and relative research is very meaningful and worthwhile.

4. Conclusion

The distribution network reconfiguration could modify and optimize the network operation pattern according to its own characters. It could reduce power loss on the premise of balancing power load and improving voltage quality without additional investment, which makes it a very important method in operation and control of the distribution power system.

This article has elaborated basic principles of distribution network reconfiguration in normal operation state and after faults. Then the author analyzed several algorithms mainly heuristic and artificial intelligence algorithms applied in distribution network reconfiguration. The advantages and deficiency of all algorithms have been exposed and summarized in former chapters. Further research on searching for ideal algorithm that fits for optimization of distribution network is still of great importance and beneficial.

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