A self-healing reconfiguration technique for smart distribution networks with DGs

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Abstract—**The requirement for power supply reliability and power quality has been increasing. When a fault occurs in distribution networks, fast locating and isolating the fault, restoring the power, and reducing outage time and area are becoming more and more crucial. The concept of fast self-healing has been proposed, which is also the requirement for smart grid development. In this paper, a self-healing reconfiguration technique is proposed for smart distribution networks with insertion of distributed generations (DGs). And a tree structure algorithm based on heuristic rules is proposed. Islands formed by DGs are used to deal with fault isolation and power restoration after a fault occurs. The effectiveness of the proposed algorithm is verified using a 26 bus bars test system with DGs.**

Keyword—self-healing; reconfiguration; smart distribution network; distributed generation (DG)

I. INTRODUCTION

The demand for energy is increasing with the economic and social development, not only in quantity but also in quality, i.e. it not only must meet electricity demand for customers, but also meet the power supply reliability and power quality requirements. Being directly connected to the customers, distribution network will have a great influence on daily lives and economic activities when it fails. So how to fast locate, isolate and restore the fault has become an arduous task for electric power industry [1-5]. In addition, the insertion of numerous distributed generations (DGs) and Microgrids in distribution network bring new challenges and opportunities for self-healing of power systems [6].

In smart grid development planning self-healing is one of the most import features and functions. The main function of self-healing is to locate, isolate and restore the fault and achieve the security and reliable operation of power grid with little or no human intervention, minimize or avoid the power interruption.

II. OUTLINE OF SELF-HEALING RECONFIGURATION OF DISTRIBUTION NETWORKS

There are two kinds of switches in distribution networks, most of which are normally closed disconnect switches, and a small number of which are normally open loop switches. For ensuring the reliability and economy of power supply, loads can be transferred to another different branch through switching operations. The process of load transferring is called reconfiguration of distribution networks.

Reconfiguration of distribution networks can be divided into two situations. One is used to adjust the power supply of loads for radial distribution network in the normal operating situation with the premise of ensuring security and reliability of power supply. The purpose is to achieve economy operating of the network through switch swapping and load transferring. The other is the self-healing reconfiguration after the network is out of service, which consider restoring power supply of customers as soon as possible and minimizing the network losses that also means optimal operation.

Under the premise of meeting the operational requirements, the purpose of reconfiguration of distribution network is to find the operation scheme which minimize objective functions by changing the state of disconnect switches and loop switches after locating and isolating the fault. Self-healing reconfiguration is a multi-objectives, high-dimensional discrete combinatorial optimized problem. Due to the number of switches is large, the core of the reconfiguration algorithm is to eliminate unnecessary combination search and reduce the difficulty of calculations to avoid the "combinatorial explosion". In addition, it must reach a sufficient accuracy to make results optimal or near optimal.

Detailed process of self-healing reconfiguration is as follows. After the distribution network failure, the power recovery system judges the fault according to the information on the distribution network in real-time. Then it proposes correct and effective reconfiguration strategy to help the dispatchers determine fault location accurately, isolate the fault area, and fast restore non-fault regions. By considering the number of switching operations, feeder load margin, the amount of load recovery, network constraints, user priority, self-healing reconfiguration of distribution networks is a multi-objective, multi-period, multi-combined, multi-constrained nonlinear optimization problem.

III. OBJECTIVE FUNCTIONS AND CONSTRAINTS FOR SELF-HEALING RECONFIGURATION

A. Objective Functions

Different objective functions for self-healing reconfiguration algorithm of distribution networks have been presented according to different requirements of reconfiguration objective [2]. The following two objectives are considered in this paper.

1) The objective functions with the fewest number of switch operation and the minimum loss of power.

$$\min F(I, Y, Z) = \min \left\{ b_1 \left[\sum_{i=1}^{m} a_i (1 - y_i) + \sum_{j=1}^{n} a_{m+j} z_j \right] + b_2 \sum_{i=1}^{l} \left| i_i \right|^2 R_i \right\} \quad (1)$$

Where y_i, z_j are the state of disconnect switches and loop switches, m, n are the number of disconnect switches and

loop switches, a_i is the weight coefficient, l is the number of branches, I_i is the current amplitude of branch i, R_i is the resistance of branch i, b_1 is the switch operation cost coefficient, b_2 is the active power loss weight coefficient.

Maximize the power restoration without causing overload in non-outage region, and with the most simple and convenient operation, this is a big problem of self-healing reconfiguration in distribution networks. Expert systems (ES) were widely used in the past. But there are some shortcomings of expert systems: it is difficult for ES to cover all the failure modes and operating modes. ES can not handle the special situations that seldom encounters. It has heavy burden of knowledge acquisition. It is difficult to be expressed as rules. It can not sure to get the optimal solution.

2) To avoid equipment overload, and ensure the power supply security and quality, the objective function with uniform load as:

$$LB_i = \frac{S_i}{S_i^{\max}} \tag{2}$$

$$LB_{sys} = \frac{1}{n} \sum_{i=1}^{Nb} \frac{S_i}{S_i^{\max}} \tag{3}$$

Where LB_i, LB_{sys} are load balance indexes of branches and the system, S_i is the power flow through branch, S_i^{max} is the capacity of branch, Nb is the number of branches of the system.

Because of the rapid increasing in loads and lagging in power construction, the load distribution of distribution networks is extremely uneven, which has brought great harms to the system such as the energy consumption increasing, the power quality decreasing, and the risk of overload. There are two main means to achieve load balance. One is transferring the load between different feeders in the system. The other is transferring the load between different phases in the feeder.

B. Constraints

Constraints for self-healing reconfiguration algorithm of distribution networks contain a series of equality constraints, mainly power flow constraint, and inequality constraints, such as feeder capacity constraint, Line current constraint, bus voltage constraint, transformer overload constraint [1-2].

1) Feeder capacity constraint

$$S_j \le S_{j\max} \tag{4}$$

Where S_j is the power flowing in the j-way, S_{jmax} is the maximum power in the j-way.

2) Line current constraint

$$I_{ij} \le I_{ij\max} \tag{5}$$

Where I_{ij} is the current flowing in the ij-way, I_{ijmax} is the maximum current in the ij-way.

3) Bus voltage constraint

$$V_{j\min} \le V_j \le V_{j\max} \tag{6}$$

Where V_{jmin}, V_{jmax} are upper and lower limit of voltage of j-node.

4) Transformer overload constraint

$$S_t \le S_{t\max} \tag{7}$$

Where S_t is the power of transformer, S_{tmax} is the maximum power of transformer.

In the process of self-healing reconfiguration, inequality constraints are ensured through adding penalty function to objective functions.

IV. HEURISTIC SELF-HEALING RECONFIGURATION ALGORITHM BASED ON TREE-STRUCTURED GRID

A. Heuristic rules [2-5]

We divide switches into the following three sets:

Set A: switches which can not be closed

Set B: switches which can not be open

Set C: switches which can not be operated freely.

The following heuristic rules are proposed according to the characteristics of distribution networks and requirements of self-healing reconfiguration.

- Give operation priority to the switches connected to transformers.

- Give operation priority to the loop switches closed to the power supply terminal. The positions that the loads are connected to the distribution network affect the loss of system, the shorter the distance between the load and the power supply terminal, the smaller the network loss.

- Give operation priority to the lines whose current margin is maximal.

B. Process of the algorithm

Step1: First, search and find out all the out-of-service area, count the quantity of the lost power loads, and mark all of the switches in the area.

Step2: Count the number (defined as n) of the loop switches which can be operated and not belong to the set A between the charged area and the out-of-service area. If n=0, that means there is no path to restore power, so end the process.

Step3: If n≠0, select a loop switch as the root node in accordance with the heuristic rules, the other nodes in the out-of-service area are structured in a tree according to the connection relationship. Then put numbers to the buses and the lines sorted by layer according to the distance from the root node.

Step4: Close this loop switch, if meet the constraints, back to step one.

Step5: If the constraints have not been met, search upward from the bottom of the tree, and open the switches in this layer until satisfying the constraints, then go back to step one. If the switches in this layer belong to set B and set C, just open the switches for set C. If the switches in this layer only belong to set B, open all. Constraints are met until switching on the loop switch of the root node, which means that the loop switch can not be closed, so mark it to set A.
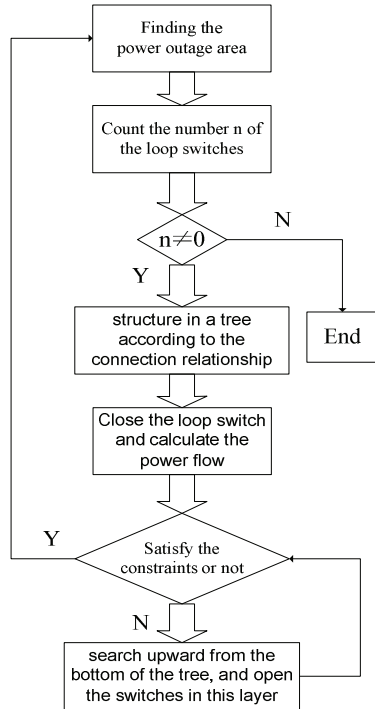

Figure 1. Process of the algorithm

V. SELF-HEALING RECONFIGURATION OF DISTRIBUTION NETWORK WITH DGS

A. Operation mode of DGs

There are two main operation modes between DGs and the system: islanded operation mode and grid-connected operation mode. The operation mode of DGs will affect the reliability of distribution networks with DGs.

Fig. 2 shows a simple distribution network model with one DG. It is assumed that failure occurred in the F1. It is clear that DG must be disconnected from the network, if the island is not allowed, bus 7 and bus 8 will be out of operation. Similarly when failure occurred in the F2, it is assumed that the load of the whole network is heavier, main network can only supply power to the load in trunk line, bus 7 and bus 8 will be out of operation too. Since the electric power market reform is imperative, the demand for quality and reliability of power supply and the number of DG connected to the network is increasing year after year. In this case, DGs should operate in form of micro-grid by taking certain measures to control the power, voltage and frequency, when failure occurs.
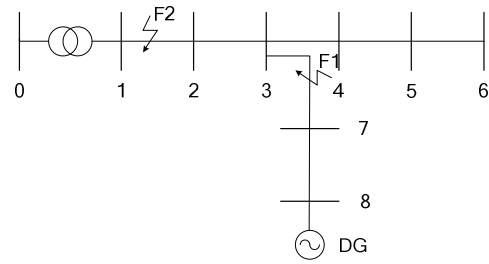

Figure 2.   A simple distribution network model with one DG

It is clear that the reliability of the system will be effectively enhanced when DGs can provide power to the load in the out-of-service area continuously. To achieve this purpose, the system need reliable distributed generation devices, and reasonable cooperation between disconnect switches and relay protection devices.

B. Self-healing reconfiguration method of distributed network with DGs

DGs generally adopt control strategy of PQ or PV when being connected to the network, while use V/f control strategy when operating disconnected from the network. According to different control strategies, DGs can be divided into: DGs which can run independently and DGs which can not.

Under the premise of ensuring the safety of power system, according to different kinds of DGs, when a failure occurs in distributed networks, DGs which can run independently will form a controllable island [6], while DGs which can not run independently are cut off, the rest of the network is restored by self-healing reconfiguration method. Fig. 3 shows the process.
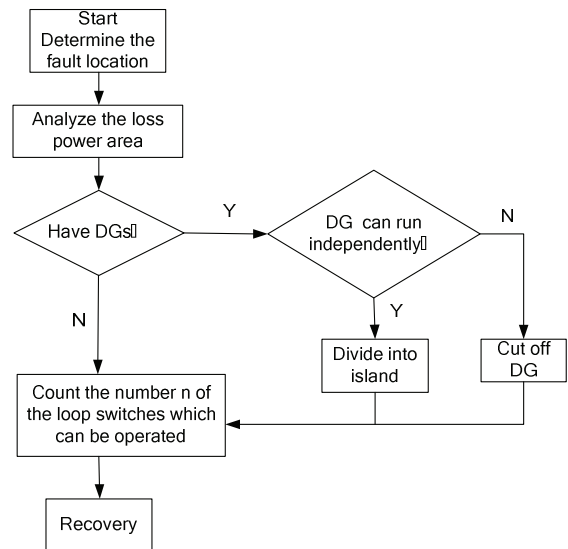

Figure 3.   Process of self-healing reconfiguration of distributed network with DGs

An additional constraint of distributed networks with DGs is the island power constraint, which means the loads within an island should be less than the total supply of DGs for the island.

$$P_{DG} + \sum_{i \in \phi} P_i \geq 0 \qquad (8)$$

Where P_{DG} is the output of DG within the island, ϕ is the island collection, P_i is the loads in the island.

VI. EXAMPLE OF APPLICATION

When a permanent fault occurs in a distributed network, relay protection devices will act to isolate the fault. Fig.4 shows a 26-busbar test system with DGs. DGs in distributed networks can be divided into two categories: DGs in the out-of-service area and DGs in charged area. DG 2 in Fig. 4 is the latter, which has little effect on the distribution network, so it can be ignored. For DG1 in Fig. 4, due to directly connected with the point of failure, according to the principle of division of island, it can form a tree with DG1 as the root node through opening the corresponding switches to form an island. Then the proposed algorithm is applied to recover system from the fault. Table 1 shows the restoration strategies.
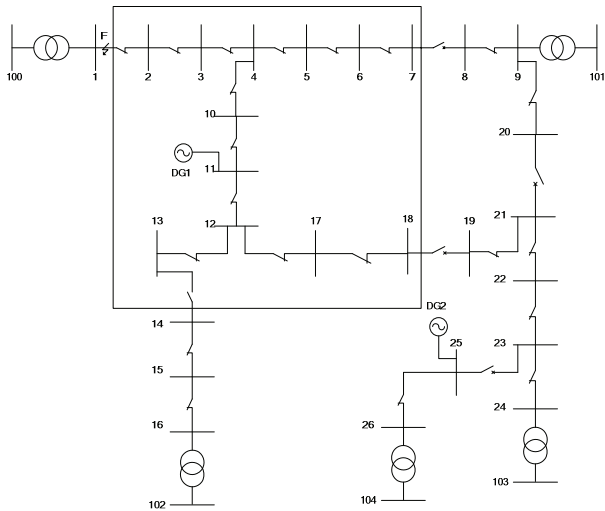

Figure 4. 26-busbar test system with DGs

TABLE I.   RECOVERY STRATEGIES OF 26-BUSBAR TEST SYSTEM WITH DG

No.	operation	illustration
1	Open 4-10 Open 11-12	Island operation
2	Close 7-8 Close 13-14	Recovery of power supply

We can see that in the conditions with DGs, the isolated island can effectively reduce the area of power outage, and improve power supply reliability, so it is a strongly recommended operation mode in distribution networks. When the distributed network is out of service, the following steps can be applied: first, relay protection devices act to isolate the fault; then, in accordance with real-time data, reasonable islanding solution is adopted using islanding algorithm; finally, the network is divided into islands. The operational characteristics of isolated island and requirements of power supply reliability should be taken into account. The principle is both to ensure the stable operation of the island, but also to minimize power outage of system as far as possible. Heuristic search method meets the requirements.

VII. CONCLUSION

In this paper, a self-healing reconfiguration technique is presented for smart distribution networks with DGs, and a heuristic algorithm is proposed based on tree-structured grid. According to the characteristics of DGs and the principle of isolated island operation, the network is divided into islands when the distributed network is out of service. Self-healing reconfiguration can be achieved through the proposed algorithm. Through the calculation analysis of test system, we can see that isolated islands can effectively reduce the area of power outage and improve power supply reliability.

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