An Efficient Controlled Islanding Technique for Smart Grids

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Abstract- In recent years, power systems are more complicated and prone to instability due to the presence of renewable energy resources. Among the various strategies to prevent the power system instability, controlled islanding is proposed as the last resort. The aim of controlled islanding is to create stable islands in the grid, in order to prevent global blackout and facilitate total system restoration. Therefore, a proper decision-making algorithm is required to determine the separation points in a very short time. In this paper, a novel hierarchical spectral clustering method is introduced, which meets the practical requirements and constraints of power system islanding. Moreover, this approach leads to several clustering candidate solutions simultaneously, which can be optimally selected based on a desired objective function. The proposed approach is evaluated on IEEE test systems and compared with the existing methods. The simulation results show that the proposed method is computationally more efficient than other existing approaches.

Keywords Graph Partitioning, Hierarchical Spectral Clustering, Power System Islanding, Smart Grid.

1. Introduction

Today, power systems are more complicated due to the presence of renewable energy resources [1-3]. Regarding the recent blackouts in the world, special efforts have been made to prevent power grid instability [4-5]. One of the most comprehensive reports in this field was presented by the IEEE Power and Energy Committee [6]. In this report, power system controlled islanding through a special protection system has been highly recommended to prevent a blackout and to facilitate grid restoration [7].

When a fault occurs in the power grid, generators begin to oscillate in several groups. If the failure expanded and no control measure is performed, generators oscillation will be increased and the power grid will be divided into several islands by operation of protective relays on generators and transmission lines. Since this separation is not based on a predetermined plan, in many cases, not only doesn't it improve the condition but also it leads to extensive blackout due to the propagation of the failures [8]. The problems caused by unintentional islanding are due to three main factors: 1) generation-load imbalance in the islands, 2) overload of some transmission lines, and (3) the possibility of instability in each island.

In order to form stable islands, many practical constraints must be satisfied. These constraints are generation-load balance, coherency of generators in each island, availability of transmission lines for separation, thermal limitation of equipment, voltage stability, and angle stability. Hence, finding a proper strategy to satisfy all the constraints is very complicated. Therefore, a subset of these constraints including the generation-load balance and the generators' coherency can be used as a basis for separation [9]. In the next step, other constraints can also be satisfied using secondary corrective actions e.g. load shedding, fast valving, etc [10]. This approach simplifies the problem and also allows its employment for large grids [11].

Existing methods for power system islanding are classified into two general categories based on their objective function: 1) minimum power imbalance in the islands, and 2) minimum power flow disruption. The methods based on the minimum power imbalance look for the separation lines that provide the least power imbalance in the islands. The methods in the second group try to find separation lines to minimize the pattern change of power system load flow as much as possible [10]. These methods improve transient stability in islands, reduce the likelihood of overloading on transmission lines and make grid restoration easier [12]. Moreover, the implementation of their objective function is simpler due to the utilization of graph partitioning theory [10].

Many studies have been conducted in recent years to find proper separation lines after disturbances. Most of the proposed methods are based on the graph partitioning theory. Considering the numerical complexity of the graph separation problems, computational burden has been the most important concern of the researchers. In [13], the power system separation has been performed based on the objective function of the minimum power imbalance in the islands. In the aforementioned study, only the static constraints, namely the balance of the power in the islands, are considered. In [14], the authors proposed a simplifying strategy to reduce the computational complexity of the algorithm. In [15], separation is performed in three steps: definition of a domain for each generator, determination of initial separation points considering the coherent grouping of the generators, and shifting the splitting points to reach the optimal islands.

Due to the benefits of the second objective function, many methods have been established based on minimum power flow disruption. In [10], a two-stage islanding method has been proposed based on spectral clustering. In the first step, the coherent groups of generators are determined using normalized spectral clustering according to the dynamical model of the generators. In the next step, separation lines are determined using constrained spectral clustering to minimize power flow disruption and satisfy generator coherency constraints. This method can only be used for bisection cases with two islands. To overcome this limitation, a recursive two-step method was suggested [10]. The required computations for this method are too complicated [16] and in many cases, it does not lead to the desirable results for islanding [17]. Later in [16], a new method was proposed based on constrained spectral clustering. The method determined separation points based on the minimum power flow disruption while taking into account the generators coherency. Meanwhile, the algorithm allows the operator to remove some lines from the separation solution. The method is based on the transmission line power values at the moment of disturbance in the power grids. Due to the extreme oscillation of power during disturbances, this method could not be practically implemented.

In [18], hierarchical spectral clustering has been used to determine splitting points. This method is computationally innovative but the power system requirements are not completely foreseen and coherency constraints are not considered. In [19], the k-medoids algorithm in spectral clustering has been used to increase the accuracy of islanding, but the computational time is more prolonged than the previous methods.

In order to improve the existing methods for power system islanding and find a comprehensive solution to be used in the real power systems, this paper proposes a new algorithm based on minimum power flow disruption. In the developed method, the hierarchical clustering in graph theory is well adjusted to the requirements of power system islanding and all technical constraints are satisfied by defining a proper similarity matrix. This method considers the coherency of generators in each island and allows the operator to exclude any transmission line from the solution. The number of islands is considered equal to the number of coherent group of generators as a default, similar to [16], [20] and [21], but can be changed easily based on the operational requirement. The proposed algorithm is implemented on IEEE 39-bus and IEEE 118-bus test grids and its performance is compared with other existing methods. According to the simulation results, this method has more computational efficiency even while leads to several islanding scenarios simultaneously.

The rest of this paper is organized as follows. Section 2 presents the background and fundamental concepts. In section 3 the graph spectral clustering is discussed. In section 4, the proposed algorithm is introduced in detail and in the next section, the effectiveness of the new method is studied through simulation on the test systems along with comparative analysis with the existing methods. Finally, section 6 concludes the paper.

2. Fundamentals

2.1. Power System Graph Representation

The *N*-bus electrical grids can be represented with a non-directional weighted graph as $G = (V, E, W)$. In this graph, V and E denote the vertices and edges respectively, which represent the buses and transmission lines in the power grid. Hence:

$$v_i \in V, i = 1,2, \dots, N \tag{1}$$

$$e_{ij} \in E \subset V \times V, i,j = 1, 2, \dots, N \tag{2}$$

Based on the nature of the power system, this graph is a simple type without multiple edges and loops. W denotes the weights of the edges, which are the values of power flow in the branches. Assuming no network losses, $w_{ij} = |P_{ij}| = |P_{ji}|$ (where $|P_{ij}|$ is the active power flow between the two buses *i* and *j*).

2.2. The Objective Function for Islanding

As mentioned in section 1, the objective functions in power system islanding are classified into two categories. As many recent methods, minimum power disruption has been utilized in this paper as the objective function. This objective function leads to ease of implementation and computational advantages. The aim of this optimization is to find the biggest stable islands, which are connected to each other through the transmission lines with the minimum power flow.

To measure the quality of the clustering approach, two quantities are defined in the graph theory: 1) the boundary and 2) the volume of the subgraph. The sub-graph S is defined as a set of vertices of the original graph, where $i \in S$ indicates the vertices of this graph. The boundary of the subgraph is the total weight of edges between vertices in *S* and vertices not in *S*. So the boundary value is defined as

$$\partial(S) = \sum_{i \in S, j \notin S} w_{ij} \tag{3}$$

In power system islanding, this quantity shows the sum of power flow of tie-lines around the island.

The volume of a subgraph is equal to the sum of weighted degrees of its vertices:

$$vol(S) = \sum_{i \in S} d_i \quad (4)$$

where d_i is the weighted degree of the ith vertex (v_i) as follows:

$$d_i = \sum_{j=1}^{N} w_{ij} \quad (5)$$

In this problem, the volume represents the internal power flow of an island plus boundaries.

Given the above quantities, in order to measure the quality of an island, an index is defined as the expansion of *S*:

$$\phi(S) = 1 - \frac{\partial(S)}{vol(S)} \quad (6)$$

The higher the expansion, the higher quality of the island, that is, the bigger island is selected by cutting off the transmission lines with lower power flow. Therefore, the quality of power system separation with k islands is determined as

$$\min_{1 \le i \le k} \phi(S_i) \quad (7)$$

Hence, the general objective function for power system islanding is defined as follows:

$$\rho_G(k) = \max_{0 \ne S_1, \dots, S_k \subseteq V} \left\{ \min_{1 \le i \le k} \phi(S_i) \right\} \quad (8)$$

The target is to find the separation points to maximize the minimum expansions of the islands. Moreover, any required constraint in the grouping of buses should be added to the objective function. It should be noted that finding the optimal solution for such a large graph of a power system is not computationally feasible and it is generally an NP (Nondeterministic Polynomial time)-hard problem [22]. To achieve an acceptable approximation solution, the use of spectral clustering and Cheeger inequality has been proposed [23].

3. Graph Spectral Clustering

The goal of clustering in the graph is to find a group of vertices, which have a stronger connection with each other (with regard to the weight of the edges) and a weaker connection with the vertices of other groups. Spectral clustering is a method that is based on the eigenvalues and eigenvectors of the graph Laplacian matrix [23-27].

3.1. Graph Laplacian

The Laplacian matrices are used extensively in graph analysis. Two types of Laplacian matrices are defined for undirected weighted simple graph $G = (V, E, W)$,: 1) Unnormalized Laplacian ($\boldsymbol{L}$), 2) Normalized Laplacian ($\boldsymbol{L_N}$).

Laplacian matrix of *G*, which is an $N \times N$ matrix, is defined as follows [25]:

$$[L]_{i,j} = \begin{cases} d_i, & if\ i = j; \\ -w_{ij}, & if\ i \ne j\ and\ (i,j) \in E; \\ 0, & otherwise. \end{cases} \quad (9)$$

The normalized Laplacian is defined as

$$L_N = D^{\frac{-1}{2}} L D^{\frac{-1}{2}} \quad (10)$$

where *D* is a diagonal matrix with non-zero values of d_i. Normalized Laplacian matrix can be expressed as

$$[L]_{i,j} = \begin{cases} 1, & if\ i = j; \\ \frac{-w_{ij}}{\sqrt{d_i}\sqrt{d_j}}, & if\ i \ne j\ and\ (i,j) \in E; \\ 0, & otherwise. \end{cases} \quad (11)$$

The normalized Laplacian matrix is scale-independent and it is more advantageous for clustering applications [17].

3.2. Eigenvalues of Normalized Laplacian Matrix

The eigenvalues of Laplacian matrices have the following properties: 1) All of them are non-negative and real numbers, 2) The number of zero eigenvalues indicates the number of islands in the graph [24].

The eigenvalues are written as

$$0 = v_1 \le v_2 \le \cdots \le v_N, \quad (12)$$

hence, from property (2) above, it is clear that $v_2 > 0$ if the relevant graph is connected. Moreover, based on graph theory, the following inequality is true for all eigenvalues of the normalized Laplacian matrix:

$$0 \le v_i \le 2 \quad (13)$$

The general approach for spectral clustering is using k eigenvectors of the normalized Laplacian matrix ($2 \le k \le N$) to choose a geometric coordinate for all vertices (*N*) in $\mathbb{R}^k$ space. In other words, each vertex is mapped to a k dimensional subspace. New coordinates are *N* rows of a $N \times k$ matrix, whose columns are k eigenvectors of the normalized Laplacian matrix.

3.3. Cheeger Inequality

In order to solve the optimization problem in (7), spectral clustering provides an approximate solution, using the smallest k eigenvalues and eigenvectors associated with the normalized Laplacian matrix. The computational complexity of this method is at most N^3 for the normalized Laplacian matrix of size *N* [25].

Cheeger inequality shows how close the approximate solution is to the optimal level and thus, measures the quality of separation to k partitions. In the case of $k = 2$, this inequality is [24]:

$$1 - \sqrt{2v_2} \le \rho_G(2) \le 1 - \frac{v_2}{2} \quad (14)$$

This inequality is recently generalized in the following approximate form for $k \ge 2$ [17]:

$$1 - O(k^2)\sqrt{v_k} \le \rho_G(k) \le 1 - \frac{v_k}{2} \quad (15)$$

Therefore, it is obvious that choosing smaller v_k leads to a more appropriate solution in clustering. If v_k is high, the approximate solution is far away from the optimal solution and does not lead to proper islanding.

3.4. Clustering of Obtained Coordinates

The nature of spectral clustering is using k eigenvectors of the Laplacian matrix to obtain the vertices in a k-dimensional Euclidean space of $\mathbb{R}^k$, which is known as spectral k-embedding. The results of previous investigations show that using the normalized Laplacian in spectral clustering leads to more appropriate solutions [17, 26]. In addition, it has been suggested that if the normalized Laplacian is used, an extra normalization performs in which all vectors become normal (with the 1-unit length) [17, 23]. In the next step, the vertices should be clustered using a proper clustering algorithm in Euclidean space.

4. The Proposed Method

For the clustering of vertices in the new coordinates, k-mean and k-medoids algorithms have been used in existing methods. Despite all the benefits of clustering through these algorithms, there are some limitations in overall controlling of the islanding process: 1) The number of clusters must be defined in advance and the algorithm cannot infer it automatically, 2) Lack of access to the internal structure of the islanding algorithm, and 3) Ignoring the connections of vertices in the graph [23]. To overcome these limitations, the use of spectral hierarchical clustering was proposed [27, 29].

4.1. Constrained Hierarchical Spectral Clustering

Hierarchical clustering is a clustering method, which aims to build a hierarchy of clusters. Among various hierarchical methods, the agglomerative method has been used for power grid islanding [18]. The approach used in this method is "bottom-up"; starting from the bottom, two more similar clusters are aggregated in each stage and a new cluster is formed. New clusters are located on higher levels and this process is repeated. Each level of the hierarchy indicates a category of data, which can be viewed as a tree. The results of hierarchical clustering are generally represented as a dendrogram (Fig. 3). In this method, there are two options for defining the number of clusters: 1) The number of clusters can be pre-defined, 2) The algorithm can calculate the number of clusters based on a predefined reasonable error. Using the dendrogram display has several benefits: 1) Changing the number of clusters without performing any additional calculation, 2) Providing an overview of the clustering process.

A measure for the similarity (or distance) between clusters should be defined in order to decide on the aggregation of clusters at each stage. Reference [18] provided a novel criteria for the distance of two vertices in the graph in the spectral space, in which the information of the edges is also considered. Suppose that $u_i \in \mathbb{R}^k$, is the normalized coordinate of the ith vertex of the graph. The distance between two adjacent vertices is defined as $dist(i,j) = \|u_i - u_j\|$. For non-adjacent vertices, the distance between them can be calculated based on the Floyd-Marshall algorithm for determining the shortest path in the graph [28]. Thus, the possibility to merge already existing islands, which have been connected with at least one link is provided and the third limitation of the k-mean and k-medoids methods is also overcome.

In this paper, correction of the distance matrix before clustering is proposed in order to apply power system constraints on the clustering (e.g. coherency of generators in each island). Hence, by assigning a very large value to the distance matrix element relevant to two given buses, the possibility of aggregating these buses is excluded from the process of clustering.

4.2. The Algorithm

According to the previous section, the hierarchical spectral clustering algorithm could be properly adapted to the requirements of the power grid separation and it is efficient computationally. Hence, the algorithm of the proposed method is suggested based on hierarchical spectral clustering technique as follows and is summarized in Fig.1:

1) Identifying the need for intentional islanding based on power system vulnerability analysis according to the existing methods [30].
2) Using online power system quantities:

2-1) Updating the adjacency matrix of the weighted graph of the power system (G) based on the new configuration of electrical grids (some branches may be disconnected by protective relays during the disturbance) and the power flows before disturbance occurrence:

$$w_{ij} = |P_{ij}| = |P_{ji}| \quad (16)$$

P_{ij}: Power flow between the i and j buses before the disturbance

2-2) Specifying the coherent generators using measurement-based methods [31] (In grid monitoring and control system, this process can be kept continuous and its output would be available at any time):

$$G_i \in C_j, \quad i = 1, \dots, N_G, j = 1, \dots, k \quad (17)$$

G_i: ith generator,

C_j: j^{th} group of coherent generators

N_G: number of generator buses

2-3) Determining the number of coherent groups of generators (k)

$$C_1, \dots, C_k \quad (18)$$

2-4) Assigning the number of the islands (n) equal to the number of coherent groups of the generators (k) as a default

3) Identify the M branches to be excluded from the cutset and the corresponding buses are merged

together to create a new $(N' \times N')$ adjacency matrix, where $N' = N - M$.

4) Calculation of normalized Laplacian matrix of power grid graph $(\boldsymbol{L_N})$ based on the new adjacency matrix.

5) Determination of eigenvectors related to the smallest k eigenvalues:

$$\Psi_1, \ldots, \Psi_k \tag{19}$$

6) Formation of new coordinates of vertices in new k dimensioned Euclidean space $\mathbb{R}^k$:

$$x_i = [\Psi_{i1}, \ldots, \Psi_{ik}] \tag{20}$$

7) Normalization of coordinate vectors of vertices:

$$u_i = \frac{x_i}{\|x_i\|} \qquad 1 \le i \le N' \tag{21}$$

8) Calculating the distance between vertices based on the proposed method in Section 4-1:

$$Dist_{N' \times N'} = \begin{bmatrix} dist_{11} & \cdots & dist_{1N'} \\ \vdots & \ddots & \vdots \\ dist_{N'1} & \cdots & dist_{N'N'} \end{bmatrix} \tag{22}$$

$dist_{ij}$: The distance between the i and j vertices

9) Correction of the distance matrix to satisfy coherency constraints of generators in each island:

$$Dist_{ij} = 10 \times Max(Dist),\ v_i \in C_k, v_j \in C_l, k \neq l \tag{23}$$

10) Compute the dendrogram of buses with respect to the distance matrix

11) Changing the number of islands (n), if required

12) Determining the clusters and separation edges

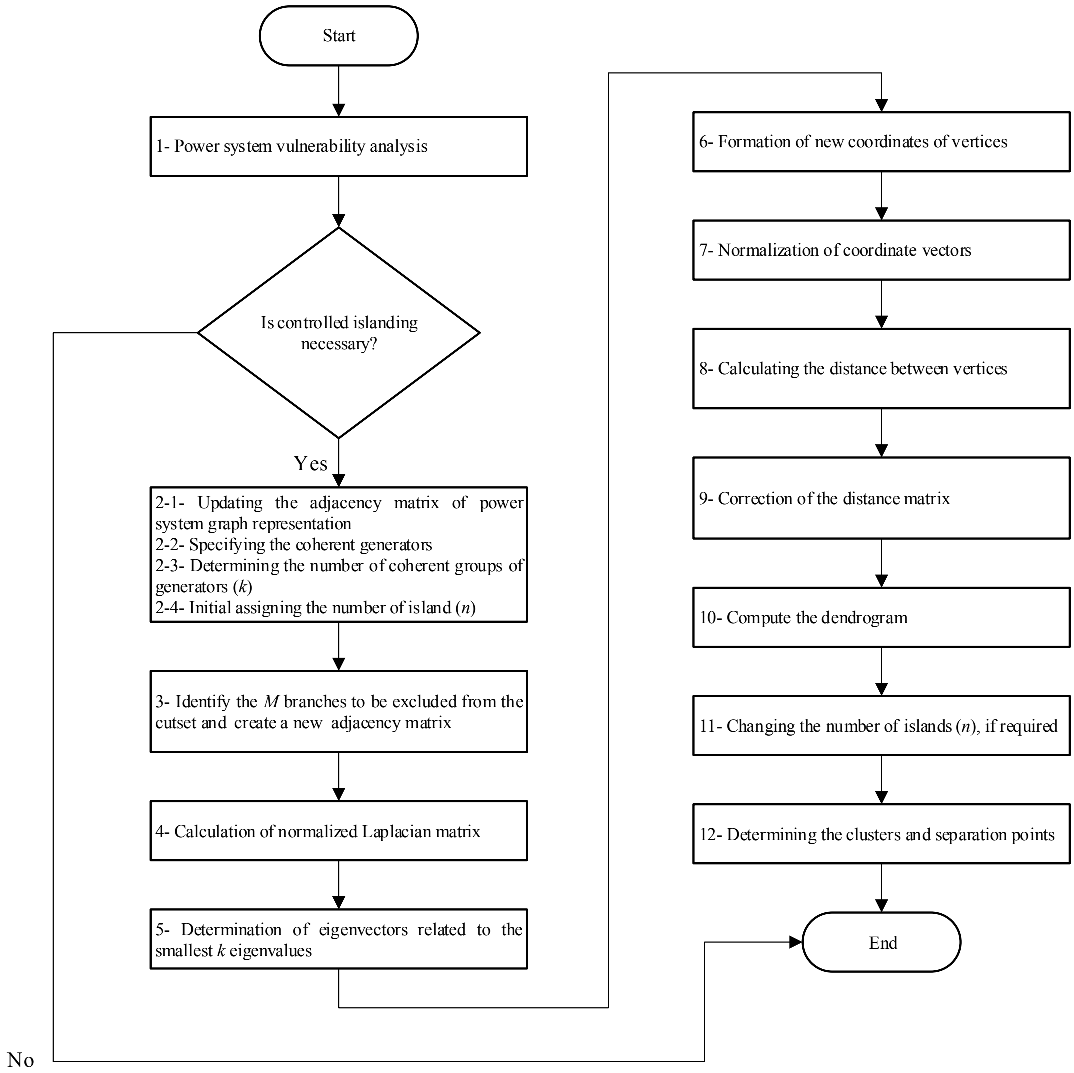

Fig. 1. Flowchart of the proposed method

5. Simulation results

In this section, the proposed method is evaluated on the IEEE 39- and IEEE 118-bus test grids. All time-domain simulations are performed in DIgSILENT PowerFactory [32], and the methodology has been implemented in MATLAB.

5.1. Simulation of the IEEE 39-bus test grid

To evaluate the proposed algorithm in a small grid, the model of the IEEE 39-bus test system has been used [33]. It is assumed that a three-phase to ground short circuit occurred on the line between 16 and 17 buses and it was cleared after 150 ms by protective relays. According to the simulation results, which are illustrated in Fig. 2 and 3, severe oscillations occur in the grid and it moves forward toward the instability in the absence of proper control action. Hence, vulnerability analysis shows the necessity of power system separation as a last resort to prevent wide area instability.

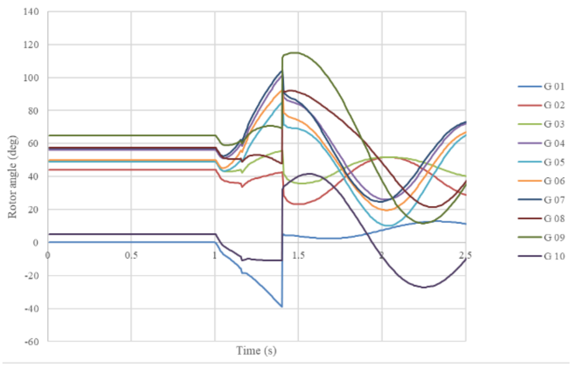

Fig. 2. Simulation results of generator rotor angle for IEEE 39-bus without islanding

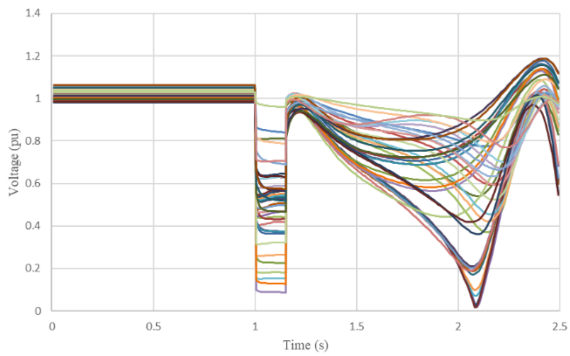

Fig. 3. Simulation results of bus voltage magnitude for IEEE 39-bus without islanding

Fig. 2, shows that the generators oscillate in two coherent groups as:

$$V_{G1} = \{v_{30}, v_{37}, v_{38}, v_{39}\} \quad (24)$$

$$V_{G2} = \{v_{31}, v_{32}, v_{33}, v_{34}, v_{35}, v_{36}\} \quad (25)$$

According to the number of coherent groups, k is chosen as 2; the default number of required islands will be similar. By considering the power flow before the disturbance and removal of the faulted line between 16 and 17 buses, the power grid relevant graph, and the corresponding normalized Laplacian matrix are updated. Then, according to the proposed algorithm, new geometric coordinates of vertices are obtained based on the eigenvectors of the Laplacian matrix. By calculation of distance matrix and running the clustering algorithm, the dendrogram is obtained as shown in Fig. 4. It is clear that the vertices of each island could be identified by selecting the number of required islands (n) on the dendrogram. In addition, changing the number of islands could be easily applied to obtain any other islanding pattern and there is no need to do any additional calculation.

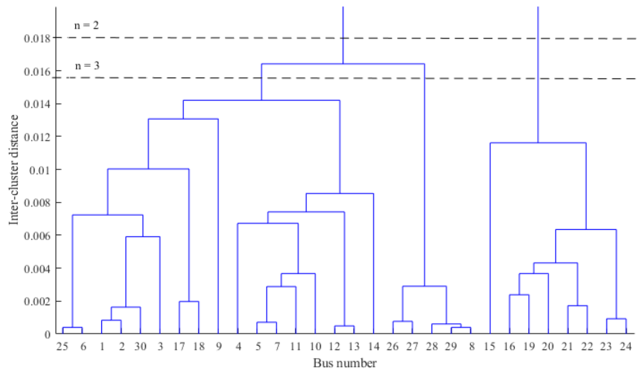

Fig. 4. Dendrogram of the clustering for IEEE 39-bus test system

The output results of the proposed algorithm for the bisection case are presented in Fig. 5 and Table 1. It is observed that the lowest value of expansion ($\phi(S)$) is 99.94%. Comparison between this value and the maximum possible value according to the Cheeger inequality (99.96%) shows the high quality of simulation results. Generation shortage of 199 MW in the 2nd island is not significant compared to the total power of the grid (6100MW) and could be easily managed by power system control measures like load shedding. According to Fig. 6 and 7 which are present the dynamic simulation results, the islanding scheme leads to two stable islands.

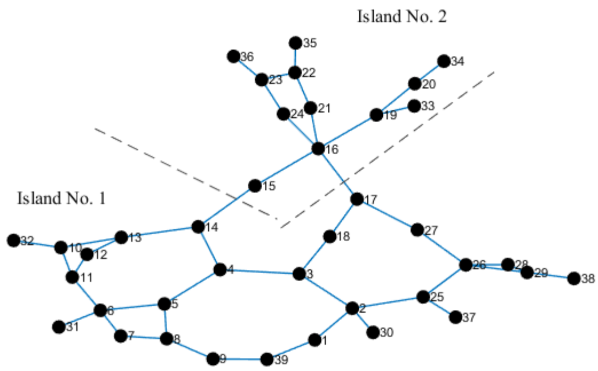

Fig. 5. Bisection islanding of the IEEE 39-bus test grid

Table 1. The simulation results on IEEE 39-bus test system

Number of islands (n)	Island no.	Bus no.	Line outage	$\partial(S)$ (MW)	$vol(S)$ (MW)	$\phi(S_i)$ (%)	$Min(\phi(S))$ (%)	Power imbalance (MW)
2	1	15, 16, 19-24, 33-36	14-15	5.137	9331	99.94	99.94	243
	2	1-14, 17, 18, 25-32, 37-39		5.137	16294	99.97		-199
3	1	26-29, 38	14-15, 25-26, 17-27	90	3631	97.52	97.52	-79
	2	1-14, 17, 18, 25, 30-32, 37,39		95	12661	99.24		-120
	3	15, 16, 19-24, 33-36		5	9331	99.94		243

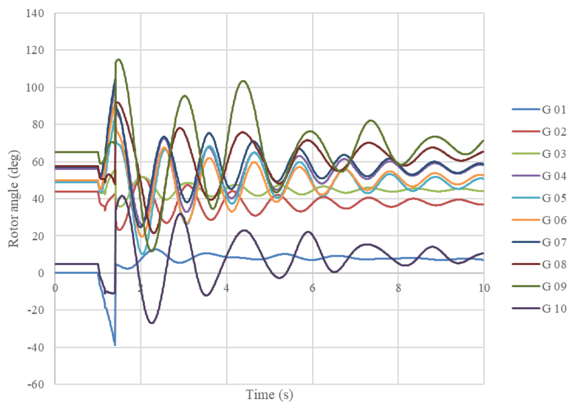

Fig. 6. Simulation results of generator rotor angle for IEEE 39-bus with islanding

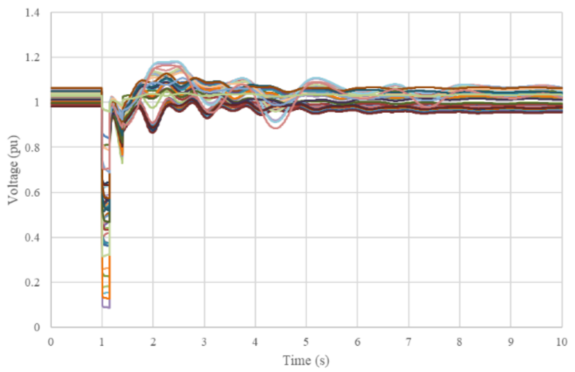

Fig. 7. Simulation results of bus voltage magnitude for IEEE 39-bus with islanding

The main advantage of the proposed approach is that it leads to several independent islanding scenarios without further computations. Thus, power system restrictions can also be studied using the power flow analysis to select the best scenario. For example, according to Table 1, the scenario with three islands leads to a 199MW power shortage similar to the bi-section case. It is surprising that the total computational time of the algorithm is less than one millisecond; therefore, this method could be utilized for short time decision making of islanding in real power systems.

5.2. Simulation of the IEEE 118-bus test grid

The proposed method is applied to the larger system known as IEEE 118-bus. The dynamic parameters of the system are completely provided in [34]. According to the simulation carried out in DIgSILENT software, after a short circuit in the transmission line between the 23th and 25th buses near the 25th bus, and the disconnection of the line by the protective relay, the generators start to oscillate in the following two groups:

$$V_{G1} = \{v_{10}, v_{12}, v_{25}, v_{26,} v_{31}\} \quad (26)$$

$$V_{G2} = \{v_{46}, v_{49}, v_{54}, v_{59}, v_{61}, v_{65}, v_{66}, v_{69}, v_{80}, v_{87}, v_{89}, v_{100}, v_{103}, v_{111}\} \quad (27)$$

According to the vulnerability analysis, separation of the grid is necessary to avoid blackouts. To find the splitting lines, the proposed method is carried out and the results are tabulated in Table 2. It shows that no load shedding is required for the bisection case. Meanwhile, the proper performance of the proposed method has been verified through dynamic simulation results which are shown in Fig. 8 and 9.

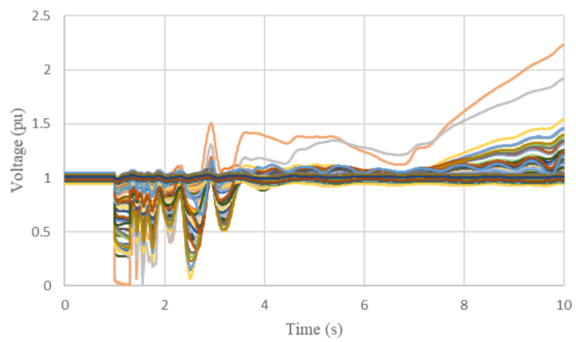

Fig. 8. Simulation results of bus voltage magnitude for IEEE 118-bus without islanding

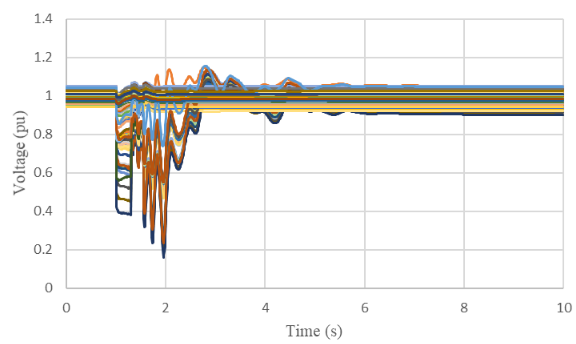

Fig. 9. Simulation results of bus voltage magnitude for IEEE 118-bus with islanding

Table 2. The simulation results on IEEE 118-bus test system

Number of islands (n)	Island no.	Line outage	$\partial(S)$ (MW)	$vol(S)$ (MW)	$\phi(S_i)$ (%)	$Min(\phi(S))$ (%)	Power imbalance (MW)
2	1	15-33, 19-34, 30-38, 24-70, 24-72	80.9288	8778	99.08	99.08	100
	2		80.9288	18835	99.57		34
3	1	15-33, 19-34, 30-38, 24-70, 24-72, 69-77, 75-77, 68-81, 76-118	148.2053	7692	98.07	97.94	52
	2		229.1341	11144	97.94		-18
	3		80.9288	8778	98.08		100

6. Computational Efficiency of the Proposed Method

Due to the time limitations in decision making for power system islanding, the computational speed is very important. In order to evaluate the computational efficiency of the proposed method, the calculation time has been compared to some other existing methods for the two islands. The comparative analysis, as summarized in Table 3, shows the computational efficiency of the proposed method.

Table 3. Evaluation of computational time of the proposed method for two islands

Performance time (ms)					
Test system	Proposed method	[35]	[19]	[16]	[10]
IEEE 39-bus	1.1	-	3.2	1.4	14.1
IEEE 118-bus	4.3	103.5	97.3	8.1	45.5

7. Conclusion

Regarding the importance of controlled islanding as the last resort to prevent catastrophic blackouts, this paper proposes a new islanding approach based on the hierarchical spectral clustering. The proposed method identifies the separation points based on minimum power flow disruption with the following improvements to the existing methods:

- Development of a hierarchical spectral clustering algorithm to satisfy the power system islanding constraints like generator coherency and circuit breakers remote control limitations.
- Determining the number of islanding schemes simultaneously without further calculations.

This method is evaluated on IEEE 39- and IEEE 118-bus test grids and the calculation time is compared with some other existing methods for the two islands. The comparative analysis shows the computational efficiency of the proposed method. It should be noted that this method, unlike the other ones, leads to the number of islanding scenarios in such a short time.

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