Fault recovery of distribution network containing distributed generation based on heuristic search algorithm and multi-population genetic algorithm

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ABSTRACT
In order to solve low optimization efficiency and ‘premature convergence’ of the traditional genetic algorithm in fault recovery of the distribution network with DG, a new recovery scheme based on the heuristic algorithm and multi-population genetic algorithm is proposed. During the initial process, the heuristic algorithm is used to obtain certain individuals who are close to the local optimized solutions, so that it can search in the better individuals. And then, the multi-population genetic algorithm is introduced to achieve co-evolution among various groups, which takes into account the balance between the global and local searching abilities. Due to existing large number of infeasible solutions that do not satisfy the radial requirements in the searching process, topology simplification is performed to improve the searching speed and computational efficiency. Before the failure recovery, this paper determines whether to put into load shedding by using the repeated power flow method. Finally, the feasibility and validity of the optimization algorithm are demonstrated by case studies in the paper.

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1. Introduction
The fault recovery of the distribution network is the problem which realizes the optimization of power restoration in the un-faulted region on the basis of fault location and isolation. Its essence is the network reconfiguration after the failure. Specifically, under the premise of meeting various constraints of the distribution network, the open or closed state of the switch can be reasonably changed, the outage area may be effectively reduced, the power loss should be remarkably decreased, and the power supply ought to be restored quickly.

With the continuous development of economic society, more and more new energy and storage devices have been applied to the power system. Distributed generations (DG) refer specifically to environmentally friendly devices and energy-saving independent power source that are distributed in the vicinity of the load, and they have a capacity of several kilowatts to several tens of megawatts. DG plays an important role in stabilizing the voltage after being connected to the distribution network, but it may also cause reverse power flow and affect system security. When the distribution network loses power supply due to an accident or overhaul, if the DG’s output matches the local load, an islanding may occur (Su et al., 2015).

In order to meet the new challenges brought by DG access to the distribution network, many experts and scholars have recently made plenty of attempts. Among them, the main research results include the mathematical optimization algorithm (Barlow, 2002; Carpinelli, Celli, Mocci, Pilo, & Proto, 2013; Celli, Ghiani, Mocci, & Pilo, 2005; Feng, Liang, & Guo, 2012; Gan, Li, Topcu, & Low, 2012; Geoffrion, 1972; Lingwen, Na, Topcu, & Low, 2015; Mateo, Reneses, Rodriguez, Frias, & Sanchez, 2016; Nick, Cherkaoui, & Paolone, 2014; Nicks, Hohnman, Cherkaoui, & Hu, 2013; Sheng, Zhang, & Gao, 2014; Taylor & Hover, 2012; You & Grossmann, 2013), heuristic algorithm (Foster, Berry, Boland, & Water, 2014; Ipakchi & Albuyeh, 2009; Jabr, 2013; Siano, Chen, Chen, & Piccolo, 2010; Xie et al., 2013; Xing, Cheng, Zhang, & Zeng, 2016), artificial intelligence algorithm (Aoki, Satoh, & Itoh, 1988; Baran & Wu, 1989; Civanlar, Grainger, & Yin, 1988; Cui, Liu, & Li, 2008; Ding, Pan, & Cong, 2008; Jasmon & Lee, 1991), and so on. For example, Feng et al. (2012) proposed a minimum spanning tree and dynamic programming method, which ensures stable operation of islanding and quick synchronization with the upper power grid. It can be applied to the complex network with the structure containing rings, but it is inadequate in large scale and high complexity of the scene. Ding et al. (2008) used the rooted
The organizational structure of this paper is as follows: Section 2 introduces the mathematical model of the failure recovery, Section 3 introduces the optimization algorithm for fault recovery in the distribution network, Section 4 gives the restoration strategy, and Section 5 performs simulation analysis. In Section 6, the conclusions of this paper are made.

2. Fault recovery mathematical model of distribution network with DG

In this section, according to different roles played by DG in the distribution networks, and taking the impact of fault recovery into account, the types of DG are classified. Then, the objective functions of the fault recovery are set to the least load loss, minimal network loss, and the minimum numbers of switching operations. At the last, this paper gives the corresponding constraint conditions for fault recovery in distribution networks with DG.

2.1. The classification of DG

In the power flow calculation of distribution network, different DG can perform different equivalent processes based on their control methods and grid connection methods. Combining with the ideas of network reconfiguration, DG can be classified as follows (Meng, Wang, Liu, & Chen, 2016)

1) BDG (Black-start DG) and NBDG (Non Black-start DG) in accordance with whether DG has the black-start ability.

The multi-population genetic algorithm is introduced, which overcomes 'premature convergence' in the traditional genetic algorithm. Due to multiple populations being introduced, different populations take different control parameters. In addition, the immigration operators are used to connect among various groups to realize co-evolution. Finally, artificial selection operators are used to preserve the optimal individuals in each group.

(3) Due to the large number of infeasible solutions during the iterative process, this paper proposes three topology simplification rules to reduce the dimension of the solution and the search space.

The idea and theory of reconfiguration can also be applied to fault recovery. Meng, Wang, & Liu, (2016) analysed the influence of distributed generation on fault recovery; and then, the DGs were classified. The advantages and disadvantages based on the artificial intelligence algorithm, mathematical optimization algorithm and heuristic search algorithm were illustrated, respectively. In Tang et al. (2017), a dynamic reconfiguration method of the distribution network with DG was proposed in this paper, which considered the economical efficiency and power quality comprehensively. The maximum standard deviation of the indicator was set to determine the reconfiguration periods. Xue, Wu, and Wei (2016) built the mathematical model with minimum network power loss based on minimum spanning tree in order to further improve the efficiency of distribution network reconfiguration, and proposed a coding strategy to combine loop group search. In Zhang and He (2017), a genetic algorithm based on all spanning trees of the simplified graph of the distribution network was proposed for its reconfiguration. The simplified graph of the distribution network was searched to find all its spanning trees, which were subtracted from the simplified graph to obtain the connecting branches. Since only one of the switches in each connecting edge of a connecting branch could be opened, a decimal coding method was proposed, which took the switch quantity of each edge of a connecting branch as the base vector and the identification number of its opened switch as the optimization variable to significantly shorten the code length.

In this paper, aiming at the above problems, combined with the idea of network reconfiguration, a method based on heuristic search and the multi-population genetic algorithm is proposed to recover the faults of the distribution network containing DG. The main contributions of the paper are as follows:

1) By using the improved branch exchange algorithm, the heuristic information is added to the early searching, and some individuals that are close to the local optimal solution are selected. Then, these individuals are introduced into the initial population, so that the algorithm can start searching from the better individuals at the beginning, and the computing efficiency is remarkably improved.

2) BDG (Black-start DG) and NBDG (Non Black-start DG) in accordance with whether DG has the black-start ability.
2) CDG (Controllable DG) and NCDG (Non Controllable DG) according to whether DG has the communication capability and control protocol.

In order to simplify the calculation, this paper replaces all kinds of DGs with PQ nodes, which is equivalent to a ‘negative’ load.

2.2. The objective function

When the distribution network fails, it is hoped that the system will minimize the loss of load and network, at the same time, the number of switch operations should be as small as possible in order to extend the service life. Based on the above three ideas, this paper establishes a multi-objective function for fault recovery in distribution networks.

The least load loss:

$$\min f_1 = \sum_{i \in K} P_i,$$

where $K$ is a set of nodes that have not recovered supply after failure and $P_i$ is the load of node $i$.

The minimal network loss:

$$\min f_2 = \sum_{j=1}^{n} k_j r_j \frac{P_j^2 + Q_j^2}{U_j^2},$$

where $n$ is the total numbers of branches; $k_j$ is the switching state of branch $j$; $0$ is open, $1$ is closed; $r_j$ is the total resistance of branch $j$; $P_j$, $Q_j$, and $U_j$ are the terminal active power, reactive power and node voltage at the end of branch $j$, respectively.

The minimum number of switch operations:

$$\min f_3 = \sum_{i=1}^{m} (1 - C_i) + \sum_{j=0}^{n} S_j,$$

where $m$ and $n$ are the number of section switches and connective switches in the network, respectively; $C_i = 1$ indicates that the section switch $i$ maintains a closed state during the fault recovery, and $C_i = 0$ indicates that the section switch $i$ is turned open during failure recovery; $S_j = 0$ indicates that the connective switch $j$ remains in an open state in the recovery, and $S_j = 1$ indicates that the connective switch $j$ is turned to close in the failure recovery.

2.3. The constraint condition

The constraints of fault recovery include the network topology, node voltage, branch power, and so on.

$$g_k \in G,$$

$$U_{i,\min} \leq U_i \leq U_{i,\max},$$

$$S_j \leq S_{j,\max}.$$ (4)

In this section, this paper proposes a kind of distribution network fault recovery strategy containing DG. Firstly, the improved method branch exchange is used to optimize the population in the initial stage, and some individuals with local optimal solutions are introduced into the initial population. Then, the multi-population genetic algorithm is introduced to perform optimization to make it jump out of local optimum. In addition, combined with the theory of network reconfiguration, this paper simplifies the network topology which reduces the generation of a large number of infeasible solutions. Finally, the repeated power flow method is applied to judge whether it is necessary to put into load shedding, which can improve the computing efficiency.

3. Optimization algorithm for fault recovery in distribution network

3.1. Improved method of branch exchange

For the problem of fault recovery in the distribution network, heuristic information can be added to the search process to optimize it in the direction of optimal solution, which can accelerate the speed of searching and increase the computational efficiency. Based on this idea, the improved branch exchange method is introduced in the early optimization (Wang & Wang, 2014).

The traditional method of branch exchange maintains its radial topology in the distribution system. While closing a connective switch, a section switch that minimizes network loss must be opened in order to avoid forming a loop. Assuming that our system has good reactive power compensation, the reactive power flow can be ignored. The branch exchange formula is changed to

$$\Delta P = 2 \left( \sum_{i \in D} l_i \left( E_m - E_n \right) + R_{\text{loop}} \left( \sum_{i \in D} l_i \right)^2 \right),$$ (5)

where $D$ is a set of bus bars connected to the feeder I after the feeder II is separated; $l_i$ is the current before the load is transferred from bus $i$; $R_{\text{loop}}$ is the sum of resistors on the loop formed by the two feeders when connective
switches are closed; $E_m$ and $E_n$ are the voltage of the bus $m$ and the bus $n$ before the load is transferred, respectively.

The improved formula of network loss has secondary characteristics, and the open switches should make the current distribution close to

$$I(x_{opt}) = \frac{E_n - E_m}{R_{loop}}, \quad (6)$$

Now,

$$\Delta P_{min} = -\frac{(E_n - E_m)^2}{R_{loop}}. \quad (7)$$

By using the improved method of branch exchange, it can pick out some individuals that are close to the local optimal solutions at the beginning of the algorithm and put those individuals into the initial population. It makes the algorithm to be able to start from the better individuals, finally, the quality and efficiency of calculation are improved.

### 3.2. Multi-population genetic algorithm

Aiming at solving the problem of ‘premature convergence’, experts and scholars have extensively studied, and the concept of the multi-population genetic algorithm (Yu, 2015) is put forward. Firstly, the parallel search of multiple populations is introduced. Different groups are assigned with different control parameters to achieve different searching purposes. Then, the immigrant operator conducts the connections among various groups, and the best individuals appearing in the process of evolution are introduced into other populations regularly in order to realize the co-evolution. Among various control parameters, the values of crossover probability and mutation probability determine the global and the local searching capability. Finally, artificial selection operators are used to preserve the optimal individuals in each group. The elite populations do not participate in selection, crossover and mutation operations, so that the optimal individuals generated by various groups in evolution are not destroyed or lost.

### 3.3. Coding and topology simplification

In the process of fault recovery in the distribution network, the heuristic algorithm and multi-population genetic algorithm are used to find out the optimal combination that meets all constraints. Taking the 33-bus distribution system as an example, if the traditional ‘0–1’ binary encoding is adopted, the dimension and the search space will grow geometrically with the increase in the number of network nodes. Meanwhile, there are many infeasible solutions that do not satisfy the radial requirements in the
distribution network, which not only reduce the computing efficiency but also affect the quality of solutions to some extent (Tang et al., 2017; Xue et al., 2016). Aiming at the above problem, topology simplification is performed as follows:

1) In the operation of simplification, only the nodes with a dimension of 3 remain.
2) Since the independent branches that do not constitute a loop will inevitably form an island when its switches are opened, it may not consider the disconnection of its branch switches.
3) According to the power flow equations, the switches which are connected directly to a power source generally are not considered.

Combined with three simplification principles, Figure 1 is simplified to the form of Figure 2. After simplification, the space of the optimal solutions is greatly reduced.

### 3.4. Load shedding strategy

On the basis of guaranteeing the radial constraints in the distribution network, it is necessary to turn off the corresponding switches and cut off part of the load to meet the actual needs of the project, once the power loss exceeds
the supply capacity of the power grid during the process of recovery.

In this paper, the method of repeated power flow is used to evaluate the capacity supplement in the distribution network (Wang, Yao, Guo, & Qi, 2015), and then it is judged whether the algorithm needs to perform load shedding. The basic idea divides the distribution network into three parts before failure recovery: normal supply area, faulted area and non-faulted power loss area. Firstly, find all the switches that connect directly to the normal supply area and the non-faulted power loss area. Then, select an appropriate step size based on all the switches, increasing the load according to a certain amount of load increase and performing power flow calculation. Finally, during the load growth process, the step length of each switch is continuously adjusted in a certain way until the total load of all the switches is greater than the load of the non-faulted power loss area or satisfies the accuracy requirement of the step length.

4. Fault recovery scheme

Based on the heuristic algorithm and multi-population genetic algorithm, the specific steps of the fault recovery in the distribution network with DG are as follows (Figure 3):

Step 1: Initialization. Enter the basic electrical information, including the number of nodes, the number of switches, the power of branches, nodes load, the data of DGs and others. Then, enter the parameters of the algorithm: the number of populations, the number of individuals in the initial population, and the crossover probability and mutation probability.

Step 2: Coding and optimizing by using the method of ‘0–1’ binary and the topology simplification.

Step 3: Determining whether the load must be cut by the repeated flow method. The load shedding will be carried out if need be.

Step 4: By using the improved method of branch exchange in the early stage, it picks out some individuals who are close to the local optimal solutions, and then it introduces those into the initial population. In addition, the multi-population genetic algorithm is used to make optimization calculation, and it carries out the operations of choosing, crossing and mutating to generate new individuals.

Step 5: Calculating the fitness value of the current population, and then comparing with the fitness of the optimal individual. If it is superior to the latter, it updates the optimal fitness value.

Step 6: If the algorithm no longer satisfies the convergence condition or exceeds the maximum number of

![Figure 3](image-url). Fault recovery flow based on the heuristic algorithm and multi-population genetic algorithm.
iterations, the final recovery scheme will be output; otherwise, it will continue to iterate.

Step 7: Outputting fault recovery scheme.

5. Simulation analysis

In this section, as shown in Figure 1, the 33-bus distribution system is selected as an example, and it performs simulation experiments in the environment of MatlabR2014a. When the fault occurs in section 4–5 and section 2–3 of the 33-bus distribution system, respectively, the fault recovery strategy that this paper has proposed verifies the superiority of reducing network loss and improving power supply reliability.

Zhang, & He’s (2016) network electrical parameters are referred in this paper. The basic parameters of the algorithm are as follows: the number of populations is set to 3, the number of individuals is set to 30, the lengths of individuals are set to 15; the crossover probability is randomly selected in (0.7,0.9), and the variation probability is randomly selected in (0.001,0.05); the maximum number of iterations is set to 100; in the repeated flow method, the initial searching step size is set to 1, and the convergence accuracy is set to 0.01.

In Table 1, the expanded 33-bus distribution system includes three different types of DGs, all DGs are treated as PQ nodes in the simulation.

5.1. The fault occurred in section 4–5 of 33-bus distribution system with DGs

Supposed that a permanent fault occurs in section 4–5 of the 33-bus distribution system, the above three DGs are put into operation.

Firstly, they are identified by using the repeating power flow method, and no load shedding is required. Then the proposed fault recovery strategy is simulated in the 33-bus distribution system; at the same time, the heuristic algorithm and the traditional genetic algorithm are introduced. The simulation results of the fault recovery scheme, power loss load, network loss, and switching times are as follows:

In Table 2 and Figure 4, it can be seen that the three algorithms have basically the same load loss and the number of switching times; and the load loss is reduced to zero. However, in Figure 4, the network loss, caused by the fault recovery strategy proposed in this paper, is about 106 kW, and the network loss, caused by the other algorithms, is higher than 120 kW, which indicates that the optimization algorithm proposed in this paper is better at reducing network loss.

In order to demonstrate the superiority of the proposed algorithm in performance, the above three algorithms are used to run 100 times separately when a permanent fault occurs in section 4–5. The curves of iterative convergence and time-consuming are shown as follows.

In Figure 5, it can be roughly seen that the optimization algorithm proposed in this paper converges about the 14th generation, and the number of iterations required for the other algorithms to achieve convergence is significantly higher than the algorithm proposed in this paper. Meanwhile, Figure 6 is a time-consuming graph obtained by continuously running the program 100 times for the optimization algorithm proposed in this paper, heuristic algorithm and the genetic algorithm when the fault occurred in section 4–5. It can be clearly seen that the time-consuming curve by the optimization algorithm proposed in this paper (the blue curve in Figure 6) when completing the fault recovery is basically under the other two curves during the simulations. The optimization algorithm proposed in this paper takes less time when it completed the failure recovery, which

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**Table 1.** The information of DGs in expanded 33-bus distribution system.

| Number | Kinds  | Location | Capacity |
|--------|--------|----------|----------|
| DG1    | NBDG   | 10       | 100 kW   |
| DG2    | BDG    | 16       | 100 kW   |
| DG3    | BCDG   | 22       | 100 kW   |

**Table 2.** Fault recovery results when the fault occurred in section 4–5 of 33-bus distribution system with DGs.

| Kinds                      | Algorithm in this paper | Heuristic algorithm | Genetic algorithm |
|----------------------------|--------------------------|---------------------|-------------------|
| Recovery scheme            | Open29-30,Close8-21,25-29| Open6-26,Close12-22,25-29| Open8-9,Close12-22,25-29 |
| Switching times            | 3                        | 3                   | 3                 |

**Figure 4.** Loss analysis when the fault occurred in section 4–5 of 33-bus distribution system with DGs.
means that the optimization algorithm can speed up the calculation to a certain extent.

For the sake of further verifying the advantages of the optimization algorithm in performance, the reconfiguration in the 33-bus distribution system (without DG) is performed under normal conditions. Figure 7 shows the nodes’ voltages comparison before and after reconfiguration using the optimization algorithm proposed in this paper. It can be seen that compared with the former reconfiguration, the optimization algorithm improved the node voltage at the overall level, thereby it enhanced the stability of the system.

By analysing the above information, the optimization algorithm proposed in this paper can not only reduce load loss, network loss and switching times, but also the number of iterations and time-consuming which are relatively small. The convergence speed is remarkably accelerated, and computational efficiency is greatly improved.

5.2. The fault occurred in section 2–3 of 33-bus distribution system with DGs

Assuming that a permanent fault occurs in section 2–3 of the 33-bus distribution system with DGs. The switches 8–21 and 12–22 are directly connected to the non-faulted area. The repeated power flow method is used to calculate the corresponding nodes. Due to the more power loss and the power supply of the system being insufficient at this time, load shedding should be carried out.

Suppose that the nodes 16, 22, 24, and 25 belong to the first-level load, and the rest of the nodes belong to secondary loads. The lower the level of load is, the higher the importance is. Based on that, simulation experiments which compared with the genetic algorithm are carried out, the simulation results are shown in Table 3.

From the results of Table 3 and Figure 8, it can be seen that the fault recovery strategy adopted in this paper has some advantages compared with the genetic algorithm.
The optimization algorithm proposed in this paper is significantly smaller than the genetic algorithm in terms of the power load loss and network loss.

In Figure 9, the cut-out area is marked with a dashed frame, and the order of the load nodes are 33, 32, 31, 30, 29, 28, 27, 18, 26 and 17. Although a part of the load loses power, most of the primary load can still maintain power supply.

The simulation results show that when the distribution network fails, the fault recovery strategy proposed in this paper can not only protect the power supply of the important load to a certain extent, but also play an important role in reducing the network loss and load loss.

6. Conclusion
In this paper, a fault recovery strategy based on the heuristic search algorithm and multi-population genetic algorithm in the distribution network containing DG is proposed. First of all, the heuristic algorithm optimizes the population at the beginning of searching, and some individuals who are close to the optimal solution are introduced to the initial population, so as to improve the computational efficiency. In addition, the multi-population genetic algorithm proposed in this paper overcomes the drawbacks of 'premature convergence'. In order to further reduce the space of optimal solutions, the network topology is simplified, and the quality of the solutions is improved. Before the fault recovery strategy is formed, the repeated power flow method is used to judge whether the load shedding is needed. It not only ensures the power supply of the important load in the system but also decreases the network loss as well. Through some analysis of examples, the results show that this algorithm has good accuracy and rapidity and has a certain engineering value.

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