A Power System Controlled Islanding Scheme for Emergency Control

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Abstract—During major system disturbances, uncontrolled separation of the power system may take place, leading to further network stability degradation and likely a large-scale blackout. Intentional controlled islanding has been proposed as an effective approach to split the power system into several sustainable islands and prevent cascading outages. This paper proposes a novel methodology that determines suitable islanding solutions for minimal power imbalance or minimal power flow disruption while ensuring that only coherent generators are in each island. It also enables system operators to exclude any branch from islanding solutions, i.e. from its disconnection. In real applications, the actual power flow data and the prior-identification of the coherent groups of generators are required. The proposed methodology is illustrated using the IEEE 9-bus test system. Simulation results demonstrate the effectiveness and practicality of the proposed methodology to determine an islanding solution.

Index Terms—Intentional controlled islanding, power flow disruption, power imbalance.

I. INTRODUCTION

INTERCONNECTED power systems very often operate close to their stability limits [1] increasing the probability of cascading outages [2]. Recent blackouts across the world [3-6] highlighted the need to propose effective and efficient solutions to avoid the socio-economic consequences that cascading blackouts can cause [7].

Intentional Controlled Islanding (ICI) has been proposed as a last resort to attempt to save the power system when vulnerability analysis indicates that it is threatened by cascading outages [1], [7]. The islanding of a power system must be performed in a very limited timeframe [8-12] as system operators have only a few seconds to respond and attempt to save the power system. Thus, determining an islanding solution in real-time, i.e. quickly enough to ensure effective islanding within a limited timeframe, is an extremely complex analytical and practical problem [8], [9].

The objective of ICI methods is to determine the set of transmission lines that must be disconnected to create stable and sustainable islands [7]. When finding the solution, multiple constraints, such as generator coherency, load-generation balance, thermal limits, voltage and transient stability, must be considered [11]. Nevertheless, it would be impractical to attempt to find a solution including all of these; thus, only a set of selected constraints is usually taken into consideration when finding an islanding solution; therefore extra corrective measures [1], [7] are required in the post-islanding stage to retain the stability of the islands.

The existing ICI methods can be classified based on the objective function used. Two major classes are: a) minimal power imbalance or b) minimal power flow disruption. While methods for the former minimize the load-generation imbalance within the proposed islands, reducing the amount of load to be shed in the post-islanding stage [8], [9], methods for the latter minimize the change of the power flow pattern within the network following system islanding, reducing the possibility of overloading the branches in the created islands [11-13].

Overall, the existing methods have focused on solving the ICI problem for a single objective function, whilst the constraints are limited to ensure that only dynamically coherent generators are in each island [8-12]. For example, methods based on ordered binary decision diagrams (OBDDs) [8], [9], tracing power flows [14] and metaheuristic algorithms [15], [16] have been used to find islanding solutions for minimal power imbalance. Moreover, to determine an islanding solution for minimal power flow disruption, spectral clustering [10], [11] and multi-level kernel k-means algorithms [17] have been proposed.

Even though the existing ICI methods can determine suitable islanding solutions, these can only cope with a given single objective function. For example, spectral clustering algorithm cannot be used to find a solution for minimal power imbalance [11]. Hence, a more flexible method which allows system operators to change the objective function for different system scenarios is needed. This paper proposes a novel islanding methodology that is computationally efficient and can determine islanding solutions for any of the abovementioned objective functions while ensuring that only coherent generators are in each island. The methodology initially uses the topological characteristics of the electrical network to find “suitable islanding solutions”, defined in this paper as solutions that split the power system into the given number of islands, while guaranteeing generator coherency. The optimal islanding solution is finally defined by computing either the power imbalance or the power flow disruption and the cutset with the minimum value is selected as the final solution.

The main advantage of the proposed methodology is its flexibility to cope with any objective function, allowing system operators to change this, based on their criteria and experience, while maintaining the efficiency of it. Moreover, it can provide various islanding solutions to prevent wide-area blackouts. The methodology demonstrates to be capable
of handling unexpected systems changes and to be able to constrain branches to be excluded from islanding solutions.

The proposed methodology is illustrated using the IEEE 9-bus test system and simulations are used to discuss in detail its benefits and limitations. This paper focuses on steady-state studies only and it is assumed that the coherent groups of generators are known in advance, e.g. obtained using existing algorithms [18], [19].

The paper is organized as follows. Section II presents the preliminaries and the proposed methodology to determine islanding solutions. Simulation studies using the IEEE 9-bus test system are presented in Section III. Finally, concluding remarks are provided in Section IV.

II. PROPOSED METHODOLOGY FOR INTENTIONAL CONTROLLED ISLANDING

A. Preliminaries

An electrical power system with \( n \) buses and \( L \) branches (transmission lines and transformers) can naturally be represented as a graph \( G = (V(G), E(G)) \) [20]. The graph consists of a pair of sets \( (V(G), E(G)) \). When there is no scope of ambiguity, the letter \( G \) from graph theoretic symbols is omitted and \( V \) and \( E \) are used instead of \( V(G) \) and \( E(G) \). The elements of \( V = \{v_1, v_2, \ldots, v_n\} \) are the nodes, or vertices, and the elements of \( E \subset V \times V = \{e_1, e_2, \ldots, e_L\} \) are the edges, or links, in the graph \( G \), respectively. The sets \( V \) and \( E \) represent the buses and branches of the power system, respectively. Due to the nature of power systems, the graph \( G \) can be assumed to be simple, i.e. no multiple edges and no loops are allowed.

If the edges have a direction associated with them, e.g. power flow direction, the graph is called directed graph or digraph, otherwise the graph is called undirected graph. For a digraph, the edge \( e_k = (v_i, v_j) \in E \), \( i, j = 1, 2, \ldots, n \), is an ordered pair of vertices indicating that the edge \( e_k \) is incident to vertices \( v_i \) and \( v_j \), where \( v_i \) and \( v_j \) are called the tail and the head, respectively. A similar definition can be drawn for undirected graphs by ignoring the direction of the edge, that is, \( e_k = (v_i, v_j) = (v_j, v_i) \in E \), \( i, j = 1, 2, \ldots, n \).

Since the functional information about the system cannot be captured by the topological structure of the graph, we use weight factors associated with the edges. An edge-weight is a function \( \omega: V \times V \rightarrow \mathbb{R}^{>0} \) such that \( w_k = \omega(e_k) \). To accommodate network losses, the value of \( w_k \) is calculated as follows.

\[
w_k = \begin{cases} \frac{|P_o| + |P_p|}{2} & \text{if } e_k \in E; \\ 0 & \text{otherwise.} \end{cases}
\] (1)

In (1), \( P_o \) and \( P_p \) represent the active power-flow in the branch from bus \( i \) to bus \( j \), and from bus \( j \) to bus \( i \), respectively.

B. Proposed Methodology

The ICI problem can be modeled as a constrained combinatorial optimization problem and its complexity increases exponentially with the size of the system [8], [9]. This combinatorial problem can be solved for the status of the branches (connected/disconnected) or the location of the buses in the islands (island number). The existing methods [8], [9] have attempted to solve the ICI problem for the status of the branches. Nevertheless, determining whether a branch requires to be disconnected or not to create islands is computationally more demanding as the number of branches is commonly larger than the number of buses \( (l > n) \).

Having identified the advantage of solving the combinatorial problem for the location of the buses, this paper aims to identify suitable islanding solution by defining the location of the buses first. This information then determines whether a branch needs to be disconnected or not. If a line connects two buses in the same island, this line should not be disconnected; however, the line must be disconnected if the buses are located in different islands.

This paper represents the results of the combinatorial problem in the matrix \( B \). For a given number of islands, the matrix \( B \) is the \( n \times c \) matrix, where \( c \) is the total number of combinations that can be obtained with the nodes (see example below). After solving this combinatorial problem, the methodology then provides a label (a number 1 or 2) to each node in \( G \) for each possible combination. For a given combination, the label of the node \( v_i \) indicates the number of the island at which that node should belong.

To illustrate the approach, consider the digraph shown in Fig. 1. The digraph will be split into two subgraphs \( G_1 \) and \( G_2 \). Mathematically, there are 16 possible combinations to split this graph into two subgraphs (see (2)). In other words, the matrix \( B \) will be of size \( 4 \times 16 \). However, some combinations are not suitable, that is, they do not actually split the graph, or the number of subgraphs induced by the cutset is larger than two. We highlight in (2) the solutions that are not suitable. Furthermore, it must be noted that some combinations, e.g. \( \text{comb}_2 \) and \( \text{comb}_{13} \) will produce the same cutset. The suitable cutsets can be defined by evaluating the rank of the graph induced by the corresponding cutset.

![Fig. 1. Digraph with four nodes and four edges to exemplify the combinatorial problem to be solved.](image)

\[
B^t = \begin{bmatrix}
\text{comb}_1 & 1 & 1 & 1 & 1 \\
\text{comb}_2 & 1 & 1 & 1 & 2 \\
\text{comb}_3 & 1 & 1 & 2 & 1 \\
\text{comb}_4 & 1 & 2 & 1 & 1 \\
\text{comb}_5 & 1 & 2 & 1 & 2 \\
\text{comb}_6 & 1 & 2 & 2 & 1 \\
\text{comb}_7 & 1 & 2 & 2 & 2 \\
\text{comb}_8 & 2 & 1 & 1 & 1 \\
\text{comb}_9 & 2 & 1 & 1 & 2 \\
\text{comb}_{10} & 2 & 1 & 2 & 1 \\
\text{comb}_{11} & 2 & 1 & 2 & 2 \\
\text{comb}_{12} & 2 & 2 & 1 & 1 \\
\text{comb}_{13} & 2 & 2 & 1 & 2 \\
\text{comb}_{14} & 2 & 2 & 2 & 1 \\
\text{comb}_{15} & 2 & 2 & 2 & 2 \\
\end{bmatrix}
\] (2)

Our methodology can also constrain certain nodes to
belong to a given island. For example, we assume that node $v_1$ must be allocated in the island 1 and node $v_4$ in the island 2. The nodes $v_2$ and $v_3$ can be assigned to any island. Since two islands can be created, four combinations can be obtained (3). Again, we evaluate whether a cutset is feasible or not by computing the rank of the resulting digraph. For this particular case, the four solutions are suitable in the sense that these split the graph into two subgraphs.

$$B^k = \begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 2 & 2 \\ 1 & 2 & 1 & 2 \\ 1 & 2 & 2 & 2 \end{bmatrix}$$ (3)

When the matrix $B$ is computed, the cutset for each possible combination can be determined. These cutsets can be computed by using the incidence matrix $M$ associated with the digraph [20]. The possible cutsets are represented in the matrix $C = B^k M$. The $i$-th entry of $C$ is -1, 0 or 1. The sign depends on the orientation of the edge, respect to the cutset orientation [20]:

$$C = \begin{bmatrix} \text{cutset}_1 & e_1 & e_2 & e_3 & e_4 \\ \text{cutset}_2 & 0 & 0 & 0 & 1 \\ \text{cutset}_3 & 0 & -1 & 1 & 0 \\ \text{cutset}_4 & -1 & -1 & 0 & 0 \end{bmatrix}$$ (4)

As noticed in (4), if we implement the first combination, the lines represented by the edges $e_1$ and $e_4$ will have to be disconnected The matrix $C$ is used to determine a solution for minimal power imbalance. To find a solution for minimal power flow disruption, we ignore the direction of the edges, and thus, we create the matrix $C_U$:

$$C_U = \begin{bmatrix} \text{cutset}_1 & e_1 & e_2 & e_3 & e_4 \\ \text{cutset}_2 & 0 & 0 & 1 & 1 \\ \text{cutset}_3 & 0 & 1 & 0 & 1 \\ \text{cutset}_4 & 1 & 0 & 1 & 0 \end{bmatrix}$$ (5)

To identify the splitting strategy, we then compute a row vector $w$ which contains in the $k$-th row the average power flow (1) in the branch $k$ (represented by the edge $e_k$).

Then, by simply multiplying the matrix $C$, or $C_U$, by this row vector $w$, the power imbalance, or power flow disruption, induced by each cutset can be determined. Then, the islanding solution is determined by minimizing the value of the cut, i.e. min (cut), where the cut for minimal power imbalance (cut (MPI)) and the cut for minimal power flow disruption (cut (MPFD)) are computed as follows.

$$\text{cut (MPI)} = |C \cdot w|$$

$$\text{cut (MPFD)} = C_U \cdot w$$ (6)

III. ILLUSTRATION OF THE PROPOSED ISLANDING METHODOLOGY

We illustrate the proposed methodology using the IEEE 9-bus test system [21]. Fig. 2 and Fig. 3 show the topology of the system and the equivalent digraph representation. The weight factors associated with the edges are obtained by computing the power flow solution using MATPOWER [22]. Note that the direction of the edges is based on the power flow results. Simulations are performed using MATLAB 7.10 (R2010a) [23] on an Intel® Core™ 2 Duo CPU E7500 @ 2.93 GHz, 4 GB of RAM.

Fig. 2. Single line diagram of the IEEE 9-bus test system.

Fig. 3. Directed graph of the IEEE 9-bus test system.

As previously mentioned, the number of coherent groups of generators defines the number of islands to be created. In this paper, we assume that there exist two the coherent groups of generators: group 1: {G1} and group 2: {G2, G3}. Therefore, to compute the matrix $B$, we label the nodes $v_1, v_2$ and $v_3$ as 1, 2 and 2, respectively. Moreover, since bus 4 is connected to bus 1 through a transformer, an operational constraint is given to the edge $e_1$; thus, the node $v_4$ will be assigned to the same island as node $v_2$, i.e. the label associated with the node $v_i$ will be 1. Similar conclusion is drawn for nodes $v_7$ and $v_9$.

By implementing the previous operational constraints (transformer cannot be disconnected to create electrical islands), it can be noticed that the searching area is reduced from the entire power system to a single area which is shown in Fig. 4. Considering the case of two islands and the coherent groups of generators previously mentioned, it can be noticed that there are three nodes ($v_3, v_6$ and $v_9$) that can be assigned to Island 1 or 2.

Fig. 4. Reduced searching area for the IEEE 9-bus test system.

We compute matrix $B$ and eight possible combinations are obtained (see (7)). We then use (7) and the incidence matrix $M$ (not shown in this paper) to create the matrix $C$.

We then use the obtained matrix $C$ to evaluate whether the cutsets included in $C$ are suitable or not. We compute the
rank of the digraph induced by each cutset and we notice that the node \( v_6 \) must be labeled 2. Therefore, the matrix \( C \) with suitable islanding solutions is found to be as in (8). The area in the system with suitable solutions is shown in Fig. 5.

We then compute the row vector \( w \) which contains in the \( k \)-th row the weight factor associated with the edge \( e_k \):

\[
w = \begin{bmatrix}
    w_1 & 71.6 \\
    w_2 & 40.8 \\
    w_3 & 85.5 \\
    w_4 & 163.0 \\
    w_5 & 76.2 \\
    w_6 & 24.1 \\
    w_7 & 85.0 \\
    w_8 & 60.2 \\
    w_9 & 30.6
\end{bmatrix}
\]

By using the vector \( w \), we then compute the value of the cut for each cutset shown in (8). As mentioned above, the final islanding solution depends on the objective function.

We use the matrix \( C \) and the vector \( w \) for minimal power imbalance. Therefore, the value of the cut for minimal power imbalance for each possible cutset is:

\[
cut(MPI) = \begin{bmatrix} 145.7 \\ 54.9 \\ 19.4 \\ 71.4 \end{bmatrix}
\]

As noticed, the first cutset, i.e. \( \{e_3, e_8\} \), produces a load-generation imbalance of 145.7 MW in each island. We conclude from (10) that the optimal islanding solution is represented by the edges \( \{e_2, e_6\} \) and it produces a power imbalance of 19.4 MW in each island.

The runtime of the methodology for this scenario was less than 0.5 ms. Fig. 6 shows the two electrical islands for minimal power imbalance.

We use the proposed methodology to determine the optimal islanding solution for minimal power flow disruption. We create the matrix \( C \) and use the vector \( w \) to compute the value of the cut for each cutset. The power flow disruption induced by each cutset is shown (11).

The methodology finds that the cutset that produces minimal power flow disruption is across the edges \( \{e_3, e_8\} \). After approximately 0.5 ms, the two islands created for minimal power flow disruption (see Fig. 7) are found to be represented by the subsets \( V_1 = \{v_1,v_4\} \) and \( V_2 = \{v_2,v_3,v_5,v_6, v_7,v_8,v_9\} \).

\[
cut(MPFD) = \begin{bmatrix} 145.7 \\ 116.1 \\ 101.0 \\ 71.4 \end{bmatrix}
\]

As noticed, the first cutset, i.e. \( \{e_3, e_8\} \), produces a load-generation imbalance of 145.7 MW in each island. We conclude from (10) that the optimal islanding solution is represented by the edges \( \{e_2, e_6\} \) and it produces a power imbalance of 19.4 MW in each island.

The runtime of the methodology for this scenario was less than 0.5 ms. Fig. 6 shows the two electrical islands for minimal power imbalance.

The simulations shown above demonstrate the effectiveness of the proposed methodology and clearly demonstrate that different objective functions can be used using our new approach. Moreover, they show that different objective function produces different islanding solution. The methodology is more flexible than the existing methods in
the sense that system operators can change the criteria to find islanding solution based on experience and operational features, for example, different load levels.

This paper presents results on a small test system and the results clearly demonstrate the efficiency and the potential benefits of the proposed methodology. Further studies in large-scale system must be carried out. In comparison to existing methods, we found that our approach identifies similar results. For example, the islanding solution shown in Fig. 6 is similar to that one obtained with the OBDD-based method [8], [9] and the solution shown in Fig. 7 is similar to the solution achieved using the method introduced in [11].

IV. CONCLUSIONS AND FUTURE WORK

This paper presents a novel controlled islanding methodology that is computationally efficient and determines a set of suitable islanding solutions to be used for the purpose of intentional controlled islanding. In comparison to existing approaches, the methodology presents the significant advantage that it can find an optimal islanding solution for minimal power imbalance or minimal power flow disruption while ensuring that only coherent generators are in each island. This important advantage allows system operators to change the objective function based on system operating points and experience. The methodology considers the inherent topology of the network to find multiple islanding solutions. The optimal islanding solution, for any of the objective function, is then evaluated in the last step of the methodology. The proposed methodology was illustrated using the IEEE 9-bus test system. Simulations results demonstrate the efficiency and effectiveness of the new approach on small test systems. We are now planning to test and evaluate the performance of the new methodology on large-scale power systems.

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VI. REFERENCES


