Prevention of Power Grid Blackouts Using Intentional Islanding Scheme

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***Abstract*—Intentional islanding is often conducted as the last resort to preserve the electric grid from severe blackouts. The intentional islanding scheme deliberately segregates the power system into a number of self-sustained islands to enhance the transient stability of the power network. In this study, a spectral clustering algorithm is presented to obtain an islanding solution, which results in minimal power flow disruption across boundaries of islands. The constraint in the spectral clustering method is introduced based on generator coherency grouping. The proposed scheme ensures that each island is only comprised of generators, which are synchronized with each other. The proposed clustering scheme utilizes a more computationally efficient and accurate *k*-medoids algorithm comparing to *k*-means ones. The proposed intentional islanding method is scrutinized using the IEEE 9-bus and IEEE 118-bus models. The results of simulations demonstrate that the proposed method can effectively prevent blackouts by separating the systems into stable islands.**

***Index Terms*—Cascading outage, controlled islanding, graph theory, intentional islanding, spectral clustering.**

I. Introduction

A NUMBER of severe blackouts have been reported in recent decades as the outcome of increasing electricity demand and power grid restructuring [1]. For example, on August 14, 2003, a devastating blackout hit the Northeastern U.S. and Canada, affecting 50 million people with an estimated total damage of 4–10 billion dollars [2].

Normally, cascading outages divide into two stages. Initially, slowly evolving successive events occur while the overall performance of the system remains intact and can be resembled with steady-state analysis. In this stage, utility operators may have enough time to evaluate the system condition and take some control actions to prevent the possibility of further outages. If the cascade outages progress to the second stage, a fast transient instability process unfolds resulting in a collapse of the entire system [3].

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Various remedial and emergency actions, including load and generator tripping, excitation controls, and intentional islanding, are deployed to prevent cascading blackouts [4]. The intentional islanding method preserves stable areas from further outages and at the same time expedites the restoration process by reducing transient stability problems during system reconnection.

The majority of controlled islanding schemes were classified as optimization problems. In [5]–[9], the slow coherency grouping of generators is utilized to split system into islands. In these studies, the coherent groups of generators are obtained by solving max-flow-min-cut optimization problem. However, due to the highly nonlinear nature of the power system, the linearized electromechanical modeling of it which is used in these methods may fail to obtain appropriate islanding solution.

Another islanding scheme is obtained considering a graph-search-based method called ordered binary decision diagrams (OBDD) [10], [11]. In this method, the original power system is substituted with a simplified equivalent obtained using a graph-based reduction algorithm. Then, the solution space is narrowed down using OBDDs to fulfill the equality constraints. Then, power flow result is used to decide whether any of the islanding solutions satisfy inequality constraints or not. The major drawbacks of this method are the additional calculation burden required for simplification process and the risk that the superior optimal solutions may be lost due to simplification.

In recent years, several efforts were devoted to development of intentional islanding schemes based on clustering methods [12], [13]. In [12], a *k*-way spectral clustering method to split power systems into self-sustained islands considering minimum load-generation imbalance is presented. In [13], a multilevel kernel *k*-means algorithm to form islands based on minimum power flow disruption is proposed. The computational efficiency of these methods is good, but without dynamic constraints in the clustering process, some of created islands may divide into unstable sub-islands, eventually driving them to total blackouts.

Liu *et al*. [14] proposed a controlled islanding scheme based on particle swarm optimization. The method uses minimal power imbalance criteria to form islands. In this method, connection among subgraphs are neglected to reduce computational burden, while it may increase possibility of isolated buses within the created islands.

In this paper, an intentional islanding method considering spectral clustering formulation is presented. The proposed scheme offers stable islanding solution and high-speed performance, without downsizing the power system model.

The remaining sections are organized as follows. Section II gives the background of clustering methods. In Section III, the

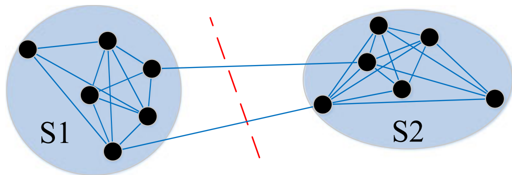

Fig. 1. Solving graph-cut problem using spectral clustering.

intentional islanding method is presented. Section IV represents the test results for the proposed method using several scenarios. Main contributions are given in Section V.

II. Background Theory

A. Power System as a Graph

Any electric grid can be represented using a graph where the vertices (nodes) and edges (links) of the graph stands for power system's buses and lines, respectively. To represent characteristics of the mapped power grid, edges of the graph can be weighted using different parameters such as admittance, active or reactive power flow.

In this study, active power flow across transmission lines is used as the edge weight to determine cost of cutsets in the controlled islanding study. The edge weight matrix W is defined as

$$W = \begin{cases} w_{\mathrm{ij}} = \frac{|P_{\mathrm{ij}}|+|P_{\mathrm{ji}}|}{2} & i \neq j \\ w_{\mathrm{ij}} = 0 & i = j \end{cases} \tag{1}$$

where P_{ij} and P_{ji} are the active power injected into the line from buses i and j, respectively. In (1), w_{ij} is calculated as the average power flow from two ends of the line to compensate power loss across the line. The edge weight matrix W is calculated based on power flow, which can represent the dynamic nature of power system as it alters according to system operating states.

The unnormalized Laplacian of the graph is defined as [15]

$$L = \begin{cases} -w_{\mathrm{ij}}, & i \neq j \\ d_i, & i = j \end{cases} \quad d_i = \sum_{j=1}^{n} w_{\mathrm{ij}} \tag{2}$$

where w_{ij} is the element of edge weight matrix calculated in (1). The Laplacian matrix L can also be written as

$$L = D - W \tag{3}$$

where D is the degree matrix with diagonal nonzero entries d_i. The normalized Laplacian matrix L_N is constructed using

$$L_N = D^{-1/2} L \, D^{-1/2}. \tag{4}$$

The distinct features of the Laplacian matrix of the graph G are explained in the next section.

B. Spectral Clustering

As depicted in Fig. 1, a graph-cut problem is referred to as the splitting of graph G into S_1 and S_2 by cutting the connecting edges between S_1 and S_2. The set of edges and the sum of their weights are known as cutset and cut, respectively

$$\mathrm{cut}(S_1, S_2) = \sum_{i \in S_1,\, j \in S_2} w_{\mathrm{ij}}. \tag{5}$$

The graph-cut problem defined in (5) can be solved utilizing unnormalized spectral clustering method. It uses the two eigenvectors associated with the two smallest positive eigenvalues of the Laplacian matrix of G to form S_1 and S_2. The unnormalized spectral clustering method is defined using the following steps [16].

1) Compute the two eigenvectors (v_1, v_2) of the Laplacian matrix L associated with the two smallest eigenvalues.
2) Define V as the matrix constructed using two columns of v_1 and v_2.
3) Define y_i as the *i*th row of V.
4) Apply a *k*-means or *k*-medoids clustering methods to cluster y_i into S_1 and S_2.

Achieving a proper islanding solution using unnormalized spectral clustering of the graph, which represents power system, might be infeasible as it splits power system into two islands without considering transient behavior of the system. Besides, it might also be necessary to divide the system into more than two islands to interrupt sequences of cascade outages. In the next section, a controlled islanding scheme utilizing constrained spectral clustering to address these issues is introduced.

III. Proposed Controlled Islanding Method

Once successive disturbances take place in the electric grid, its stability margin degrades, which eventually may lead to system separation and formation of unwanted islands. The intentional islanding of the grid during the preliminary state of cascading outages progression can decrease or eliminate the possibility of severe blackouts. The controlled islanding concept is primarily introduced to work at the transmission level, while it can operate at the substation level, all the way down to a distribution feeder. The control islanding scheme can also expedite the restoration process of the power system.

To create an ideal self-sustained islanding solution, different constraints such as thermal limits, load-generation imbalance, generator coherency, and transient stability should be taken into account [11]. Hence, a controlled islanding strategy is considered as a multiconstraint and multiobjective optimization problem in which it would rarely be possible to reach the best solution. So, a viable solution is to consider a sub-set of objectives and constraints to reduce the complexity of the problem. In this study, generator coherency is considered as a constraint to the minimization problem, while the power flow disruption between islands is defined as the objective function to be minimized.

A. Static Constraints

To attain a successful intentional islanding strategy, it is more influential to secure the transient stability rather than load-generation balance, since an island with negative stability index may ultimately fall apart even if the load-generation balance is satisfied within the island. There are two types of objective

Fig. 2. Two types of objective function using active power flow.

functions used in literature, formulated as

$$\underset{S_1,S_2\subset G}{\mathrm{Min}}\left(\left|\sum_{i\in S_1,j\in S_2}\left(\frac{P_{\mathrm{ij}}+P_{\mathrm{ji}}}{2}\right)\right|\right) \tag{6}$$

$$\underset{S_1,S_2\subset G}{\mathrm{Min}}\left(\sum_{i\in S_1,j\in S_2}\left(\frac{|P_{\mathrm{ij}}|+|P_{\mathrm{ji}}|}{2}\right)\right). \tag{7}$$

In (6), the objective function is defined to minimize the sum of active power flows between islands, which is known as a "power flow imbalance." Solving the optimization problem with this objective function secures islands with good load-generation balances. As shown in Fig. 2(a), the solution may result in the switching of major transmission lines which transfer higher active power. Disconnection of such lines can cause transient stability problem at both islanding creation and system restoration stages.

In (7), the objective function is defined to minimize the absolute value of the active power flow between islands, known as "power flow disruption." Solving the optimization problem with this objective function avoids the overloading of transmission lines within the islands. It can also facilitate reconnection of the islands in the restoration process due to the minimum power flow changes compared to the predisturbance condition [see Fig. 2(b)].

In this study, the latter objective function is selected to formulate the optimization problem.

B. Dynamic Constraints

A strong disturbance in an electric grid may trigger electromechanical wave oscillations, which propagate through the entire network and may result in generators' out of synchronism [17], [18]. The generators with stronger dynamic couplings remain synchronized with each other and are called coherent generators [19], [20]. To achieve reliable islanding strategy, each group of the coherent generators must be kept in the same islands.

In this study, the generator coherency problem is determined using normalized spectral clustering. First, the dynamic graph of system L_D is defined as [16]

$$L_D=\begin{cases}\dfrac{\left|{}^{\partial P_{\mathrm{ij}}}\!/\!_{\partial\delta_{\mathrm{ij}}}\right|+\left|{}^{\partial P_{\mathrm{ji}}}\!/\!_{\partial\delta_{\mathrm{ji}}}\right|}{2}, & i\neq j\\ -\displaystyle\sum_{l=1,l\neq i}^{n}L_D^{il}, & i=j.\end{cases} \tag{8}$$

By applying the four steps of spectral clustering method introduced in Section II-B, the generators are divided into two coherent groups, S_{G1} and S_{G2}. Then, each group can be treated as a separate graph to perform recursive bisection spectral clustering till the desired number of coherent groups is achieved.

Once coherent generators are determined, it can be used as a constraint to *k*-embedded clustering method. Next, the constrained spectral *k*-embedded clustering method to achieve self-sustained islands will be discussed and formulated.

C. Constrained Spectral k-Embedded Clustering

Constrained spectral clustering is defined as a semi-supervised clustering method with the additional information converted in the form of pairwise constraints. This section describes how the generator coherency information is incorporated into constrained spectral clustering. The new constrained optimization formulation to solve controlled islanding problem is proposed.

In the constrained spectral clustering the terms must link (ML) and cannot link (CL) refer to vertices which must remain and removed in the final solution, respectively [21], [22]. A ML-constraint ensures that the vertices that are connected through the ML remain within the same cluster. A CL-constraint ensures the vertices which are connected through the CL are grouped in different clusters. The constraint matrix Q is defined as

$$Q=\begin{cases}-1, & \text{if } (x_i,x_j)\in \mathrm{CL}\\ +1, & \text{if } (x_i,x_j)\in \mathrm{ML}.\\ 0, & \text{else}\end{cases} \tag{9}$$

The standard constrained clustering can only holds binary constraints for ML and CL. The following index is defined to verify satisfaction of constraints matrix Q:

$$u^TQu=\sum_{i,j}u_iu_jq_{\mathrm{ij}} \tag{10}$$

where $u\in\{-1,+1\}^N$ is the indicator vector. The further extension is achieved when u and Q are relaxed

$$u\in R^N \qquad Q\in R^{N\times N}. \tag{11}$$

If $Q_{\mathrm{ij}}>0$, then i and j are in the same cluster; if $Q_{\mathrm{ij}}<0$, then i and j are in different clusters. As the value of u^TQu becomes higher, the constraint matrix Q is more satisfied. The normalized form of constraint matrix Q is defined as follows:

$$Q_N=D^{-1/2}QD^{-1/2} \tag{12}$$

where D is the degree matrix.

The controlled islanding problem is defined as a constrained optimization problem with the following definition [22]:

$$\begin{aligned}&\arg\min\ v^TL_Nv\\ &\quad s.t.\ v^TQ_Nv>\beta,\quad v^Tv=\mathrm{vol},\\ &\quad v\neq D^{1/2}1\end{aligned} \tag{13}$$

where $\mathrm{vol}=\sum_{i=1}^N d_{ii}$ is the graph volume and β is the satisfaction threshold. v^TL_Nv is the cost of the cut, $v^Tv=\mathrm{vol}$ is defined to normalize v and $v\neq D^{1/2}1$ is defined to avoid trivial solutions.

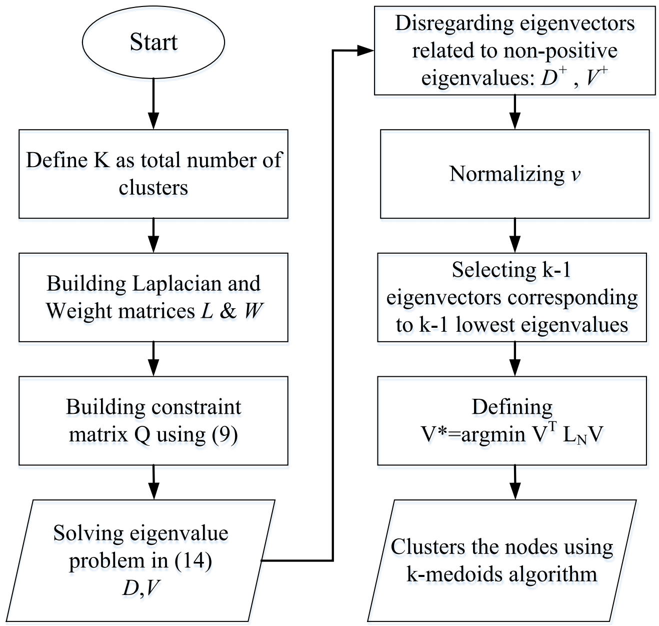

Fig. 3. Proposed controlled islanding method.

The Karush–Kuhn–Tucker Theorem [23] is used to solve the objective function in (13). After several mathematical steps [22], the solution of optimization equation in (13) can be attained by solving the generalized eigenvalue equation in (14)

$$L_N v = \lambda\left(Q_N - \frac{\beta}{\text{vol}} I\right) v. \tag{14}$$

In summary, as shown in Fig. 3, the step-by-step-constrained spectral k-embedded clustering algorithm is defined as follows:

1) Determine k as the total number of clusters obtained from generator coherency grouping.
2) Use graph representation of the power system to obtain edge weight matrix W and normalized Laplacian matrix L_{N} using (1) and (4), respectively.
3) Build constraint matrix Q using (9).
4) Solve the generalized eigenvalue problem in (14).
5) Disregard the eigenvectors related to nonpositive eigenvalues.
6) Normalize eigenvectors using $v \leftarrow \frac{v}{\|v\|}\sqrt{\text{vol}}$.
7) Select $k-1$ eigenvectors $(v_1, \ldots, v_{k-1})$ related to the $k-1$ lowest eigenvalues.

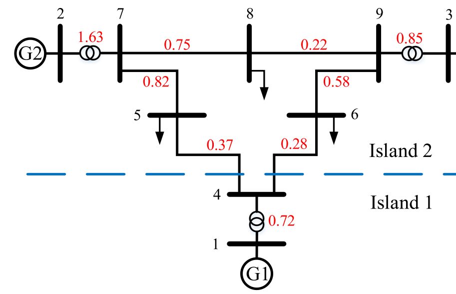

Fig. 4. Studying controlled islanding using the IEEE 9-bus.

8) Define $V^* \leftarrow \arg\min \; V^T L_N V$, where $V \in R^{n\times k-1}$ is the matrix built by vectors $v_1, \ldots, v_{k-1}$ as columns.
9) Apply k-medoids algorithm to obtain the final islanding solution [24].

Comparing to bisection spectral clustering [25], the proposed k-embedded spectral clustering has higher flexibility in adjusting clusters and partitioning process. Despite the k-means method, which uses squared distances among data points, the k-medoids method eliminates data anomalies and noises as it minimizes the sum of variances.

IV. Test Results

First, the proposed controlled islanding method is demonstrated using the simple IEEE 9-bus system with a detailed explanation of matrix formations. Then, it is tested by creating hypothetical cascade outage scenarios using IEEE 118-bus test system [26], [27]. To achieve more accurate results hardware-in-the-loop simulation is performed using real-time simulator. The method is developed using MATLAB environment.

A. IEEE 9-Bus System

The generator coherency analysis results in separation of generators in two groups {G1} and {G2, G3}, which can be seen in Fig. 4. In this figure, the number attached to each line represents the per unit average active power flow across it.

Fig. 4 can be seen as a graph G where the lines and buses are edges and vertices, respectively. The weight of each edge is labeled next to it. Therefore, one can build the Laplacian matrix using (2), see (15) shown at the bottom of the page.

$$L = \begin{bmatrix} 0.72 & 0 & 0 & -0.72 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.63 & 0 & 0 & 0 & 0 & -1.63 & 0 & 0 \\ 0 & 0 & 0.85 & 0 & 0 & 0 & 0 & 0 & -0.85 \\ -0.72 & 0 & 0 & 1.37 & -0.37 & -0.28 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.37 & 1.19 & 0 & -0.82 & 0 & 0 \\ 0 & 0 & 0 & -0.28 & 0 & 0.86 & 0 & 0 & -0.58 \\ 0 & -1.63 & 0 & 0 & -0.82 & 0 & 3.2 & -0.75 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.75 & 0.97 & -0.22 \\ 0 & 0 & -0.85 & 0 & 0 & -0.58 & 0 & -0.22 & 1.65 \end{bmatrix} \tag{15}$$

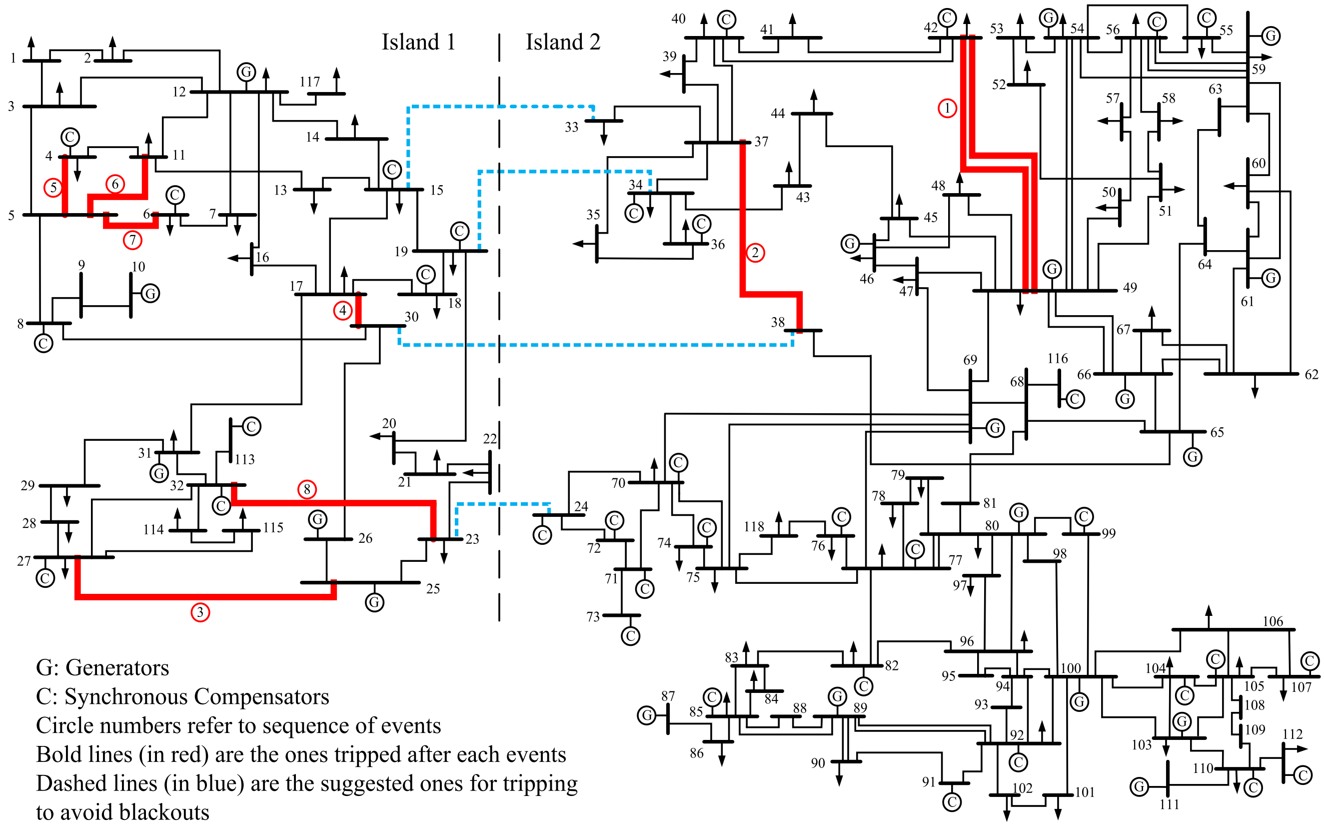

Fig. 5. IEEE 118-bus test system.

The ML constraint between G2 and G3 are replaced by $+1$, and the CL constraint between G1 and $\{$G2 and G3$\}$ are replaced by -1 to build matrix Q

$$Q = \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \qquad (16)$$

By calculating steps 4–9 in Fig. 3, a single cutset is obtained as shown with dashed line in Fig. 4. The cost of cut is the sum of average power flow across lines (4–5 and 4–6) and is equal to $(0.28 + 0.37 =)$ 0.65 p.u. The two islands include buses $\{1, 4\}$ and $\{2, 3, 5, 6, 7, 8, 9\}$, respectively. Since $\{$G1$\}$ is in the island1 and $\{$G2, G3$\}$ are in the island2, the suggested islanding scheme guarantees generator coherency constraints, too.

B. IEEE 118-Bus System

1) Cascade Outage Scenario Creation: From Fig. 5, one can observe that the IEEE118 bus test system consists of several areas, which are loosely connected to each other. It is expected that following several consecutive outages, those areas might be disconnected from each other. In such cases, unless the generation capacity of each area matches the amount of loads in that area, one or more areas may experience brownout or blackout. Next, the sequence of events to create a hypothetical cascading event outage scenario is described, which will result in blackout. It should be noted that undervoltage load shedding is not considered in the scenario creation process to assist creating a system blackout, and 10 s intervals are deliberately inserted between outages to help understanding of transient behavior after each step and assure readability of plots.

1) Parallel lines between buses (42–49) are tripped at $t = 10$ s due to intercircuit fault.
2) Line between buses (37–38) is tripped at $t = 20$ s due to a phase to ground fault.
3) Line between buses (25–27) is tripped at $t = 30$ s due to another phase to ground fault.
4) Line between buses (17–30) is tripped at $t = 40$ s due to malfunction of distance relay caused by power swing.
5) Line between buses (4–5) is overloaded and a single phase fault occurs due to sagging of the line. The corresponding relays trip the line at $t = 50$ s.
6) Line between buses (5–11) is deenergized due to misoperation of third zone relay under overload condition at $t = 60$ s.
7) Line between buses (5–6) is deenergized due to misoperation of third zone relay under overload condition at $t = 70$ s.

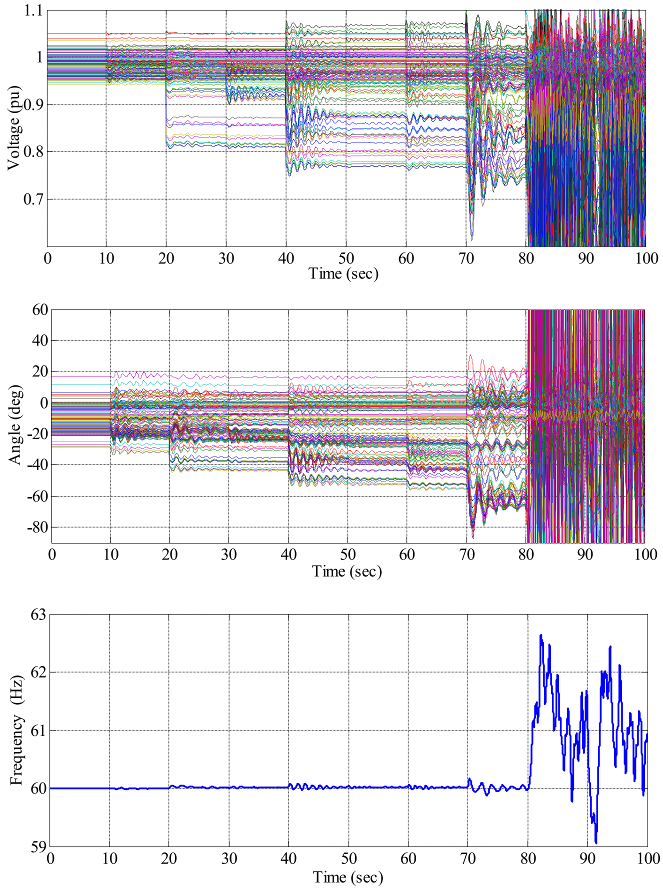

Fig. 6. Bus voltage, bus angle, and frequency of system during cascade outages, without controlled islanding scheme.

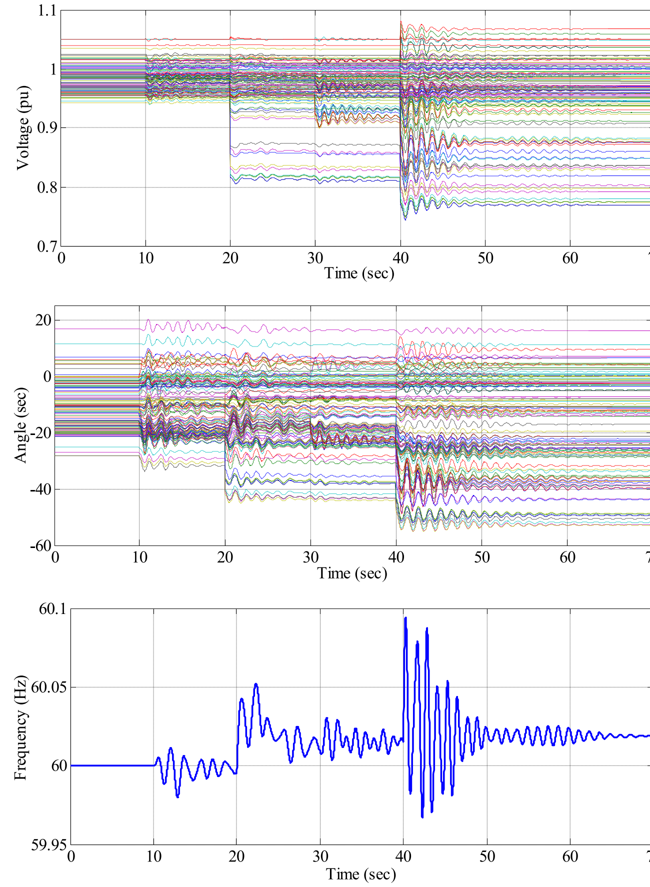

Fig. 7. Bus voltage, bus angle, and frequency of the system equipped with controlled islanding scheme.

8) Line between buses (23–25) is deenergized due to misoperation of third zone relay under overload condition at $t = 80$ s. Following the outage of the line (23–25), the voltage profile of the system collapses and blackout occurs.

Fig. 6 shows the bus voltage, bus phase angle, and frequency of the system in this cascade outage scenario. The first three events are considered as unstoppable outages (maintenance, faults, etc.), which may occur anytime in the system.

After the fourth event, voltage of buses (33 to 37 and 39 to 42) dropped below 0.8 p.u., as the line (17–30) was the major route of transferring power from generators (10, 25, and 26) to that load area. Following this outage, redistribution of power flow caused overloads on lines (4–5, 5–6, and 5–11), which resulted in events 5–7.

2) Controlled Islanding Scheme: After several outages occurred, the operator should trigger the controlled islanding scheme to determine the switching actions resulting in a self-sustained islanding solution. Ultimately, the scheme should be triggered automatically using a system global vulnerability index, which is defined as the future work of this study. In this example, the islanding scheme is manually triggered after the third outage (line 25–27) occurred.

The generator coherency spectral clustering method determines that generators at buses (10, 12, 25, 26, and 31) form the first coherent group while other generators form the second group. The constraint matrix Q is built using the generator coherency information. The constrained spectral clustering algorithm suggests switching of lines (15–33, 19–34, 23–24, and 30–38), which divides the system into two islands, as depicted in Fig. 5.

Fig. 7 shows the bus voltage, bus phase angle, and frequency of the IEEE 118-bus system under cascade outage scenario and following switching lines (15–33, 19–34, 23–24, and 30–38) at $t = 40$ s. The islanding solution prevents transferring power from island 2 to island 1 through line (38–30) and from island 1 to island 2 through lines (15–33 and 19–34), which avoids overloading of lines (4–5, 5–6, 5–11, 17–30, and 23–25). Comparing Figs. 6 and 7, it is obvious that the proposed islanding solution prevents cascade outages and conserves the system from blackout. In Fig. 7, the voltage profile of buses 40, 41, and 42 are below 0.8 p.u. following separation of the system. Further studies prove that shedding load at bus 42 can increase the voltage profile of these buses above 0.8 p.u. threshold.

The relatively small size of the IEEE 118-bus system limited the scheme to a handful of scenarios. The authors are currently working on applying the proposed scheme to a real-sized system. Table I is a summary of results of deploying the proposed scheme for all the created scenarios. The amount of load shedding (to maintain voltage profile above 0.8 p.u.) is much lower than when

TABLE I
SUMMARY OF SIMULATED CASCADE OUTAGE SCENARIOS

	Scenario_1	Scenario_2	Scenario_3	Scenario_4
Number of islands	2	2	3	3
Switched lines	15–33, 19–34 23–24, 30–38	68–81, 69–77 75–77, 76–77	15–33, 17–31 19–20, 19–34 23–24, 26–30, 30–38	15–33, 19–34 23–24, 30–3868–81, 69–77 75–118,76–77
Load shed without scheme	4242 MW	4242 MW	4242 MW	4242 MW
Load shed with scheme	96 MW	0 MW	71 MW	33 MW

TABLE II
PROPOSED METHOD EXECUTION TIME

Test Systems	IEEE 9-bus system	IEEE 118-bus system
Execution Time (s)	<0.001	0.0973

the controlled islanding scheme is deployed, which verifies the effectiveness of the scheme in preventing blackouts.

C. Computational Efficiency

A successful intentional islanding scheme must be computationally efficient to be applicable to a real-sized system. Utilizing minimal power imbalance results in nondeterministic polynomial-time hard (NP-hard) problems. The computational solution time of NP-hard problems grows in an exponential order [28]. In the proposed method, minimal power flow disruption is used as objective function, which can be solved in polynomial time order [28], [29].

The required run time of the presented scheme using MATLAB R2012b for the two test systems are shown in Table II. Simulations are executed using Windows 7, Intel(R) Xeon(R) 3.2 GHz CPU, 12 GB RAM PC.

V. CONCLUSION

In this study, we expanded our previously proposed constrained spectral k-embedded clustering method [30] to obtain a viable solution for intentional islanding problem as the last resort to rescue power system from state of blackouts. The major contributions of this paper is listed as follows.

1) Achieving more stabilized islands due to usage of minimal power flow disruption in defining objective function.
2) Reducing the required time and complexity of the islands reconnection process.
3) Including generator coherency data using constraint matrix to avoid the creation of islands with noncoherent generators, which will eventually collapse.
4) Flexible adjustment of clusters achieved by spectral k-embedded clustering resulted in more stable islands.
5) Minimizing amount of load shedding by minimizing power flow disruption across islands' boundaries.
6) Proposing the objective function, which can be solved in polynomial time order. The proposed method is timely efficient and can be deployed as a real-time intentional islanding application to disrupt successive cascading outages and prevent severe blackouts in the electric grid.

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