# A Novel Method for Islanding in Active Distribution Network Considering Distributed Generation

Jun Wang[1✉], Xinran Wang[1], Bart Di[2], Chao Sun[3], and Wei Zheng[3]

[1]College of Information and Electrical Engineering, Shenyang Agricultural University, Liaoning Province, 110866, China
[2]Emanden Technical Solutions Pty Ltd, Adelaide, Australia
[3]Yingkou Power Supply Company, Liaoning Electric Power Co. Ltd, State Grid Co. Ltd, Liaoning Province, 115000, China
✉wddream2016@syau.edu.cn

**Abstract**

The output of distributed generation (DG) has strong randomness, and its randomness has a great influence on the division of islands. To simulate the impact of DG output on island division when dividing islands, this study proposed an island division method that considers the randomness of DG output. The basic idea of this method is as follows. First, Monte Carlo sampling was used to obtain the output power of DG under different confidence levels to simulate the randomness of DG output. Furthermore, a multi-objective and multi-constraint considering the randomness of DG output were established. The niche genetic algorithm was used to solve the model, and the effectiveness of the proposed model and algorithm was verified through the analysis of examples. The results show that the risk reserve power introduced by simulating the randomness of DG output is inversely proportional to the confidence level. The minimum value of the system node voltage level after islanding is 0.9495 pu, which meets the requirements of the constraint. Under the same conditions, compared with the island division method of not considering the random DG, the method proposed in this study not only has a larger total load recovery and a higher priority load recovery rate but also has a higher DG utilization rate, which can meet the needs of practical applications. This study provides a certain reference for the establishment and solution method of the islanding model of the distribution network with DG.

**Keywords**: Distributed Generation (DG), Island Partitioning, Uncertainty, Monte Carlo Sampling, Multi Objective Optimization

## 1 Introduction

With the rapid development of distributed generation (DG) of power, the number of DG power sources in the grid has gradually increased. Its operation is flexible, and dismantling and investing in it are not limited to grid dispatching. It was a power generation method that is flexible, reliable, and efficient [1, 2, 3, 4]. The application demand for DG has shown an upward trend, and related studies have also achieved unprecedented development. More and more units are participating in the study of island division with distributed power generation. When the distributed power source is connected to the distribution network, the distributed power supply can independently supply power for part of the load after the grid fails. The power system needs to be divided into islands to form an island-operating state [5, 6, 7, 8].

However, with the access of DG distributed power sources, the traditional power distribution network has been converted from a single power supply to a multi-power supply system, which has complicated the operation and control of the power system [9, 10, 11]. Furthermore, DG with random output (such as wind power) is connected to the power system. The output of DG is affected by a variety of factors, resulting in the random power flow in the system. The traditional islanding strategy is no longer applicable. Therefore, considering DG output is necessary. The random island division strategy makes the island division result more accurate.

Based on the above analysis, scholars have found that, after an island in the distribution network, that is, after a line failure, on the basis of meeting certain network structure and electrical constraints, the switch combination of the line can be optimized to improve the power flow distribution and quickly restore electricity in the non-faulty outage area. The reliability and stability of the system power supply have been improved [12, 13, 14].

For this reason, Monte Carlo sampling is used to obtain the output power of DG under different confidence levels, which can simulate the randomness of

DG output accurately. Reference for the reasonable division of islands is provided.

## 2 State of art

Scholars all over the world have done a lot of work on the method of island partitioning with DG. A multi-period islanding strategy considering load response was proposed to model the load in time sequence. However, the randomness of its output cannot be accurately considered when modeling the probability of DG [15]. On the basis of considering load fluctuations, an islanding model was established to minimize failure cost, but it did not fully consider the randomness of DG [16] . The island division method that combined depth-first and breadth-first search has improved in meeting the requirements of the objective function, but the algorithm solution process took a long time [17]. A multi-constrained islanding model considering power supply potential and network energy risk is proposed, which provides a new direction for new islanding. However, the randomness of DG was not considered when dividing islands [18]. The minimum spanning tree method was used to solve the island operation area. This method greatly mentions the reliability of the power supply, but the power recovery rate of important loads was still low [19]. In summary, these studies assume that DG can output stably and all DGs can form islands. The randomness of DG output was not considered, which led to limited results.

A heuristic islanding strategy was adopted. This strategy defined the power supply unit and the load unit under the premise of power balance in the island. The load and power supply were combined to obtain an islanding division scheme, but the randomness of DG output was not considered [20]. A tree-knapsack island division model was proposed, and the tree-knapsack algorithm was used to solve the model. Through optimization and adjustment, the divided island operation area was safe and economical. This model only considers the randomness of the load but not the randomness of the DG [21]. The interval number was introduced to consider the randomness of DG output. It can better simulate the actual operating DG but can only reflect the output within a certain range [22] . The artificial intelligence algorithm was used to solve the model of island division and fault reconstruction, which can meet the requirements of the objective function. The disadvantage was that the artificial intelligence algorithm may fall into a local optimal solution [23] . A two-stage method was used to divide islands. First, a distributed power source was divided into islands to find the possible island division range of each distributed power source. Second, the obtained island division ranges were optimally combined to obtain the optimal island division plan that includes all distributed power sources. However, the adaptability of this model was poor [24]. A two-stage solution process was studied, and optimal load management measures were taken to reduce violations. Load priority and controllability were considered, but the randomness of DG output was not considered [25]. The relay protection device was used to isolate the fault quickly, and the faulty line was used to supply power to the fault line load to minimize the power failure range. However, guaranteeing the continuous operation of the load was difficult, and the uncertainty of DG output caused part of the load to be interrupted [26]. A rooted tree based on graph theory was proposed to solve the problem of the distribution network. The island partition model uses a rooted tree with hierarchical analysis characteristics. The depth-first algorithm can finally determine the scope of the island, but this method cannot realize online island partitioning [27]. The load status and output power of the distributed power supply were taken as fixed values, and the islanding was divided based on the constant value. However, this method did not consider factors such as load priority [28]. The artificial intelligence method was used to divide the network after the failure, but the uncertainty of the load was not considered [29]. Electric vehicles were considered in the recovery of power-loss loads, and a decentralized multi-agent control system was designed to control DG for islanding and restoring power-loss loads [30].

The above-mentioned studies are mainly focused on the method of dividing islands containing DG, and few studies focused on the characteristics of DG, especially the work related to the uncertainty of DG output. To consider the influence of the randomness of DG output on the division of islands, integrate the characteristics of DG and the structure of the distribution network, and simulate the randomness of DG output by introducing the power supply capacity of DG under a certain confidence level, a method to consider DG output was proposed. The random island division method and the use of niche genetic algorithm to solve the island division model can ensure the maximum recovery of the total load and the continuous and reliable power supply of important loads. Taking the IEEE69-node example system as an example, the effectiveness of the proposed failure recovery strategy was verified.

The remainder of this study is organized as follows. Section 3 describes the objective function of the island division and constructs the model and algorithm of island division. Section 4 analyzes specific examples and compares them with the other two methods of islanding. The results of this study show that the method has a better recovery effect on the loss of power load and verifies the rationality of the proposed islanding method. Section 5 summarizes the study and gives relevant conclusions

# 3 Methodology

Island operation is a brand new operation mode of the distribution network including DG. During island operation, because of faults or human factors, some loads in the grid are separated from the grid and are only powered by DG. The system containing these loads and DG is called an island.

## 3.1 Mathematical model of island division

### 3.1.1 Objective function

(1) Maximum power restoration

The maximum total power restoration of all islands is used as the objective function, which can be expressed as

$$f(x) = max \sum_{i=1}^{n} \sum_{j=1}^{m} P_{\mathrm{Lij}}$$

where $n$ is the number of isolated island regions divided into the distribution network, $m$ is the number of load nodes in the island numbered, and $P_{\mathrm{Lij}}$ is the active load of the load node numbered $j$ in island $i$.

(2) Restoring high priority loads

$$f(x) = max \sum_{i=1}^{n} \sum_{j=1}^{m} w_{\mathrm{ij}} P_{\mathrm{Lij}}$$

where $n$ is the number of isolated island areas that divide the distribution network, $m$ is the number of load nodes in the island numbered $i$, $P_{\mathrm{Lij}}$ is the active load of the load node numbered $j$ in island $i$, and $w_{\mathrm{ij}}$ is the weight coefficient of the load numbered $j$ in island $i$. The weight coefficients of the three types of loads can be adjusted based on experience, and they generally take 10, 5, and 1.

(3) The smallest number of breaker actions

$$f(x) = min \sum_{i=1}^{n} N_i$$

where $n$ is the number of islands and $N_i$ is the number of circuit breakers required to disconnect the island numbered $i$ from the system.

### 3.1.2 Constraints

(1) Power balance constraints. The total load of the island is balanced with the active power of the DG.

$$\sum_i P_{\mathrm{Gi}} - \sum_i P_{\mathrm{Li}} > 0$$

where $\sum_i P_{\mathrm{Gi}}$ is the sum of the active power of all DGs in island $i$ and $\sum_i P_{\mathrm{Li}}$ is the sum of the active power demand of all loads in island $i$.

(2) Safety constraints of transmission lines. To ensure the safe operation of transmission lines, the power transmitted on the transmission lines must be within a specified margin.

$$P_{\mathrm{eij}} < \alpha \cdot P_{rated\_eij}$$

where $P_{\mathrm{eij}}$ is the power delivered by line $eij$, $P_{rated\_eij}$ is the rated capacity of line $eij$, and $\alpha$ is the margin factor.

(3) Node voltage constraints. To make the power quality better, the node voltage fluctuation range is required to be 5% of the rated voltage.

$$0.95U_{rated\_i} < U_i < 1.05U_{rated\_i}$$

where $U_{rated\_i}$ is the rated voltage of node $i$ and $U_i$ is the rated voltage of node $i$.

## 3.2 Algorithm for islanding

This study uses a niche genetic algorithm to divide islands. This algorithm divides a large population into several small populations and performs operations such as mutation and crossover within a small population. The calculation speed of this algorithm is faster, which can reduce the probability of falling into a local optimal solution. It has significant advantages for solving multi-objective optimization problems. The steps are as follows:

(1) initialize the population, simplify the structure of the distribution network, generate the corresponding connection diagram, and randomly generate an initial population with 100 chromosomes;

(2) perform genetic operations, such as selection, crossover, and mutation on the population;

(3) solve the fitness according to the requirements of the objective function;

(4) judge the restriction conditions of transmission line safety, node voltage, and power balance, proceed to the next step if the constraints are met, and proceed to step (2) if the constraints are not met;

(5) merge two islands in the obtained preliminary island division plan if they contain the same load node, thereby reducing the number of islands and improving the stability of operation.

According to the above steps, the flowchart of the island division algorithm is shown in Figure 1.

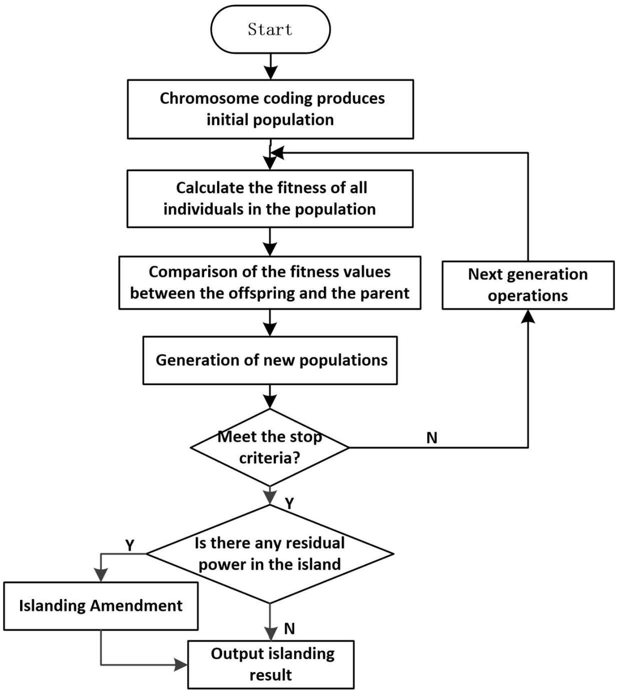


Figure 1: Flow chart of island partition algorithm

## 3.3 Calculation of distributed power supply capacity considering randomness

Wind power is a renewable distributed power source. It is the most widely used and most mature form of power generation. Given the randomness of its output power, the large-scale grid connection of wind power is restricted. Therefore, the random model of generator output power should be studied on the basis of the random distribution model of wind speed.

The relationship between wind power output power and wind speed is as follows:

$$P_w(V) = \begin{cases} 0 & V < V_{\mathrm{ci}}, V > V_{\mathrm{co}} \\ K_1 \mathrm{V} & V_{\mathrm{ci}} \le V \le V_r \\ P_r & V_r < V < V_{\mathrm{co}} \end{cases}$$

$$\begin{cases} K_1 = \frac{P_r}{V_r - V_{\mathrm{ci}}} \\ K_2 = -K_1 V_{\mathrm{ci}} \end{cases}$$

where $V$ is the wind speed at the current moment; $P_r$ is the rated active output power of wind power; and $V_{\mathrm{ci}}$ ,$V_r$, and $V_{\mathrm{co}}$ represent cut-in, rated, and cut-out wind speeds, respectively.

The current models describing the randomness of wind speed include the Weir distribution, the normal distribution, and the Gumbel distribution. This study uses Weir distribution because of its simple form and high accuracy. The expression of the cumulative probability distribution function is as follows:

$$F(V) = 1 - exp\left[-\left(\frac{V}{C}\right)^K\right]$$

This study introduces the reserve power to describe the randomness of DG output. In time T, the system's reserve power $\tilde{E}$ is greater than $E_{\mathrm{RS}}$ with a probability greater than the confidence level $\beta$, and the maximum value of all is the reserve power $E_{\mathrm{VAR}}$, which is as follows:

$$E_{\mathrm{VAR}} = P_r\left(\tilde{E} > E_{\mathrm{RS}}\right) = \beta$$

The reserve power $E_{\mathrm{VAR}}$ changes with the confidence level. The lower the confidence level, the greater the reserve power value, and the higher the confidence level, the smaller the reserve power.

The rated output of DG is divided into intervals with the same interval, and the minutes of DG output are counted at different intervals within T. From the curve of DG output, the total minutes of DG output under a certain degree of confidence can be obtained.

The shaded area in the figure 2 is the reserve power obtained by DG in a sampling simulation, which is a reserve power. The program is in the MATLAB R2016b environment, the set cut-in wind speed is

$V_{\mathrm{ci}}$=3.5 m/s, the rated wind speed is $V_{\mathrm{cr}}$=15 m/s, and the cut-out wind speed is $V_{\mathrm{co}}$=25 m/s. The rated power of the fan is 120 kW, and the Weir distribution parameters are $c$ =5.5, $k$ =1.5. The simulation time is T=120 min. Forty risk reserve powers are calculated

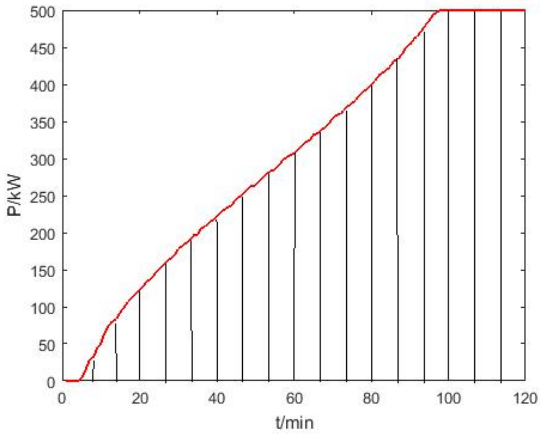


Figure 2: DG output power duration curve

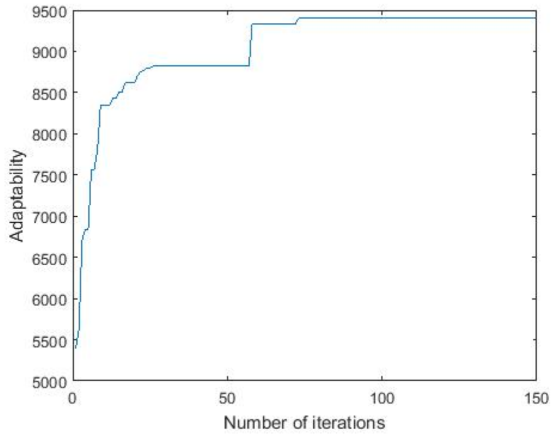


Figure 3: Genetic algorithm fitness values

and generated, and the corresponding values between multiple reserve powers and the confidence level $\beta$ are obtained. Photovoltaic power supplies can also be programmed and simulated in MATLAB to obtain the output power within a certain period (120 min), and multiple simulations can be performed to obtain multiple risk reserve power.

# 4 Result Analysis and Discussion

This study uses the PG&E69 node system for analysis, connecting six nodes with DG. The total active capacity is 1640 kW, and the total network active load is 3058.19 kW. According to the analysis of the output power of DG, the confidence level $\beta$ is selected as 0.9. The external output power and access location of DG are shown in Table 1, the controllability of the load is shown in Table 2, and the load level is shown in Table 3.

Suppose that the main branches 2–3 fails, and the entire distribution network has no electricity. Assume that the interruption lasts for 2 hours. Niche genetic algorithm is used to divide islands. Table 4 shows the best fitness values of 10 trials.

When the best fitness value is 9410.2, the maximum fitness value of each generation of the population varies with the evolutionary generation, as shown in Figure 3.

The optimal islanding scheme can be obtained as shown in Figure 4. The same color represents the division range of the same island.

Figure 4 shows that the PG&E69 node system is divided into five independent islands. Given that the islands formed by DG1 and DG4 contain the same

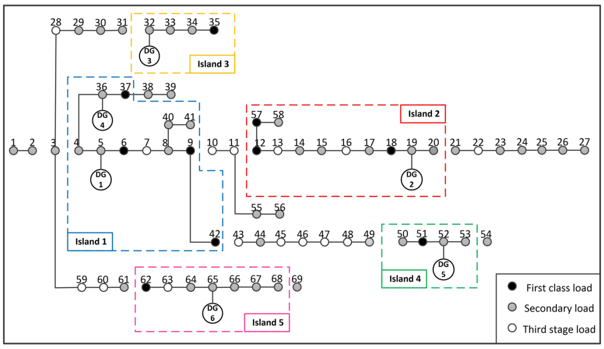


Figure 4: Schematic diagram of primary isolated islands

load node, merging these islands is necessary to form a joint island such that the number of islands is as small as possible. Given the large capacity and strong impact resistance of the joint island, the power quality and stable operation of the island can be guaranteed, and the main island is generated. At this time, checking whether the DG on the island has remaining power is necessary. If surplus power is available, the generated main island should be corrected to maximize the utilization of the island and increase the utilization rate of DG.

According to the division range of the main island, the total active capacity in island 1 is 300 kW, the total load active capacity in the initial island is 274.45 kW, and the remaining active capacity in island 1 is 24.55 kW. Load nodes 38, 10, and 43 are adjacent to island 1, where node 38 is a secondary load, nodes 10 and 43 are three loads, node 38 has a higher priority, and load 38 is a 100% controllable load. The remaining 24.55 kW active power of the island 1 is all provided to load 38. At this time, the active capacity utilization rate on the island is 100%. According to this study, the

Table 1: DG external output power and access location table

| DG number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Access node | 5 | 19 | 32 | 39 | 52 | 65 |
| ADG rated power/kW | 120 | 1000 | 100 | 600 | 2000 | 250 |
| Calculation of external power/kW | 50.618 | 421.505 | 41.711 | 250.765 | 829.707 | 105.310 |
| Adjusted output power/kw | 50 | 420 | 40 | 250 | 820 | 100 |

Table 2: Node load controllability

| Node Number | Controllability |
|---|---|
| 21, 29, 34, 38, 39–41, 53, 54, 58, 66, 68, 69 | 100% controllable |
| 11, 13, 16, 26, 55, 56 | 40% controllable |
| Other nodes | 50.618 |

Table 3: Node load level

| Node Number | Load rating | Load weights |
|---|---|---|
| 6, 9, 12, 18, 35, 37, 42, 51, 57, 62 | First-class load | 10 |
| Other nodes | Second-class load | 5 |
| 7, 10, 11, 13, 16, 22, 28, 43, 45, 46, 47, 48, 59, 60, 63 | Third-class load | 1 |

Table 4: Table of best fitness values

| Adaptability | | | | | Maximum value | Average value |
|---|---|---|---|---|---|---|
| 8830.5 | 9402.1 | 8913.3 | 9401.2 | 9410.2 | 9410.2 | 9299.4 |
| 9408.2 | 9410.2 | 9408.2 | 9400.1 | 9410.2 | | |

remaining four islands are reviewed separately, and the revised final island division scope is shown in Figure 5.

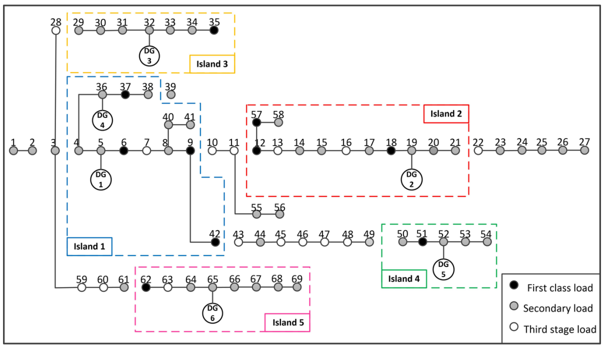


Figure 5: The final island partition

Table 5 shows the various indicators of the results of the island division plan, including the DG capacity in the island, the load set contained in the island, the number of short-circuit breaker actions, and the number of adjusted controllable loads.

The final division result of the island shows that the power recovery rate of the entire network after the failure is 53.63%, the first-level load recovery rate is 100%, and the second-level load recovery rate is 51.76%. The three-level load recovery rate is 23.55%. The number of actions is eight times. It satisfies the requirements of the target function and maximizes the recovery of power and gives priority to the constraints of the first load as much as possible.

After separating the island, the node voltage level of the power distribution system is shown in Figure 6. The voltage levels of nodes 12 and 13 are the lowest at 0.9495 p.u., satisfying the requirements of constraints.

To verify the effectiveness and accuracy of the algorithm in this study, according to the respective islanding algorithms in references [20] and [21], they are substituted into the 69-node distribution system for calculation under the same parameter settings. Then, the three islands are divided. The load recovery rate is compared, and the specific load recovery situation is shown in Table 6.

Figure 7 shows the island segmentation range of reference [20] using the island segmentation method. The total load recovered by this method is 1579.95 kW, and the load recovery percentage of the entire net-

Table 5: Indicators of the isolated island classification program

| Island number | Total DG capacity/ kW | Number of loads in islands | Switch action times | Adjustment load number |
|---|---|---|---|---|
| 1 | 300 | 4–9, 36–38, 42 | 3 | 38 |
| 2 | 400 | 12–1, 57, 58 | 2 | 21 |
| 3 | 40 | 29-35 | 1 | 29 |
| 4 | 800 | 50-54 | 1 | 54 |
| 5 | 100 | 2-69 | 1 | 69 |

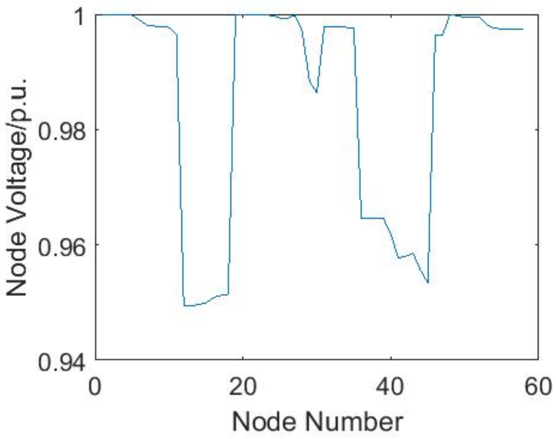


Figure 6: Voltage values for each node

work is 51.66%. Among them, the first-level load recovery rate is 93.19%, the second-level load recovery rate is 33.90%, and the third-level load recovery rate is 93.75%. This method guarantees a higher recovery rate for the first-level load and restores more than the third-level load but ignores the importance of the second-level load. The formation of this island range requires seven breaker actions, which is the smallest number of actions.

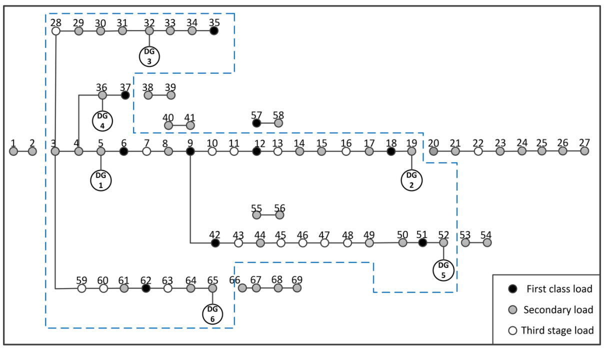


Figure 7: Range of islands in reference [20]

Figure 8 shows the island range of reference [21] using the island method. The total load recovered by this method is 1630.2 kW, which is lower than the 1640 kW in this study. The load recovery percentage of the entire network is 53.31%. Among them, the first-level load recovery rate is 98.94%, the second-level load recovery rate is 49.55%, and the third-level load recovery rate is 33.94%. The formation of this island requires 11 switching actions, which is higher than the 8 switching actions in this study.

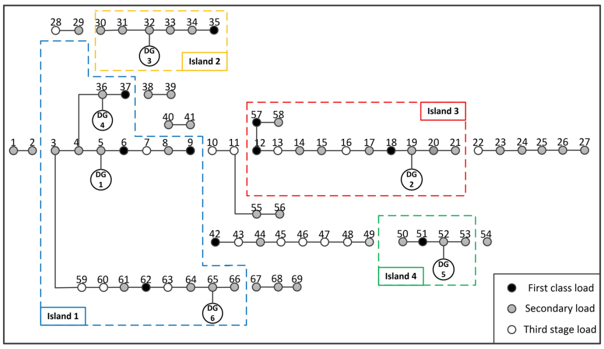


Figure 8: Range of islands in reference [21]

The specific load recovery conditions of the three methods are shown in Table 6.

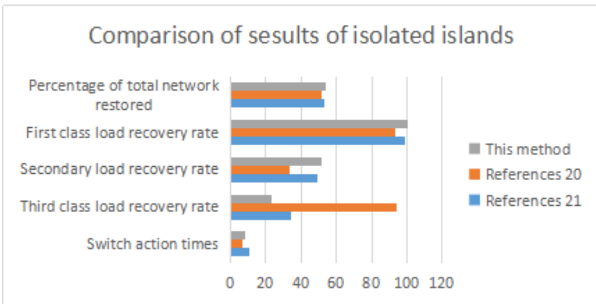


Figure 9: Column diagram of isolated islands

The above chart(Figure 9)analysis shows that this method has obvious advantages in terms of the percentage of power supply restoration of the whole network and the power restoration rate of the first-level load. This study makes the first-level load recovery rate reach 100% based on the maximum total power

Table 6: Comparison of results of isolated islands

| Method | Percentage of total network restored | First-class load recovery rate | Second-class load recovery rate | Third-class load recovery rate | Switch action times |
|---|---|---|---|---|---|
| This method | 53.63 | 100 | 51.76 | 23.55 | 8 |
| Reference 20 | 51.66 | 93.19 | 33.90 | 93.75 | 7 |
| Reference 21 | 53.31 | 98.94 | 49.55 | 33.94 | 11 |

recovery rate, strictly follows the load priority principle, fully realizes the target function requirements, and prioritizes important loads. Given that this study considers the controllability of the load, the island is amended after the main island is divided, which not only improves the power recovery rate of the entire network but also fully improves the utilization rate of DG.

In summary, the method proposed in this study can restore the power of high priority loads to the greatest extent. Although a certain gap is seen between the number of switch operations and reference [20], the method can meet the needs of actual engineering applications. It has great advantages in terms of quantity and recovery of advanced loads. Under the same conditions, the objective function of this method has the maximum adaptability, the utilization rate of DG is relatively high, and this method is simple and easy to program and has important significance in actual operation.

## 5 Conclusion

To consider the impact of the uncertainty of DG output on the division of islands and reveal the relationship between the island division and the randomness of DG output, this study started with the physical model of DG, employed Monte Carlo sampling to simulate the magnitude of DG output, and used the niche genetic algorithm to solve the model. The following conclusions could be drawn.

(1) The risk reserve power into the calculation of DG's power supply capacity is introduced. Through Monte Carlo sampling, the output power of DG under different confidence levels is obtained, and the randomness of DG output is simulated. Reference for the reasonable division of islands is provided.

(2) The niche genetic algorithm is used to divide islands. The algorithm performs genetic operations in a small group, and the calculation speed is fast, which can reduce the probability of falling into a local optimal solution. It has obvious advantages for multi-objective optimization problems.

(3) Under the same conditions, compared with the islanding method that does not consider the randomness of DG, the method proposed in this study has the largest total load recovery and the highest priority load recovery rate. The DG utilization rate is higher, which can meet the needs of actual engineering applications.

In this study, the impact of the randomness of DG output was fully considered in the process of islanding. The multi-objective islanding model established based on this impact is more in line with the actual situation. It has a certain reference for the follow-up study on the division of islands containing DG. Given that the correlation of the output of different types of DGs is not considered, in future work, the correlation between different types of DGs will be combined with this model and modified, the DG processing simulation will be more accurate, and the islanding results will be more reasonable.

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