Intentional islanding method based on community detection for distribution networks

Zhang, Haiyan; Peng, Minfang; Palensky, Peter

DOI
10.1049/iet-gtd.2018.5465

Publication date
2018

Document Version
Final published version

Published in
IET Generation, Transmission and Distribution

Citation (APA)
Zhang, H., Peng, M., & Palensky, P. (2018). Intentional islanding method based on community detection for distribution networks. *IET Generation, Transmission and Distribution*, *13*(1), 30-36.
https://doi.org/10.1049/iet-gtd.2018.5465

IET Generation, Transmission & Distribution

Research Article

Intentional islanding method based on community detection for distribution networks

ISSN 1751-8687
Received on 27th August 2017
Revised 23rd July 2018
Accepted on 11th October 2018
E-First on 7th December 2018
doi: 10.1049/iet-gtd.2018.5465
www.ietdl.org

Haiyan Zhang[1], Minfang Peng[1] ✉, Peter Palensky[2]
[1]*College of Electrical and Information Engineering, Hunan University, Changsha, People's Republic of China*
[2]*Intelligent Electrical Power Grids Department, Delft University of Technology, Delft, The Netherlands*
✉ *E-mail: haiyanzhang100520@yahoo.com*

Abstract: Complex network theory is introduced to solve the islanding problem in an emergency of distribution networks. In this study, the authors put forward an intentional islanding method based on community detection. In this method, a new index has been defined called electrical edge betweenness, on the strength of edge betweenness in complex networks, which fuses electrical characteristics with topological features of actual power lines. Based on the index, the Girvan–Newman algorithm is employed to detect the community structure of distribution networks. Through referring to the modularity value (function Q) and coherent generator groups, they can get a reasonable amount and regions of communities. Then the whole distribution network can be partitioned into several self-sustainable islands meeting the stable operation constraints. The effectiveness of the authors' proposed method is tested on a standard IEEE 118-bus system.

1 Introduction

In recent years, that large-scale blackouts occur frequently has raised an alarm to the stable operation of global power systems. Although the potential danger resulting in electricity outages cannot be eliminated completely and the blackout is inevitable, we can take initiative measures to minimise the degree of damage [1]. Intentional islanding is an effective mitigation strategy which is vital in reducing economic losses and improving the reliability of power systems [2]. That is, under the condition of emergency, the power system frame will be split into multiple independent and self-sustainable islands in a planned and optimal way, to prevent fault propagation and restore power supply quickly [3].

Significant efforts have been made to solve the problem of intentional islanding. Various methods proposed in the literature can be categorised into two types: graph-theory-based techniques and slow coherency. In the former type, the topological characteristics of power systems are modelled, and then diverse optimisation algorithms are exploited to find the optimal solution, such as layered directed tree [4], integer L-shaped algorithm [5], and agglomerative clustering algorithm [6]. Besides, some mathematical programming methods are also involved, e.g. dynamic programming [7] and mixed-integer linear programming [8]. These aforementioned algorithms or approaches are mostly on the basis of classical graph theory, with a complex computation, where the inherent electrical characteristics of power systems are ignored, especially the generator coherency, which closely relates to the stability and security of power systems. Failure to take this critical factor into account extremely restricts the utilisation of this type of method [9].

Slow coherency based methods aim to achieve that only coherent generators are possibly coexisted in an island [10]. In [11], a spectral clustering islanding method is proposed considering the generator coherency, but it can only partition the bulk power system into two islands. It's the same situations with those strategies in [12, 13], which determine the number of islands is two leading to serious losses of loads. In addition, multi-generators with the synchronous frequency and the same power angle are partitioned into one island directly, but their geographical positions might be far apart and circumstances are specific in actual power systems, increasing the difficulty of control.

So how to determine the number and areas of islands in intentional islanding is still an ongoing problem which is not enough mature yet and needs to be solved.

With the integration of distributed energy resources, micro-grids, energy storage devices and so on, distribution networks are expanding unceasingly, with a huge number of nodes and extensive interconnection, which belong to a typical kind of complex network. Recently, in the research of complex networks, it has been found that the link connecting nodes is sparse between different communities while dense within the same community, referred as community structure [14].

Inspired by the similarity between detecting communities in a network and partitioning the power system into several self-sustainable electrical islands, we put forward a novel intentional islanding method based on community detection for distribution networks. This paper proposes a new index, integrating topological and electrical characteristics, to represent the criticality of lines. The topology of the distribution network is abstracted and an adjacent matrix is established. We turn the intentional islanding issue into a community detection problem and then exploit the Girvan and Newman (GN) algorithm to solve it. The amount and ranges of communities are determined by the value of modularity function Q. Balancing the communities with coherent generators, we divide the power system into multiple islands with a reasonable number and areas and conduct further validation and modification. The final islanding solution gained could not only meet a set of operational constrains, but also generator coherency. We utilise IEEE 118-bus system to test and simulation results demonstrate that this method has distinct predominance in load restoration.

The remaining of this paper is organised as follows. The electrical edge betweenness is put forward in Section 2. Section 3 describes the concrete islanding method taking benefits of community detection. Section 4 provides the simulation experiments and the comparison of three different methods. In the end, Section 5 concludes the work with possible further improvements.

2 Electrical edge betweenness

2.1 Community structure in complex networks

Complex network theory reveals the intrinsic relationship between structure and function of complex systems, which has attracted

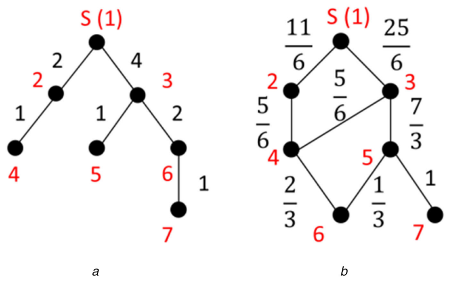


Fig. 1 *Calculation diagram of edge betweenness*

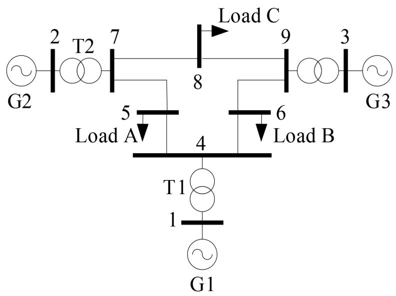


Fig. 2 *3-Machine 9-bus test system*

Table 1 Contrast of edge betweenness and electrical edge betweenness

Lines	Edge betweenness	Electrical edge betweenness
4–6	10	106.8862
5–7	10	90.8273

widespread attention since the small-world and scale-free network were proposed [15–17]. In 2002, the research in complex network theory boomed with the concept of community structure proposed. It has been found that plenty of networks have such a structural characteristic that the network can be divided into several internally dense groups or clusters, labelled as communities. The connection between the nodes belonging to different communities is weak while strong when they are in the same community.

Community detection is an important aspect in the research of complex network theory, which contributes to exploit potential significances of topology and predict the dynamic characteristics of networks. So far, the methods for community detection comprise two categories: agglomerative method and divisive method [15], according to adding or removing edges. The agglomerative method has an emphasis on continually adding an edge with the highest similarity in an original empty network where only nodes exist. Instead, in the divisive method, the edges with the lowest similarity are removed from the network step by step. There is a key index involved in these two hierarchical clustering methods to measure the similarity of node pairs: edge betweenness, as described in detail below.

Within a network, the total times of the shortest paths passing along an edge are defined as edge betweenness [16], which plays a role in evaluating whether they can fall into the same community. The shortest paths are bond to travel along the bottleneck edge connecting two separate communities. Therefore, the edge betweenness of a bottleneck edge is relatively large.

Taking the dendrogram in Fig. 1*a* as an example, there is only one shortest path. In the beginning, we take node 1 as the source node, and find out the leaves, then assign the edge connected with leaves to 1. From the farthest edge, values are distributed to each edge of the tree. Appoint each node to the source node in turn and calculate the corresponding edge value. Finally, the total weights on each edge are equal to the edge betweenness.

In the real-world networks, there is more than one shortest path between two nodes (see Fig. 1*b*). In this case, the total weight of those edges connected to the target node is 1. For example, taking node 1 as the source node, there are three shortest paths linking to node 6, where two pass through the edge (4–6) and one passes through the edge (5, 6). So the edge betweennesses of the two edges are 2/3, 1/3, respectively. Accordingly, the betweenness value of other edges can be calculated in the same way.

2.2 New index-electrical edge betweenness

The distribution network is described as a weighted and undirected graph $G = (V; L; W)$, where $V = \{v_1, v_2, v_3, \ldots, v_n\}$ represents the set of nodes standing for generators, substations or loads. $L = \{l_1, l_2, l_3, \ldots, l_m\}$ is the set of lines in the distribution network [14]. We define $|V| = n$, $|L| = m$, respectively. $\boldsymbol{W} = (w_{ij})_{n \times n}$ represents the weight matrix of the lines

$$w_{ij} = \begin{cases} \text{edge weight} & \text{a link between nodes } i \text{ and } j \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Here, a new index for edge weight, electrical edge betweenness is defined to be

$$w_{ij} = \frac{B_{ij} + \ln(1 + \sqrt{L_i^2 + L_j^2})}{Z_{ij}} \quad (2)$$

B_{ij} stands for the traditional edge betweenness of lines, L_i and L_j are the loads at nodes i and j. Z_{ij} means the impedance of the line (i, j).

From (2), we know that the value of electrical edge betweenness does not only bear on edge betweenness and impedance of lines, but also the load size connected. The higher the edge betweenness is, the larger the node loads at both ends are, the smaller the line impedance is, and then the more significant the line is.

The index put forward reflects the following physical meanings. (i) The distribution of power flow between generators and loads obeys the Kirchhoff's laws, and the power is inversely proportional to the impedance of paths. (ii) The index gives full expression to the non-linear characteristic of the power system. (iii) The traditional edge betweenness only represents the importance of edges from the view of topology structure. However, electrical edge betweenness fuses topological characteristics and electrical characteristics of edges, which can reflect the importance of actual power lines.

In order to demonstrate the effectiveness of the index proposed, we test it on the 3-machine 9-bus system (Fig. 2). Table 1 shows a piece of contrast between edge betweenness and electrical edge betweenness for the same edge.

Form Table 1, it's evident that line 4–6 and line 5–7 have the same edge betweenness. According to the complex network theory, they are equally important in the network, while actually discrepant in power systems. Based on the electrical edge betweennessd, line 4–6 is more significant than the line 5–7.

3 Intentional islanding based on community detection for distribution networks

3.1 Objective function and constraints

The core of intentional islanding for distribution networks is to solve a combinational optimisation problem [18]. We take the maximum amount of restored loads as the objective function of islanding in order to reduce economic losses as much as possible [19], which can be expressed as follows:

$$\max F = \sum_{v=0}^{n} c_v x_v \quad (3)$$

where c_v represents the weight of each load node v. x_v indicates whether the load node is restored: if restored, $x_v = 1$; otherwise $x_v = 0$.

The following operational constraints must be satisfied with the solution of islanding.

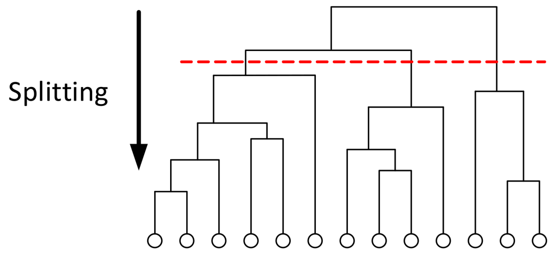


Fig. 3 *Diagram of GN algorithm*

3.1.1 Generation and load balance constraint: Generation and load balance must be complied with in partitioned islands, that is, the total capacity of generators meets the demands of local loads adequately. And furthermore, the outputs of generators are limited. Generally, local reactive power compensation is adopted in power systems, and then we only consider the active power balance.

$$\sum_{i \in V_s} P_{G_i} - \sum_{j \in V_s} P_{L_j} > 0 \tag{4}$$

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max} \tag{5}$$

where $\sum_{i \in V_s} P_{G_i}$ means the total volume of generator capacities. $\sum_{j \in V_s} P_{L_j}$ signifies the sum of restored loads. V_s is the node list of one power restored area, and the total amount of restored areas is k. $P_{G_i}^{\min}$ and $P_{G_i}^{\max}$ are the minimum and maximum active power of generator i, respectively.

3.1.2 Rated value and limit constraint: Lines and transformers are supposed to maintain in the range of stable state. Any overload occurs on lines or transformers may trigger protection action, then lead to out of service of lines or devices, resulting in a power imbalance

$$I_v < I_v^{\max} \tag{6}$$

where I_v represents the current flowing through the node v, and $I_v^{\max}$ indicates the maximum current allowed.

3.1.3 Voltage constraint: In distribution networks, overvoltage is likely to cause the devices' damage because of overheating, meanwhile, undervoltage gives rise to the unreliable action of protections and switches. Consequently, the real-time voltage must be confined to a certain boundary (±5%)

$$V_v^{\min} < V_v < V_v^{\max} \tag{7}$$

$V_v^{\max}$, $V_v^{\min}$ and V_v represent the upper limit, low limit and actual value of the voltage on the node v, respectively.

3.1.4 Radial structure constraint: The radial structure should be kept during the actual operation process of distribution networks to guarantee the interconnection between nodes

$$g_i \in G_i \tag{8}$$

where g_i signifies the network architecture of every island, G_i acts as the collection of possessory radial structure in the power system.

3.2 GN algorithm

The algorithm of Girvan and Newman is a classic divisive method, in which the edges with the highest edge betweenness are eliminated in sequence according to the calculation results, from top to bottom, until the whole network breaks down into multiple small clusters [17]. The diagram of the GN algorithm is shown in Fig. 3. If there are n nodes and m edges in the graph, the corresponding complexity of computing is $O(m^2 n)$.

The specific steps of the GN algorithm are

i. Calculate the edge betweenness of all edges in the network.
ii. Eliminate the edge with the highest edge betweenness.
iii. Recalculate the residual edges' edge betweenness.
iv. Repeat steps (ii) and (iii) until the last edge is eliminated.

For the sake of evaluating the decomposition result, Newman [20] proposes the modularity-function Q, which has been expanded to weighted undirected complex networks.

The modularity is defined as

$$Q = \frac{1}{2\boldsymbol{W}} \sum_{ij} \left[w_{ij} - \frac{s_i s_j}{2\boldsymbol{W}} \right] \delta(C_i, C_j) \tag{9}$$

In this paper, $\boldsymbol{W}$ is the sum of the electrical edge betweenness of all edges. s_i and s_j show the strength of nodes i and j, respectively, which are calculated by plusing the weights of adjacent edges. w_{ij} represents the electrical edge betweenness of the edge (i, j). For the Kronecker delta $\delta(C_i, C_j)$, if nodes i and j situate in the same community, $\delta(C_i, C_j) = 1$, otherwise $\delta(C_i, C_j) = 0$.

In Q function, the edge density of the communities and diversities of associated subgraphs under stochastic circumstance are applied to assess that whether the community structure of a network is apparent. The modularity value of Q ranges from 0 to 1, and furthermore the closer that this value is to 1, the more evident the community structure is. Usually, the value of Q for real-world networks is between 0.3 and 0.7. Therefore, the maximum of Q indicates the optimal community division scheme.

3.3 Intentional islanding method based on GN algorithm

3.3.1 Simplify the topology: There are various devices, connected lines, and extensive nodes in the distribution networks with distributed generations. To reduce the calculation effort (Fig. 4), it is necessary to simplify the topology of distribution networks firstly [13].

In the framework made up by main feeders and branch feeders, if there are no automatic switches between two nodes, such as circuit breakers, the two nodes always get or lose power supply at the same time. So we should merge the two nodes and add up the loads.

Incorporate the child nodes without any loads into their parent nodes.

3.3.2 Construct the weight matrices for nodes and edges: Here, the node weight is determined by the load size at the node. And the weights of lines are represented by employing the matrix of electrical edge betweenness, calculated according to (2).

3.3.3 Build the adjacent matrix: Adjacency matrix, a square matrix of N order, describes the adjacent relations in a network. If there is an edge between two nodes, the corresponding matrix element is 1, otherwise, it's 0.

For simplicity, taking the 3-machine 9-bus power system in Fig. 2 as an example, the adjacency matrix is expressed as

$$\boldsymbol{A} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \tag{10}$$

In this paper, the adjacency matrix element is

$$A_{(i,j)} = w_{ij} \quad (11)$$

3.3.4 Coherent generator groups: For the sake of stable operation in independent islands, generators should keep up synchronism besides power balance. In this paper, we take advantage of eigenvalues of state-matrix to obtain the number of clusters and then adopt the Gaussian elimination method to put synchronous generators together [10]. The specific steps are as follows:

i. *The number of coherent generator groups:* Compute the eigenvalues of the state matrix for power systems, and arrange them according to the order from small to large in oscillation frequency

$$|\lambda_1|, |\lambda_2|, \ldots, |\lambda_i|, |\lambda_{i+1}|, \ldots, |\lambda_{g-1}|, |\lambda_g|$$

$$m = \frac{|\lambda_r|}{|\lambda_{r+1}|} = \min_{i=1,\ldots,g} \frac{|\lambda_i|}{|\lambda_{i+1}|} \quad (12)$$

where g represents the generator nodes. On the basis of multi-time scale principle, we can see that the smaller 'm' is, the more obvious the time scale of the power system will be, namely, the diversities between generator clusters. r stands for the optimal number of coherent regions, then the slow pattern group got is $\sigma_r = \{\lambda_1, \lambda_2, \ldots, \lambda_r\}$, and the corresponding eigenvector space is $U = (u_1, u_2, \ldots, u_r)$.

ii. Determine the referential coherent generators: r groups of linear independent vectors can be obtained after dealing with the eigenvector space using Gaussian elimination by columns, and the rows left indicate the aggregated slow coherent generators. By this time, slow pattern groups σ_r correspond directly with the referential coherent generators U_1.

iii. Calculate the grouping matrix $\boldsymbol{L}$: The grouping matrix corresponding with eigenvector $\boldsymbol{U} = (U_1 \; U_2)^{\mathrm{T}}$ is represented as $\boldsymbol{L} = U_2 U_1^{-1}$.

iv. Identify the coherent generators: Find the maximum in each row in the grouping matrix $\boldsymbol{L}$, and divide the remaining generators into the corresponding reference groups $\boldsymbol{U}$, thus the slow coherency grouping regions g can be obtained.

3.3.5 Detect the communities in the power system: According to the GN algorithm, we calculate the electrical edge betweenness of all lines and eliminate the one with highest electrical edge betweenness, loop the two steps until traversal the whole system, and then detect the community structure of the network.

3.3.6 Calculate the function value of modularity Q: Calculate the function value of modularity Q, reflecting different clustering strategies, and intercept the tree structure corresponding to the peak value of Q. Then the power system will be divided into several strong internal-coupling and self-sustainable communities.

3.3.7 Verify and amend the islanding strategy: Taking the division results obtained after executing the above Sections 3.3.5 and 3.3.6 as the number and regions of islands, which may not satisfy the actual condition of the power system. So we give thought to the outcome of coherent generator identification from Section 3.3.4 to verify and amend it.

If there are incoherent generators on an island, it is necessary to separate them and allocate the loads reasonably. Moreover, if two or more communities contain coherent generators and adjacent positions, we can merge them into an island under the premise of power balance.

We calculate the power flows in the post-islanding state in order to check the feasibility of the obtained islanding strategy. If there are too many loads in an island which exceeds the upper limit of generator or line capacity, partial loads should be shed properly until meeting the constraints. Then we get the final islanding solution to guarantee the safety and stability of the power system.

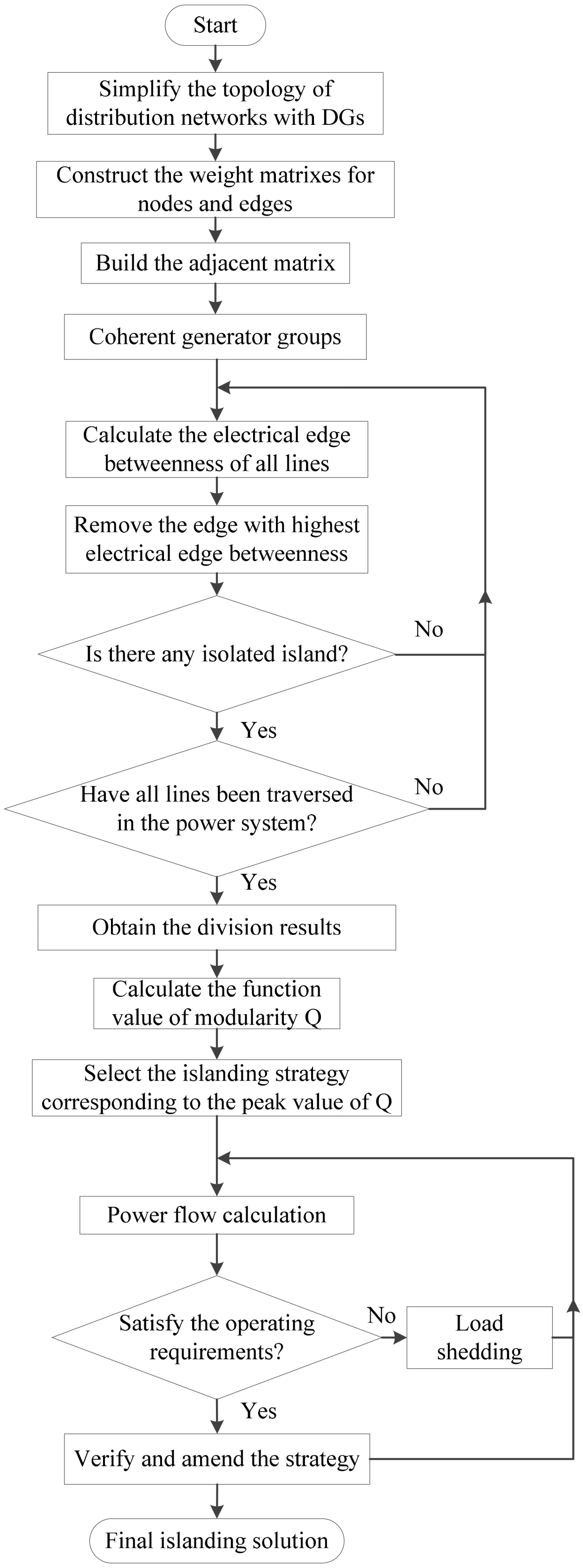


Fig. 4 *Flowchart of intentional islanding*

4 Simulation and analysis

We test the method proposed using IEEE118-bus test system (Fig. 5). There are 19 generators, 35 synchronous compensators, 9 transformers and 91 load nodes in the system [18]. The maximum active output of all generators is 4374.86 MW, and the maximum reactive output is 795.68 MVar. The active power and reactive power of loads are 4242 MW and 1438 MVar, respectively [21].

It is assumed that there is a 3-phase short-circuit fault on line 23–25 near busbar 25 at $t = 0$ s and the relays trip off at $t = 0.25$ s [22]. As can be seen from Fig. 6, the system will be at

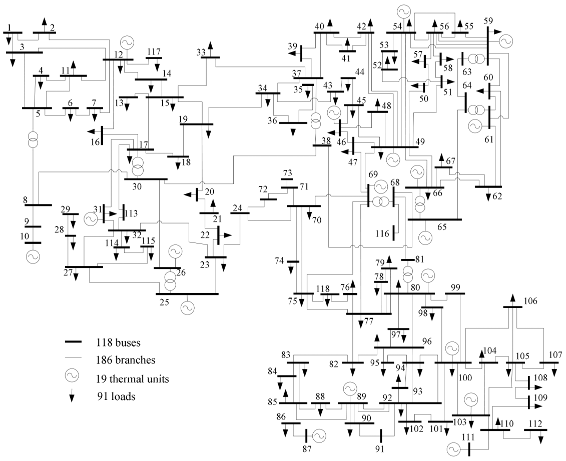


Fig. 5 *IEEE 118-bus test system*

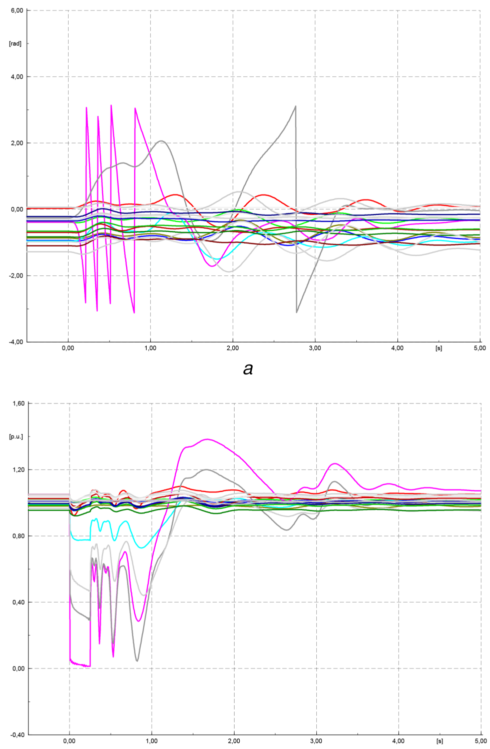


Fig. 6 *Oscillation results*
(a) Phase angle of generators, ***(b)*** Voltage of generators

Table 2 Coherent generators

Clusters	Generators
I	{10, 12, 25, 26, 31}
II	{46, 49, 54, 59, 61, 65, 66, 69}
III	{80, 87, 89, 100, 103, 111}

risk of asynchronous oscillation without any control or protection measures.

Executing our method put forward step-by-step, all generators in the power system are allocated into three coherent generator groups. See Table 2.

We employ the GN algorithm to detect the community structure of the power system, and then calculate the Q function values corresponding with different communities.

The partition strategies with modularity Q are obtained shown in Fig. 7. If the peak of modularity appears after ten iterations, we do not take this condition into account because of excessive control changes in the power system. Then it is the best case that the network is partitioned into four communities when the maximal

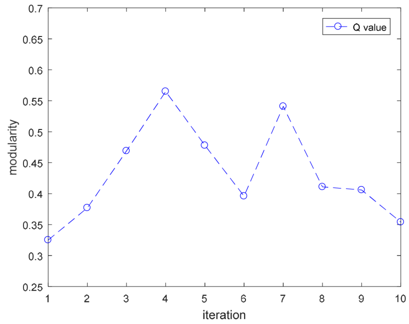


Fig. 7 *Function values of Q*

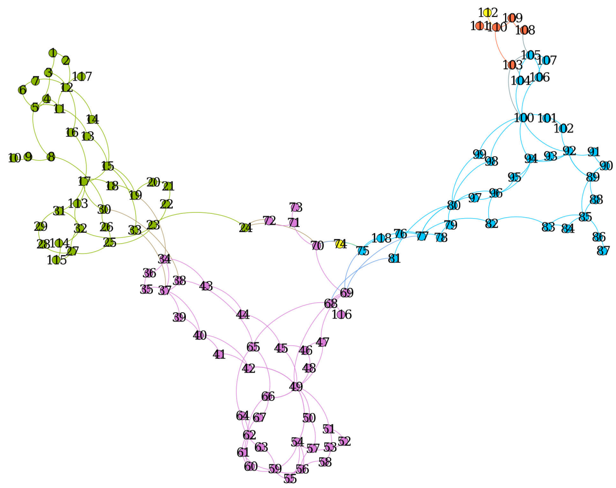


Fig. 8 *Communities in the 118-bus system*

modularity is 0.565 (see Fig. 8). The picture gives information about how the nodes are connected with each other, which does not represent the real geographical positions.

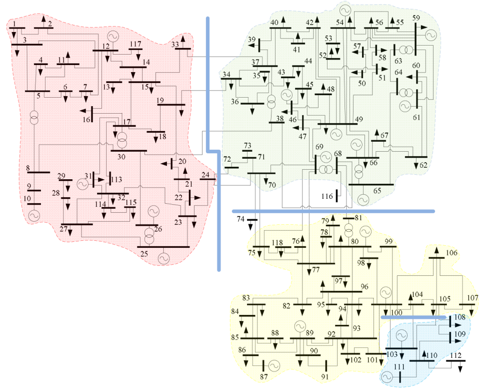
Referring to the coherent generators, the power system is divided into four regions through disconnecting these positions: 33–37, 19–34, 30–38, 24–72, 24–70; 70–74, 70–75, 69–75, 69–77, 68–81, 68–116; 100–103, 103–104, 103–105, 105–108. The final islanding solution is definitely depicted in Fig. 9*a* and Table 3.

For comparison, we also conduct the experiments on a 118-bus test system using the two-step spectral clustering controlled islanding approach in [12] and the reconstruction method based on hierarchical and partitioned restoration in [19]. Respectively, Figs. 9*b* and *c* show the simulation results. See Table 4 and 5 for the detailed information.

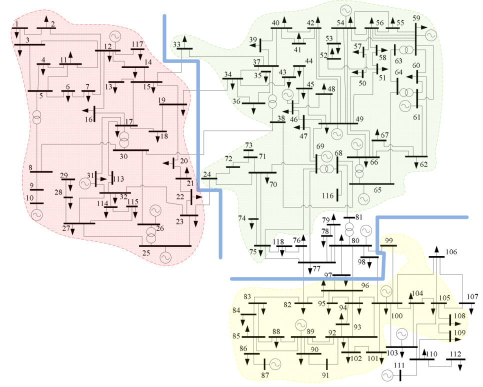
By the two-step spectral clustering controlled islanding algorithm, two cross sections take shape through disconnecting these lines: 15–33, 19–34, 30–38, 23–24; 77–82, 96–97, 80–96, 98–100, 80–99, and then the power system is split into three parts (Table 5). However, the generators at nodes 80, 103 and 111 lose synchronisation with other generators in this part later, which are shed forcedly to ensure the stability and safety of the power system. The actual restored areas are shown in Fig. 9*b*.

In the reconstruction method based on hierarchical and partitioned restoration, the network architecture of a power system is analysed on the grounds of the index-network dispersion degree. In the process of network promotion and load growth, the importance degree of the target node is declining, which directly results in a plenty of loads unrestored. What's more, the authors also ignored generator coherency.

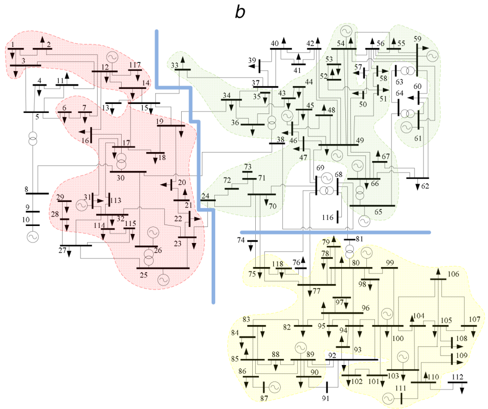
Table 6 and Fig. 10 show the comparison and analysis of three islanding solutions. As you can see from Table 6 and Fig. 10, employing our method, the power system is divided into four islands and the restoration ratio reaches up to 92.46%. We can get an effective islanding strategy in high quality. The obtained islanding solution, with a reasonable number and areas of islands, not only can guarantee the generator coherency in each island, but also make more loads restored.



a



b



c

Fig. 9 *Islanding solution of three methods*
(a) Islanding solution of this paper, ***(b)*** Islanding solution of the literature [12], ***(c)*** Islanding solution of the literature [19]

Table 3 Islanding solution of this paper

Islands	Nodes included	Restored power, MW
I	1–32, 33, 113–115, 117	999
II	34–73	1547
III	75–102, 104, 105, 106, 107, 118	1304
IV	103, 108, 109, 110, 111	72

Table 4 Islanding solution of [12]

Islands	Nodes included	Restored power, MW
I	1–23, 25–32, 113–115, 117	963
II	24, 33–75, 116	1882
III	82–96, 99–102, 104–109	816

5 Conclusion

This paper presents an intentional islanding method based on community detection for distribution networks. The key to this method locates at defining a new index about the weight of power

Table 5 Islanding solution of [19]

Islands	Nodes included	Restored power, MW
I	1–3, 6–7, 12, 14, 16–23, 25–26, 28–29, 31–32, 113–115, 117	631
II	24, 34–36, 43–55, 58–59, 61, 65–67, 70–73	1083
III	75, 77–80, 82–90, 93–111, 118	1233

Table 6 Comparison of three solutions

Methods	Total restoration, MW	Recovery ratio, %
this paper	3922	92.46
[12]	3661	86.30
[19]	2947	69.47

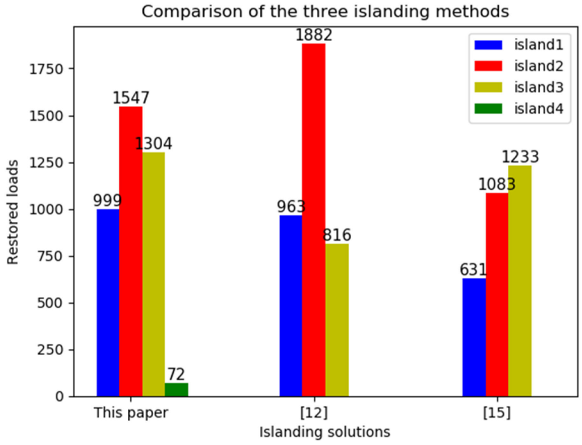


Fig. 10 *Comparison of three islanding methods*

lines and introducing the GN algorithm to solve the islanding problem. The index-electrical edge betweenness helps to represent the importance of power lines by fusing electrical characteristics with traditional edge betweenness in complex networks theory. We take the GN algorithm to detect the communities in power systems and then integrate the community detection results with coherent generator groups in order to get the optimal amount and regions of the islands. To ensure the safety and stability of power systems, we have considered multiple constraints and also conduct verification and modification before determining the final splitting strategies. The simulation experiments on IEEE118-bus test system demonstrate that our intentional islanding method has remarkable performance in load restoration and is more reliable in actual operation. However, that how to build a comprehensive dynamic model of the power system, make full use of wide-area measurement information for quick on-line coherency identification and reduce the computational complexity of the searching algorithms, still need to be further studied.

6 Acknowledgments

This work was supported by the National Natural Science Foundation of China (no. 61472128), Natural Science Foundation of Hunan Province of China (no. 14JJ1025) and China Scholarship Council.

7 References

[1] Cavalcante, P.L., López, J.C., Franco, J.F., *et al.*: 'Centralized self-healing scheme for electrical distribution systems', *IEEE Trans. Smart Grid*, 2015, **7**, (1), pp. 145–155

[2] Isazadeh, G., Khodabakhshian, A., Gholipour, E.: 'New intelligent controlled islanding scheme in large interconnected power systems', *IET Gener. Transm. Distrib.*, 2015, **9**, (16), pp. 2686–2696

[3] Sun, L., Zhang, C., Lin, Z., *et al.*: ''Network partitioning strategy for parallel power system restoration', *IET Gener. Transm. Distrib.*, 2016, **10**, (8), pp. 1883–1892

[4] Su, J., Bai, H., Zhang, P., *et al.*: 'Intentional islanding algorithm for distribution network based on layered directed tree model', *Energies*, 2016, **9**, (3), pp. 124–144
[5] Golshani, A., Sun, W., Zhou, Q., *et al.*: 'Two-stage adaptive restoration decision support system for a self-healing power grid', *IEEE Trans. Ind. Inf.*, 2017, **13**, (6), pp. 2802–2812
[6] Ganganath, N., Wang, J., Xu, X., *et al.*: 'Agglomerative clustering based network partitioning for parallel power system restoration', *IEEE Trans. Ind. Inf.*, 2018, **14**, (8), pp. 3325–3333
[7] Perez-Guerrero, R., Heydt, G.T., Jack, N.J., *et al.*: 'Optimal restoration of distribution systems using dynamic programming', *IEEE Trans. Power Deliv.*, 2015, **23**, (3), pp. 1589–1596
[8] Golshani, A., Sun, W., Sun, K.: 'Advanced power system partitioning method for fast and reliable restoration: toward a self-healing power grid', *IET Gener. Transm. Distrib.*, 2018, **12**, (1), pp. 42–52
[9] Gomez, O., Rios, M.A.: 'Real time identification of coherent groups for controlled islanding based on graph theory', *IET Gener. Transm. Distrib.*, 2015, **9**, (8), pp. 748–758
[10] Ariff, M.A.M., Pal, B.C.: 'Coherency identification in interconnected power system – an independent component analysis approach', *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 1747–1755
[11] Quiros-Tortos, J., Wall, P., Ding, L., *et al.*: 'Determination of sectionalising strategies for parallel power system restoration: a spectral clustering-based methodology', *Electr. Power Syst. Res.*, 2014, **116**, (11), pp. 381–390
[12] Ding, L., Gonzalez-Longatt, F.M., Wall, P., *et al.*: 'Two-step spectral clustering controlled islanding algorithm', *IEEE Trans. Power Syst.*, 2013, **28**, (1), pp. 75–84
[13] Quiros-Tortos, J., Panteli, M., Wall, P., *et al.*: 'Sectionalising methodology for parallel system restoration based on graph theory', *IET Gener. Transm. Distrib.*, 2015, **9**, (11), pp. 1216–1225
[14] Lin, Z., Wen, F., Xue, Y.: 'A restorative self-healing algorithm for transmission systems based on complex network theory', *IEEE Trans. Smart Grid*, 2017, **7**, (4), pp. 2154–2162
[15] Pizzuti, C.: 'A multiobjective genetic algorithm to find communities in complex networks', *IEEE Trans. Evol. Comput.*, 2012, **16**, (3), pp. 418–430
[16] Newman, M.E.J., Girvan, M.: 'Finding and evaluating community structure in networks', *Phys. Rev. E*, 2004, **69**, (2), pp. 026113-1–026113-15
[17] Newman, M.E.J.: 'Detecting community structure in networks', *Eur. Phys. J. B*, 2004, **38**, (2), pp. 321–330
[18] Kyriacou, A., Demetriou, P., Panayiotou, C., *et al.*: 'Controlled islanding solution for large-scale power systems', *IEEE Trans. Power Syst.*, 2017, **33**, (2), pp. 1591–1602
[19] Teng, Z., Yan, Z., Zhang, Z.: 'Power system reconstruction based on hierarchical and partitioned restoration', *Autom. Electr. Power Syst.*, 2015, **39**, (14), pp. 60–67
[20] Newman, M.E.J.: 'Fast algorithm for detecting community structure in networks', *Phys. Rev. E*, 2004, **69**, (2), pp. 066133-1–066133-5
[21] Ding, L., Ma, Z., Wall, P., *et al.*: 'Graph spectra based controlled islanding for low inertia power systems', *IEEE Trans. Power Deliv.*, 2017, **32**, (1), pp. 302–309
[22] DIgSILENT PowerFactory, ed. Heinrich-Hertz-Straße, Germany