

An island partition method based on heuristic algorithm and Prim topology generation in active distribution network

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ABSTRACT

More and more distributed generations (DGs) are integrated into distribution network (DN), and IEEE 1547.4-2011 standard encourages the conscious island operation of the DN. However, the fluctuation of DG output, power supply priority of load and operation state of interconnection switch are required to be considered in island partition, which greatly increases the difficulty of solving the model. An island partition method based on heuristic algorithm and Prim topology generation is proposed in the paper. In view of the shortcomings of the existing island partition methods, this method comprehensively considers the important influence of interconnection switch and power supply priority. The secondary outage constraint under fault state is also considered in the construction of island partition model, which makes the optimization result closer to the engineering practice. In addition, a heuristic prospective greedy algorithm is used to solve the island partition model. This method can effectively overcome the blindness of one-step selection and obtain a better scheme. The effectiveness of the method is verified by a case study of PG&E 69 bus system.

Keywords: island partition, distributed generation, heuristic algorithm, Prim algorithm, interconnection switch, load priority

1. INTRODUCTION

Renewable energy power generation will play a central role in reducing greenhouse gas emissions and achieving China's goal of carbon emissions peak before 2030 and carbon neutralization before 2060^[1]. Carbon neutralization requires large-scale development of renewable energy power generation, and the output of renewable energy has randomness and volatility. Its support for system power supply reliability has become a research hotspot. The island partition scheme is required to be formulated to fully utilized the power supply restoration potential of DG under fault state^[2].

Island partition modeling is the core work in the process of DN reliability evaluation based on island

partition^[3]. Based on historical data, reference [4] generates distributed generation scenarios and their probability distributions according to sequence characteristics and uncertainty output of DG. The island partition model of active distribution network with restoration load as the objective function is established. But the influence of load priority on power supply restoration sequence is not considered. Reference [5] establishes the island model of intelligent DN based on severe disturbance environment by integrating the constraints of load demand and priority. However, the expansion path of power supply recovery by interconnection switch is ignored. Therefore, the effect of various constraints should be considered comprehensively on island partition modeling to maximize the benefit of load recovery under island mode.

The existing methods for solving island partition model can be divided into: graph theory partition method^[6], tree knapsack method^[7-8] and heuristic algorithm^[9-10]. Among them, the graph theory partition method essentially transforms the island partition problem into the minimum spanning tree problem. The minimum spanning tree problem can be well solved based on Prim algorithm^[11-12]. Through tree knapsack method, the optimal island partition problem can be transformed into a tree knapsack problem. Then the problem of DGs island partition is solved base on the strategy of search and adjustment. However, graph theory partition problem and tree knapsack problem are typical NP hard problems and the proposed methods can't meet calculation speed and accuracy at the same time^[13].

To sum up, the island partition research of active DN still has the following shortcomings: (1) Aiming at the problem of island partition under fault state, the existing research in modeling has not fully considered the important factors such as interconnection switch, load priority and secondary outage constraint. (2) In order to satisfy the radial constraint, island partition model is difficult to be calculated. To solve the above problems,

an island partition method based on heuristic algorithm and Prim topology generation is proposed in the paper. The characteristic of which is that the secondary outage constraint is taken into account in island partition optimization model. A heuristic prospective greedy algorithm is used to solve the island partition model. This method can effectively overcome the blindness of one-step selection and obtain a better scheme. The final island partition scheme can be dynamically formulated based on the prospective greedy algorithm and Prim algorithm.

2. ISLAND PARTITION MODEL OF ACTIVE DISTRIBUTED NETWORK AND SOLUTION METHOD

2.1 Island partition model

The distribution network usually maintains a radial structure during operation. The power supply reliability of the system may be affected when the components are under fault state. The load downstream of the fault component cannot obtain electricity from the superior power grid. The topology of DN can be changed flexibly. The scientific island partition scheme can be formulated to fully utilized the power supply restoration potential of DG under fault state. If the system operates under fault state at time t , the superior grid can be equivalent to a DG with output no more than C_G and continue to supply power to the load together with other DGs. The necessary condition for a load node to be restored is that at least one of all nodes directly connected to it has already been restored. When the electricity of each DG cannot meet the power demand of the surrounding load, the power supply recovery process ends and the island partition scheme at t time is obtained. The recovery strategy of system load under fault state is required to consider secondary outage constraint. That is, the final island partition scheme under continuous fault state is the intersection of island partition schemes at each moment. The load nodes that can be recovered at all times is drawn into an island.

For the DN with N load nodes and M DGs, the island partition scheme can be modeled as a knapsack problem (KP). The active power of each node can be regarded as the weight of the item. The active output of DG can be regarded as the capacity of backpack. The product of active power of the knapsack node and corresponding load weight is regarded as benefit B and the value B is selected as the objective function. Then, for the k_{th} fault, the knapsack model of island partition is as follows:

$$\begin{aligned} \min & \sum_{t=t_1}^{t_2} \sum_{a=1}^A \sum_{i \in \Omega_a^{\text{load}}} B_{i,t} * (1 - ST_i), \\ & \begin{cases} B_{i,t} = P_{i,t} * PR_i \\ \sum_{i \in \Omega_a^{\text{load}}} P_{i,t} * st_{i,t} \leq \sum_{i \in \Omega_a^{\text{DG}}} G_{i,t} & \forall a \in [1, A] \\ \Omega_a^{\text{load}} \cap \Omega_b^{\text{load}} = \emptyset & \forall a \in [1, A], b \in [1, A], a \neq b \\ \Omega_a^{\text{DG}} \cap \Omega_b^{\text{DG}} = \emptyset & \forall a \in [1, A], b \in [1, A], a \neq b \end{cases} \\ \text{s.t.} & \begin{cases} st_{i,t} = \begin{cases} 1 & \text{if } i \in \bigcup_{a=1}^A \Omega_a^{\text{load}} \\ 0 & \text{else} \end{cases} \\ ST_i = \begin{cases} 1 & \text{if } st_{i,t} = 1 \quad \forall t \in [t_1, t_2] \\ 0 & \text{else} \end{cases} \\ U_i^{\min} * st_{i,t} \leq U_{i,t} \leq U_i^{\max} * st_{i,t} \\ I_{ij,t} \leq I_{ij,t}^{\max} \end{cases} \end{aligned} \quad (1)$$

Where, Ω_a^{DG} denotes the set of DG integration nodes. A denotes the number of islands in DN. The set of DG integration nodes in the a_{th} island is denoted as Ω_a^{DG} . The set of load nodes is marked as Ω_a^{load} . t_1 denotes the initial time of the fault, while t_2 represents the end time of the fault. $B_{i,t}$ denotes the benefit value of node i at time t . ST_i is a 0-1 variable, which indicates whether node i can be restored under fault state. 1 denotes that it can be restored, while 0 denotes the opposite. $st_{i,t}$ denotes whether node i can be restored at time t . 1 denotes that it can be restored, and 0 denotes the opposite. PR_i denotes the priority of load node i . $G_{i,t}$ denotes the DG power output of node i at time t . $U_{i,t}$ denotes the voltage of node i at time t . U_i^{\min} and U_i^{\max} respectively denote the lower limit and upper limit of the node voltage at time t . $I_{ij,t}$ denotes branch current of the line between node i and node j at time t . $I_{ij,t}^{\max}$ denotes the upper limit of branch current at time t .

2.2 Prospective greedy algorithm

The island partition model established in section 2.1 is a 0-1 mixed integer non-linear programming model, which is complex and difficult to solve. A heuristic prospective greedy algorithm is used to formulate the island partition scheme. The algorithm can effectively overcome the blindness of single-step selection of the existing methods. The algorithm can bring greater benefits and reduce the outage loss to a greater extent. The steps of prospective greedy algorithm under fault state at time t can be listed as follows:

(1) Update the topology of DN according to the location of fault components at time t . The outage loads

that lose connection with the superior power grid are drawn into figure **G**. Save a copy of figure **G'**.

(2) Determine the power supply order of DG and formulate restoration scheme of each DG at t time in turn.

① Select the DG with the largest capacity that is not marked, the integration node is selected as the initial node of KP. Judge whether the electricity of DG is greater than active power of integration node. If yes, update the remaining electricity of DG by subtracting the load demand of nodes. If not, mark the DG and repeat step ①.

② Set \mathbf{V} denotes the set of nodes that can be restored by DG. The total active power of all nodes in set \mathbf{V} is denoted as P_V , the sum of benefit is recorded as B_V , and the remaining electricity of DG is denoted as C_R . Update P_V , B_V and C_R of set \mathbf{V} according to equation (2) - equation (4):

$$P_V = \sum_{i \in \mathbf{V}} P_{i,t} \quad (2)$$

$$B_V = \sum_{i \in \mathbf{V}} P_{i,t} * PR_i \quad (3)$$

$$C_R = \sum_{i \in \mathbf{V} \cap \Omega_a^{DG}} G_{i,t} - P_V \quad (4)$$

③ Search the neighborhood set \mathbf{NE}^1 and prospective neighborhood \mathbf{NE}_m^2 of \mathbf{V}

Search for nodes that are directly connected to the nodes in \mathbf{V} but don't belong to set \mathbf{V} . The set composed of such nodes is named as the neighborhood set of \mathbf{V} . The set is denoted as \mathbf{NE}^1 , and the number of nodes in \mathbf{NE}^1 is denoted as N_0 . For the m th node $NE^1(m)$ in set \mathbf{NE}^1 , $m \in \{1, 2, \dots, N_0\}$, search for nodes directly connected to $NE^1(m)$ but not belonging to sets \mathbf{V} and \mathbf{NE}^1 . The set composed of such nodes is named as the prospective neighborhood of \mathbf{V} . The set is denoted as \mathbf{NE}_m^2 , and the number of nodes in \mathbf{NE}_m^2 is denoted as N_m . Among which, $NE_m^2(n)$ denotes the n th neighborhood node of $NE^1(m)$, $m \in \{1, 2, \dots, N_0\}$, $n \in \{1, 2, \dots, N_m\}$.

④ Calculate value ratio index corresponding to each neighborhood node

The value ratio $Va^1(m)$ of node $NE^1(m)$ is calculated as follows:

$$Va^1(m) = \begin{cases} \frac{B_V(NE^1(m))}{P_V(NE^1(m))}, & \text{if } P_V(NE^1(m)) \leq C_R \\ 0 & , \text{if } P_V(NE^1(m)) > C_R \end{cases} \quad (5)$$

Where, $P_V(i)$ denotes the active power of node i and $B_V(i)$ denotes the income value of node i . If $P_V(NE^1(m)) + P_V(NE_m^2(n)) \leq C_R$, the value ratio $Va_m(n)$ of the combination of neighborhood node $NE^1(m)$ and

prospective neighborhood node $NE_m^2(n)$ is calculated as follows.

$$Va_m(n) = \frac{B_V(NE^1(m)) + B_V(NE_m^2(n))}{P_V(NE^1(m)) + P_V(NE_m^2(n))} \quad (6)$$

Otherwise, the value ratio $Va_m(n)$ is 0.

⑤ Calculate the optimal value ratio Va_{\max} corresponding to neighborhood set \mathbf{NE}^1 and prospective neighborhood set \mathbf{NE}_m^2 of \mathbf{V}

$$Va_{\max} = \max \{Va^1(m), \max \{Va_m(n)\}\} \quad (7)$$

$$\forall m \in \{1, 2, \dots, N_0\}, n \in \{1, 2, \dots, N_m\}$$

If Va_{\max} is 0, mark the DG and exit the iterative calculation. Set \mathbf{V} is the load node corresponding to the current DG that can be recovered. If Va_{\max} is not 0, the node corresponding to the maximum value is drawn into the set \mathbf{V} . Then, return to step ②. If the value ratio is the same, the nodes with large active load shall be preferentially drawn into island.

(3) Compress all the nodes obtained in step (2) into new nodes s_i

For all nodes in Ω_a^{load} , check whether there is a connection relationship between them. If yes, disconnect the line and compress the scattered nodes into a new node s_i . If the node in Ω_a^{load} has a connection relationship with the external node of Ω_a^{load} , s_i will maintain the connection relationship with the external node. Check whether there are multiple nodes in Ω_a^{DG} . If yes, the multiple DGs integrated into the corresponding nodes are merged into a new DG and the new DG is integrated into the compression node s_i . The output of which is that the sum of C_R of each DG before merging.

(4) Check whether there are unmarked DGs in Figure **G**. If yes, go to step (2). Otherwise, go to step (5).

(5) Each compression node s_i denotes an island. Restore s_i to the original node and determine the island partition scheme according to **G'**.

(6) There are interconnection switches in DN, and the island partition scheme obtained by prospective greedy algorithm may have ring network. The Prim algorithm of minimum spanning tree is applied to transform the ring network into radial structure.

(7) Check the node voltage and power flow constraints. Change the island partition scheme according to the power flow calculation results until all constraints are met.

2.3 Prim algorithm

Prim algorithm is an algorithm for finding the minimum spanning tree in weighted undirected graph.

For the ring structure of weighted undirected graph, Prim algorithm can be used to search an acyclic path with all nodes. The sum edge weights composed of the path is the lowest. It is considered to minimize the operation times of interconnection switch in the process of formulating island partition and restoring power supply. When there is a ring network in the island partition scheme, it is preferred to disconnect the interconnection switch. According to the above principle, the edge weight b of interconnection switch is set to be greater than the edge weight a of distribution feeder. Then, the Prim algorithm is used to search a power supply path that meet the radial constraint, and the sum edge weights of the path is the lowest. The specific steps of Prim algorithm are as follows:

(1) According to the existing island partition results, the scheme with ring network is formed. Set the weight of the distribution feeder to 1 and the weight of the interconnection switch to 2.

(2) Establish node set W and edge set E . The two sets store all the node and edge information in the topology respectively. Establish the corresponding set W' and E' . Empty set E' . Select one node arbitrarily as the initial node w_0 to start the search. And the initial node is drawn into the set W' . $E' = \{ \}$, $W' = \{w_0\}$.

(3) Judge whether set W' is the same as set W . If yes, go to step (5). Otherwise, go to step (4).

(4) Search for the edge $l_{u,w}$ with the lowest edge weight in set E , where u is the node in W' , and node w is not in W' . Update set W' and E' , incorporate node w into W' and incorporate edges $l_{u,w}$ into set E' . If there are multiple edges that meet the above conditions, such as the edge weight is same, choose one edge at random. Return to step (3) for judgment.

(5) Stop searching, the obtained set W' and E' are the nodes and edges contained in the final island partition scheme with radial network.

The following figure describes the process of solving the minimum spanning tree based on Prim algorithm. The topology shown in Fig. 1 (a) contains a ring network, and nodes A~F are stored in set W . Select node A as the initial node, search for the edges $l_{A,E}$ as the lowest edge weight, and incorporate edges $l_{A,E}$ into set E' , node E into Set W' . For the next search, select the edge with lowest edge weight. The weights of edge $l_{E,F}$ and edge $l_{E,D}$ are 2. Randomly select edge $l_{E,F}$ and incorporate the edge into set E' , incorporate node F into Set W' . Continue the search process until the set W' is the same as the set W , as shown in Fig. 1 (e). Then, the final radial topology is obtained.

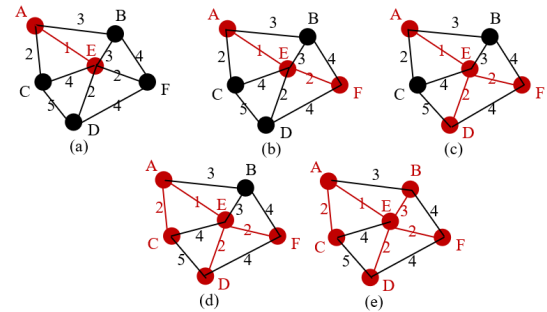


Fig.1 The calculation process of Prim algorithm

3. CASE STUDY

3.1 The parameter of system

The island partition for PG&E 69-bus system is evaluated in the paper. The topology of DN is shown in Fig. 2. DG₁ and DG₃ are integrated to 1 MW PV equipment respectively. DG₂ and DG₄ are integrated to 2 MW wind turbines respectively. The five tie-lines are 11-66, 13-21, 15-69, 27-54 and 39-48 respectively. The interconnection switch is regarded as a normally open switch, which breaks off during normal state. The edge weight of distribution feeder is 1 and the edge weight of tie-lines is 2.

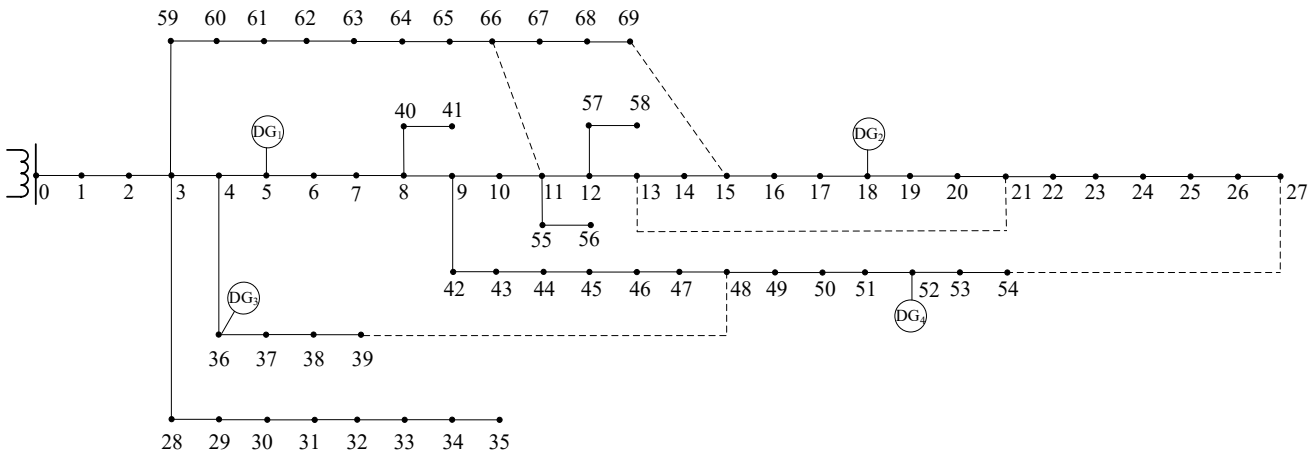


Fig.2 The topology of PG&E 69-bus network

3.2 The island partition scheme

According to random number sampling, the feeder $l_{0,1}$ breaks down during 2624-2627 hour and the load recovery process is a typical island partition. At this time, the load node of the DN cannot obtain electricity from the superior grid and DGs continue to restore power supply for load. The island partition scheme is formulated in the order of DG_4 , DG_2 , DG_1 and DG_3 .

Taking the 2627th hour as an example, DG_2 is firstly used to restore power supply. The search process of prospective greedy algorithm is shown in Table 1. Node 18 is drawn into knapsack set V , and its neighborhood set includes {17, 19}. The corresponding prospective neighborhood set includes {{17,16}, {19,20}. Calculate the value ratio, select the load node corresponding to the maximum value ratio and put it or them into backpack set V . It should be noted that the benefit B of {17, 16} is very high, while the value ratio is 0 due to the insufficient remaining DG capacity. When the value ratio of all nodes is 0, the calculation is stopped. The load node that can be restored by DG_2 at the 2627th hour is {17, 18, 19, 20}. The island partition scheme under the 2627th hour is shown in Table 2. Similarly, the power supply restoration scheme corresponding to other DG can be obtained.

Table 1 Island partition searching process of DG_2

Step 1: Put node 18 into V , search for the next restored node						
Nodes in set V	C_R/kW	NE^1 and NE_m^2	Load demand /kW	Benefit B	$Va^1(m)$ or $Va_m(n)$	Next node drawn into set V
18	65.69	17, 19, 20	62.94, 110.67, 1.05	62.94, 540.27, 10.5	1, 0, 10	19, 20
Step 2: Put node 18, 19, 20 into V , search for the next restored node						
Nodes in set V	C_R/kW	NE^1 and NE_m^2	Load demand /kW	Benefit B	$Va^1(m)$ or $Va_m(n)$	Next node drawn into set V
18, 19, 20	64.64	21, 17, 21, 22, 21, 13, 17, 16	119.59, 62.94, 125.15, 127.98, 110.67	1195.90, 62.94, 1251.52, 1279.80, 540.27	0, 1, 0, 0, 0	17
Step 3: Put node 18, 19, 20, 17 into V , search for the next restored node						
Nodes in set V	C_R/kW	NE^1 and NE_m^2	Load demand /kW	Benefit B	$Va^1(m)$ or $Va_m(n)$	Next node drawn into set V
18, 19, 20, 17	1.7	21, 16, 21, 22, 21, 13, 16, 15	119.59, 47.74, 125.15, 127.98, 47.74	1195.90, 477.44, 1251.52, 1279.80, 477.44	0, 0, 0, 0, 0	/

$Va^1(m)$ and $Va_m(n)$ are both zero, and the island search process of DG_2 ends

Table 2 Island partition scheme at 2627th hour

DG number	The initial node	Nodes in set V	Load demand /kW	Benefit B	The compression node number
DG_4	52	{52, 51}	33.57	33.57	70
DG_2	18	{17, 18, 19, 20}	126.94	703.91	71
DG_1	5	{1~15, 21~23, 28, 36~37, 40~47, 55~57, 63~69, 71}	1026.92	27190.47	72

The fault lasts for 4 hours. The island partition scheme at another three moments is shown in Fig. 3-Fig. 5. Since the secondary outage constraint is taken into account under fault state, the final load node that can be recovered under this fault is {1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 28, 36, 52, 57}. The islanding partition scheme under this fault is shown in Fig.6.

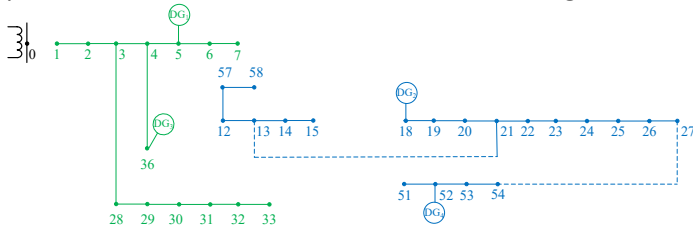


Fig.3 Island partition scheme under 2624th hour

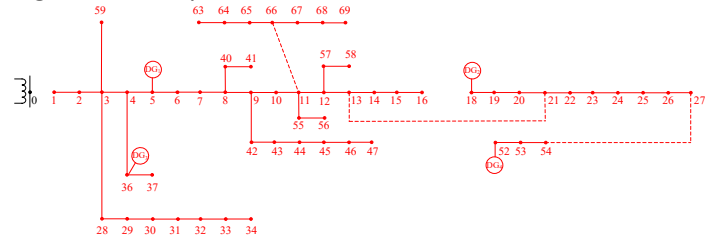


Fig.4 Island partition scheme under 2625th hour

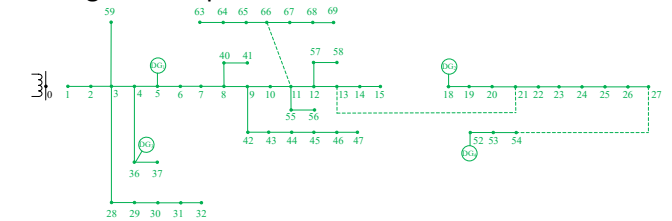


Fig.5 Island partition scheme under 2626th hour

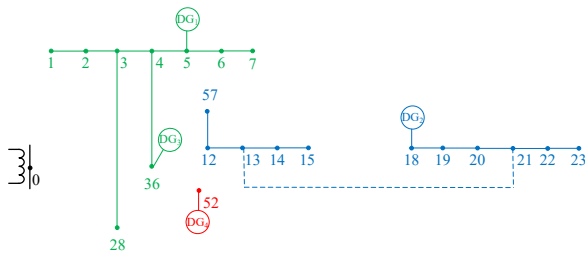


Fig.6 Island partition scheme under this fault (2624 h-2627 h)

4. CONCLUSION

An island partition method based on heuristic algorithm and Prim topology generation is proposed in the paper. The power supply restoration potential of DG is fully utilized by formulating island partition scheme under fault state. For non-linear island partition optimization model, prospective greedy algorithm is used to determine the recovery scheme of each step. The 1-neighborhood and prospective neighborhoods searching choices are analyzed through load benefit index. For the radial operation constraint of DN, the appropriate power supply recovery path can be obtained by Prim algorithm. A case study of 69-bus system is analyzed based on the method of this paper. It is found that the island partition scheme is closely related to the load recovery strategy, and the formulation of the final scheme can be completed with the optimization algorithm.

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