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Intentional Islanding Methods as Post Fault Remedial Action: A Review

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ABSTRACT

Intentional islanding is the last defense mechanism executed to avoid cascading failures and total blackout in power system network during severe or critical contingency. It is performed when other mitigation techniques are unable to save the network from collapse. Intentional islanding is preferred compared to unintentional islanding, which produces unstable islands. The objective of intentional islanding is to split the network by disconnecting appropriate transmission lines to produce electrically stable and balanced islands. There are many methods suggested by previous researchers on intentional islanding. This paper presents a comprehensive review on various intentional islanding methods proposed based on the common objective function used which are minimal power imbalance and minimal power flow disruption. The paper focuses on five intentional islanding methods which are analytical, numerical, heuristic, meta-heuristic and hybrid approaches. This review paper will serve as guideline and reference for researchers to explore further in this topic of interest.

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1. INTRODUCTION

Power system security is vital in power system operation and design in order to ensure constant and consistent availability of electricity supply. The power system security can be defined as the ability of the system to operate normally and reliably during any contingencies. Meanwhile, contingency refers to an act of losing one or two important components (such as generators, transmission lines or transformers) or sudden increase in loads caused by any failures or outages [1]. Power system networks are designed with N-1, N-2 or N-1-1 contingency. This is required for the network to operate in such a way that reliable power is delivered during single component outage (N-1), two components outage (N-2) or sequence outages (N-1-1) at a time. However, certain severe outages could violate the N-1, N-2 or N-1-1 contingency criterion, which will lead to system instability and system collapse. Generally, there are five operating states of an electric power system [2]:

a) Normal state - All system constraints are within sufficient level of stability margins to supply electricity to consumers continuously. The system is able to withstand any contingency to ensure continuous supply to the consumers.
b) Alert state - The system enters into insufficient level of stability margin as some system constraints are violated due to occurrence of contingency events. Power is still supplied to consumers. Preventive actions

have to be executed to return the system back to normal state. If preventive actions are not executed, the system will enter emergency or *in extremis* state.

c) Emergency state - This state takes place due to the contingency events occurring in alert state. System is still intact and power is supplied to the consumer. Emergency control actions need to be executed to return the system to normal state or at least to alert state. If these actions are not taken in time, it will cause the system to enter *in extremis* state. Load shedding, transmission line tripping or transformer generating unit disconnections are the corrective actions taken to avoid the system to enter *in extremis* state.
d) In extremis state - Most of the area in the system will face absence of power supply due to partial or complete blackout. Any possible remedial or control action should be executed to reduce cascading failure in order to avoid extensive damage.
e) Restorative state - Appropriate control actions need to be executed to restore and reconnect the system back to the normal operating condition. The system will return to the normal state or alert state depending on the conditions of the system.

It is essential to ensure that power system network is operating in a normal state at all times. Nevertheless, severe disturbances or outages caused by factors such as natural disaster, equipment failure, equipment malfunction, human errors, modern power systems that are operated closer to limits can introduce many problems to the network. Worst still, it can even cause instability problems to the network. These outages can trigger cascading failures that eventually result in partial or total blackout of the system.

Severe blackout cases discussed in [3]-[5] were caused by the cascading events which is initiated by single or multiple events. It is observed that millions of customers are affected due to the blackouts occurred in Italy [6], Sweden/Denmark [3] and USA/Canada [7] in 2003. In 2006 [8], the cascading event due to the severe disturbance in UCTE system caused the system to split automatically, forming three islands.

Proper remedial actions such as protective devices tripping, load shedding scheme, generator rescheduling or re-dispatch are carried out during contingency events to avoid the cascading failure to spread. These steps are also executed to aid the system to operate in the normal operating state. In some cases, the remedial actions are not able to save the network from collapse. Therefore, intentional islanding is the best option. This is implemented to avoid an unintentional islanding (automatic islanding) that happens due to some transmission lines which are tripped by the local relays during cascading failure. Worst still, unbalanced electrical islands are always produced in unintentional islanding scenarios. Therefore, many researchers have proposed several methods on intentional islanding technique which will be the main focus in this paper.

The paper is organized as follows: transmission line and intentional islanding are reviewed in Section 2. Details elaborations on intentional islanding methods are discussed in Section 3. Discussion about the improvements on intentional islanding is reviewed in Section 4. Finally, conclusion for this paper is carried out in Section 5.

2. TRANSMISSION LINE AND INTENTIONAL ISLANDING

One of the important element in national and global infrastructure is electrical power transmission systems [9]-[10]. Failure of these systems due to blackouts may lead to many direct and indirect effects that are significant towards the economy and national growth. Transmission lines and transformers are protected by protective devices such as relays and circuit breakers. Occurrences of faults or outages in the transmission lines may cause the lines to be tripped open when the permissible limits are exceeded. Transmission lines are tripped open to avoid further damage to the equipment and machines as well as to avoid any instability problem in the network. However, overloading issues might occur to other lines that shares a common bus. This will cause other lines to be overloaded and subsequently tripped by their respective protective device. This will lead to cascading failures in the network. Cascading failure can spread through the system within seconds and can result into severe load and generation imbalance. Total system blackout is the worst effect of cascading failures.

Several studies on large blackout events concluded that intentional islanding (also known as network splitting) as an emergency control action to prevent wide-area blackout. Intentional islanding is executed to partition the system into islands. The objective of intentional islanding is to disconnect the corresponding transmission lines to form balanced and stable islands. However, intentional islanding is considered challenging as the search space for cutsets grows continuously as the network size increases. Besides, the dynamic nature of the power system network which poses a challenge to researchers to determine the best splitting points in the network leading to a stable islands.

There are a number of methods for intentional islanding proposed by the previous researchers. This paper will review the methods and concepts used in intentional islanding technique. The methods used can be divided into five categories which are analytical, numerical, heuristic, meta-heuristic and hybrid approaches. Figure 1 illustrates an overall view of intentional islanding methods that are reviewed in this paper. There are two common objective functions used to select the best cutset which are minimal power imbalance and minimal power flow disruption. Minimal power imbalance as an objective function emphasizes on small tolerance between the generation and load in the islands. The objective function focuses to lessen the quantity of load that must be shed after system splitting. On the other hand, minimal power flow disruption minimizes the change in network topology during islanding execution. Apart from this, islanding solution must satisfy specific stability constraints to produce stable islands during splitting such as generation load balance, generator coherency, thermal limits, voltage stability, transient stability and frequency stability. Methods reviewed in this paper can be classified according to objective functions used to produce stable and balanced islands as shown in Table 1.

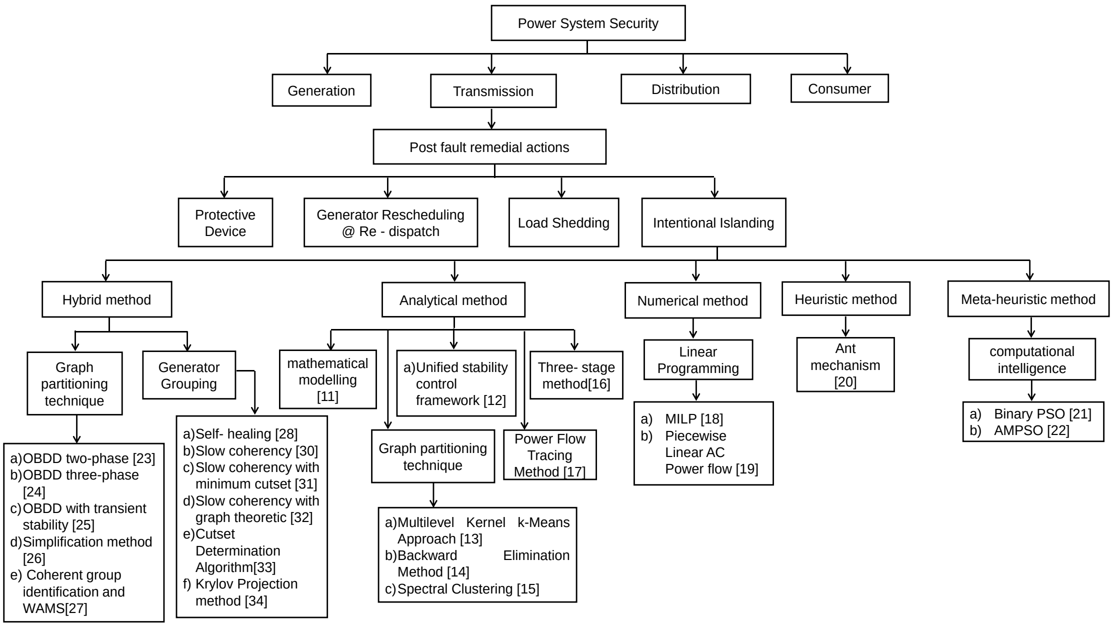


Figure 1. General overview of intentional islanding methods

Table 1. Objective Function used in the Reviewed Methods

Group	Methods		Objective Function
Analytical Method		Mathematical modelling [11]	Minimal power imbalance
		Unified stability control framework [12]	Minimal power imbalance
		Three- stage method [16]	Minimal power flow disruption
		Power Flow Tracing Method [17]	Minimal power imbalance
	Generator Partitioning Technique	Multilevel Kernel k-Means Approach [13]	Minimal power flow disruption
		Backward Elimination Method [14]	Minimal power imbalance
		Spectral Clustering [15]	Minimal power flow disruption
Numerical Method	Linear Programming	MILP [18]	Minimal power imbalance
		Piecewise Linear AC Power flow [19]	Minimal power imbalance
Heuristic Method		Ant mechanism [20]	Minimal power imbalance
Meta-Heuristic Method	Computational intelligence	Binary PSO [21]	Minimal power imbalance
		AMPSO [22]	Minimal power imbalance
Hybrid Method	Graph partitioning technique	OBDD two-phase [23]	Minimal power imbalance
		OBDD three-phase [24]	Minimal power imbalance
		OBDD with transient stability [25]	Minimal power imbalance
		Simplification method [26]	Minimal power imbalance
		Coherent group identification and WAMS[27]	Minimal power flow disruption
	Generator grouping	Self- healing [28]	Minimal power imbalance
		Slow coherency [30]	Minimal power imbalance
		Slow coherency with minimum cutset [31]	Minimal power imbalance
		Slow coherency with graph theoretic [32]	Minimal power flow disruption
		Cutset Determination Algorithm[33]	Minimal power imbalance
		Krylov projection method [34]	Minimal power imbalance

3. INTENTIONAL ISLANDING METHODS

In this section, the five categories of intentional islanding methods will be explained and elaborated.

3.1. Analytical Approach

In general, the analytical method uses step by step procedure (analysis) or constructs mathematical models and algorithms to search for an optimal solution. The following outlines some examples of this approach.

3.1.1. Mathematical Modelling

The author in [11] introduces a controlled islanding approach to avoid the blackout in Bangladesh Power Development Board (BPDB) system. The BPDB system can produce two to five stand-alone islands depending on the location and severity of the fault. In this method, a mathematical model representing the number of buses in power system with the synchronous generator is programmed using Microsoft FORTAN 77 software. The intersection lines among the number of islands are the cutset for islands formation. Microprocessors are installed at both ends of the intersection lines to monitor the response of these intersections lines in real time. In the event that recorded flow (active power) exceeds the threshold value of 15% at both ends of an intersection line, this line will be disconnected to island the system. Apart from that, load shedding is carried out if it is required to maintain the power balance in any of the islands.

3.1.2. Unified Stability Control Framework Method

Network splitting method proposed in [12] is more efficient for complex oscillation scenarios such as multiple generators outages or multiple lines outages. In this method, a unified decision-making mechanism is modelled to evaluate and compare intentional islanding execution with different control measures (such as generator shedding, fast valving, load shedding) for given possible contingencies scenarios. Possible contingencies are selected based on the most critical scenarios that can contribute to system instability problem in which emergency control actions need to be executed. Therefore, intentional islanding is only executed when it is required. The main algorithms for network splitting strategy used in this method are explained as follow:

a. Use heuristic method to find the splitting strategy
b. Perform transient stability analysis (T-D program), adjust complementary-cluster center-of-inertia relative motion (CCCOI-RM) mapping in each island, and compute the equivalent stability margins.
c. Execute splitting strategy if the stability margin becomes suitable in each island
d. Or else, additional control measures (generator shedding, fast valving, load shedding) will be proposed by the additional control designer.

3.1.3. Graph Partitioning Method

Graph partitioning methods uses graph theory to represent the power system network. Author in [13] introduced an algorithm using Multilevel Kernel k- Means approach for intentional islanding scheme of large power system network. This approach consists of three phases which are aggregation, partitioning and retrieval. In phase 1, the original network is reduced to a smaller size based on predetermined rules and assumptions. Then, graph partitioning is executed and the network is reduced in phase 2. In phase 3, the retrieval process is performed using Kernel k-Means algorithm. The phases involved in Multilevel Kernel k- Means approach is shown in Figure 2.

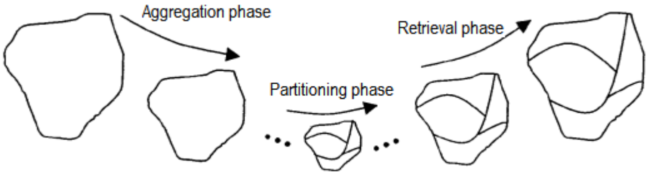


Figure 2. Phases of multilevel approach

In [14], islanding strategy for bulk power system network during severe disturbances is proposed. This approach uses slow coherency based aggregation to group the coherent generators. Graph simplification technique is also used to reduce the huge search space of splitting strategy. Backward Elimination Method (BEM) is then applied to the simplified network to obtain all the appropriate islanding solution. Evaluation of the steady state stability of the proposed islands is executed using Newton Raphson power flow technique and Q-V modal analysis. Finally, minimization of generation-load imbalance is taken into account together with the number of isolated bus, acceptable voltage range and static voltage stability using Binary Imperialistic Competitive Algorithm (BICA).

The author in [15] introduce a two-step controlled islanding algorithm to find a suitable islanding solution to avoid the initiation of wide area blackouts caused by un-damped electromechanical oscillations. Minimal power flow disruption is used as the objective function in this algorithm. In the first step of this approach, the coherent generators are grouped using normalized spectral clustering based on their dynamic models. In the second step, the islanding solution which fulfils the objective function and the constraints is determined by grouping all nodes with their desired coherent groups using constrained spectral clustering.

3.1.4. Three- Stage Method

A three- stage method of intentional controlled islanding is presented in [16] to determine the best islanding cutsets considering minimal power imbalance or minimal power disruption. The first stage of the method introduces a self- adaptive graph simplification which can determine the possible islanding cutset search area and form a two-terminal graph model. Then, an islanding cutset search algorithm (improved recursive merge algorithm) considering the weighted model is developed and used to determine all the islanding cutsets. In this stage, minimal power disruption is used as the objective function. Finally, islanding checking scheme algorithm is developed based on depth first search algorithm to verify the islanding cutsets found in second stage. The algorithm will only select the islanding cutset if more than one branch exists in each island and any PV bus is found in the island. This checking process is important to avoid any low voltage problems in the islands formed after intentional islanding execution.

3.1.5. Power Flow Tracing Method

Another technique for intentional islanding based on power flow tracing method is introduced in [17]. This technique is executed in three phases. In phase one, the domain of each generator is identified based on the power flow tracing algorithm. Each load buses are connected to the desired generator bus and this forms the domain of the appropriate generator bus. Then, an initial splitting boundary is primarily determined according to the generator's grouping information in phase two. Finally, the actual splitting point is found by refining the initial splitting point in phase three.

3.2. Numerical Approach

Numerical approach uses mathematical tool such as linear programming to solve numerical problems and complex problems. It provides approximate solutions with minimal numerical errors. The following outlines some examples of this approach.

3.2.1. Linear Programming Method

In [18], an optimization based technique is introduced for controlled islanding solution and load shedding. In this approach, Mixed Integer Linear Programming (MILP) is used to create a suitable islanding solution by isolating the affected area from the network via transmission lines disconnection, load shedding and generator switching while maximizing load supply. MILP technique used in this approach is executed in two stages. First, a DC feasible solution is determined using DC power flow equations. Then, an AC optimal load shedding optimization is used to find an AC-feasible operating point. This approach produces balanced and steady-state feasible DC islands for controlled islanding solution.

In [19], controlled islanding solution is found using piecewise linear model of AC power flow. In this method, the voltage and reactive power constraints are considered when designing the islands. Then, MILP method in [18] is used to find feasible islanding solutions. The author takes into account the reactive power constraint based on the fact that local shortage of reactive power can lead to irregular voltage problems in certain areas of the network.

3.3. Heuristic Approach

Heuristic approach uses any practical method to solve problems that are sufficient for the immediate goals even though it does not guarantee optimal solution. Some of the researchers use trial and error method to find a feasible solution to solve the problem. The following outlines some examples of this approach.

3.3.1. Ant Search Mechanism

The author in [20] proposed a probabilistic search algorithm named ant search mechanism to find an appropriate intentional islanding strategy. In this method, searching islanding scenarios begins simultaneously and in parallel with the randomly chosen initial points. These initial points represent the total number of desired islands that are being formed during an intentional islanding strategy. Generation-load balance and line loading violation are the islanding constraints that are highlighted in this approach. The method utilizes linear programming and DC load flow.

3.4. Meta-Heuristic Approach

Meta- heuristic approach is a high level problem independent (do not requires special knowledge) that is used to guide other heuristics method for a better solution in the search space.

3.4.1. Computational Intelligence

In [21], computational intelligence technique based on binary particle swarm optimization is used to find an efficient splitting solutions directly from a large scale power system network. The optimization uses fitness function by taking into accounts the real power balance between generations and loads on each island. The priorities of important loads and the desired number of islands required during islanding are also considered. Appropriate load shedding scheme is also integrated in the algorithm as well.

This technique is improved in [22], as the author proposed an optimization intelligent technique based on Angle Modulated Particle Swarm Optimization (AMPSO). In this approach, slow coherency technique is used to determine the desired groups of coherent generators. Then, AMPSO is carried out by optimizing the fitness function that emphasizes on the generation and load balance and recognize the required generator grouping. AMPSO is more efficient compared to Binary PSO [21] because this algorithm avoids fluctuations of high dimensional bit vector and discretization process.

3.5. Hybrid Approach

Hybrid approach is a combination of two or more computational techniques to obtain better result and improve data analysis. Following are the examples of methods which uses this approach.

3.5.1. Graph Partitioning Method

The author in [23] proposes a two phase method to find proper splitting strategies. This method uses analytical and heuristic approach to obtain the splitting strategies. In the first phase, the search space is reduced utilizing OBDD-based calculation on a node-weighted graph model. In the second phase, proper splitting strategies are found through power-flow analysis in the reduced search space. Three steady state constraints are considered in this method for successful system separation. They are

a. All synchronous generators must be on the same island (Separation and synchronization constraint or SSC);
b. Active power generation and loads are balanced in each island (power balance constraint or PBC) and
c. Transmission lines and transmission services must not be overloaded above their limits (rated value and limit constraints or RLC).

Symbolic Model Verifier (SMV) model checker is selected to carry out the simulations on the purposed method. Figure 3 shows a general overview of the two phase OBDD method.

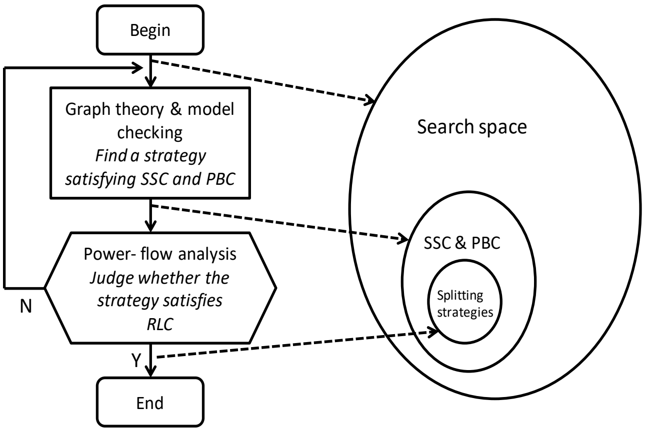


Figure 3. Methodology of OBDD two phase in [23]

This method is improved in [24], and the three phase OBDD method is introduced to find a proper splitting scheme for the large scale power system. In phase 1, the original large scale power system is simplified using graph theory by:

a. Reducing irrelevant nodes(bus) and edges(transmission lines)
b. Combining relevant nodes based on their areas.

In phase 2, the OBDD method is used to narrow the search space. Finally in phase three, DC power flow calculation is carried out to find appropriate splitting strategies. The steady state constraints that are considered in [24] are similar to [23]. BuDDy package (v2.0) software is selected to run the simulations on the proposed method. Figure 4 illustrates a general overview of the three phase OBDD method.

It is known that different splitting strategies would give different level of power flow disturbances. In general, controlled power system can maintain its stability with small disturbances. Therefore, in [25] threshold value constraint (TVC) is introduced to restrict the degrees of the allowable disturbances caused by proper splitting strategies. TVC is selected offline and checked with the random selection of splitting strategies. In the event that threshold value exists, transient simulations can discover whether they are feasible splitting strategies or not. Based on the TVC, possible splitting strategies that produce stable islands can be determined from the OBDD based splitting strategies [23], [24].

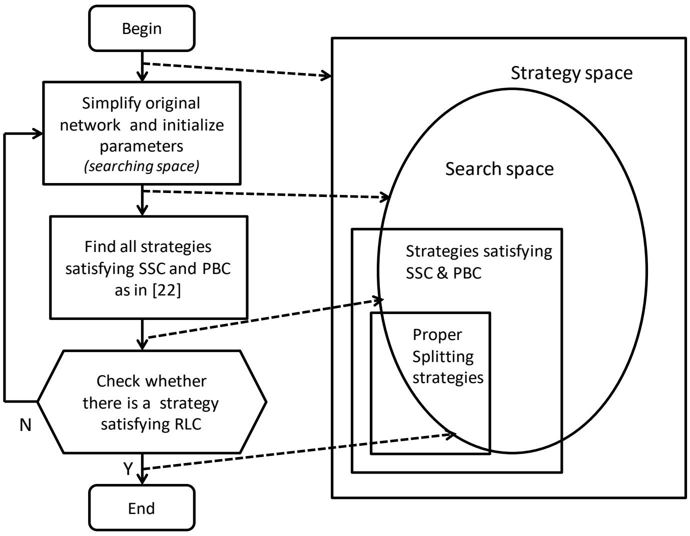


Figure 4. Methodology of OBDD three phase in [24]

The author in [26] enhances the reduction technique of OBDD method in [23], [24] by investigating the physical connection and electrical distance of the nodes, the loading condition of the lines and topological characteristics of original power network. These steps are carried out to produce a simplified network. This network is much smaller in scale than the original one but it still maintains the static and dynamic characteristics of the original system. In this approach, major portion of topology analysis and calculation are done offline as the power system network topology does not change frequently.

Another islanding method based on coherent group identification and wide area measurements is presented in [27]. Firstly, this method combine four indexes including angle deviation similarity, swing direction similarity, rotating speed deviation similarity, and corner deviation similarity into a synthesized index using entropy weight theory that consider most of the characteristics of generator trajectories during the determination of the coherent generators groups. The clustering dendrograms is used to classifying the coherent groups of generators. Then, the optimization model based on minimal cutset method with minimal power flow disruption as its objective function is developed. The optimization model will determined the optimal cutsets for the controlled islanding scheme by considering the coherent groups of generators found previously.

3.5.2. Generator Grouping Method

In [28], the author proposed a self-healing scheme which will be executed when catastrophic events occur in a power system network. The first step executed in this approach is to group the coherent generators in each island using slow coherency method [29]. Then, a computer program is used to find an optimal splitting point that considers the least generation-load imbalance in the islands formed. A new two-level load shedding scheme introduced in this approach improves the stability performance of the system by shedding less load compared to the conventional load shedding scheme.

The author in [30] proposed an intentional islanding scheme based on slow coherency determination. This method includes a procedure to group and determine the weakest connection in the network based on coherency grouping. A slow coherency method based on two-time-scale theory is employed. In this method, two assumptions are made:

a. the groups of coherent generators are independent of the size of the disturbance
b. the coherent groups are independent of the level of detail applied in modelling the generating unit.

Using brute force search, this method determines the islands based on boundary topology conditions with generation and load imbalance information.

The method in [31] introduces a new approach on slow coherency grouping using minimal flow and minimal cutsets. This method uses concept of minimal cutsets to form islands with minimal net flow via two phases:

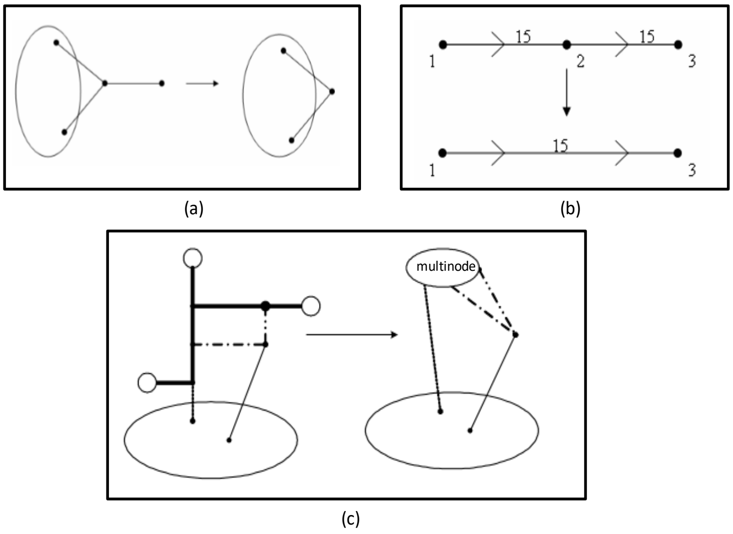
a. Find minimal cutsets
b. Acquire optimal minimal cutset fulfilled by various criterion such as generator coherency, minimal power imbalance and quick system restoration

In this method, an automatic islanding program is proposed to automatically determine the best point to create the islands. Minimal cutsets and breadth first searching (BFS) flag based on depth first searching (DFS) technique is used in the graph theory to implement this approach. The crucial requirement of this approach is the real power imbalance in each island.

In [32], the author used the graphic theoretic technique to reduce the large scale power system network into smaller scale network considering an optimal solutions. Three types of simplifications used are the vertices removal of degree one nodes, contract energy conserving vertices of degree two and tree node collapsing as shown in Figure 5. The reduced network is then segmented into necessary sub-networks considering minimum generation and load imbalance using a multi-level recursive bisection graph partition method with minimal net flow. The graphic theoretic technique is divided into two elements:

a. A graph simplification method based on the characteristic of the graph formed based on the power system
b. Multi-level graph partitioning method to work out on the graph partitioning problem.
c. This method shows that the recommended of simplification rules can reduce the original network to a smaller size and finally lessen the computational burden during islanding execution.

A method in [33] introduces an integrated algorithm based on slow coherency method to find the best splitting point for large power system network. Graph theory is used to represent the large power system network. Simplification method used in this method are parallel lines equivalence, removal of degree one nodes, removal of degree two nodes, removal of step-up transformer and removal of closed loops. Apart from that, tree collapse procedure is used to determine the cutset which guarantees that generators of the same coherent groups are located in the same island. Slow coherency approach is used for this purpose. Overall, this approach takes into consideration of the physical connection of the power system network for a better solution. Some of the simplification methods are shown in Figure 6.

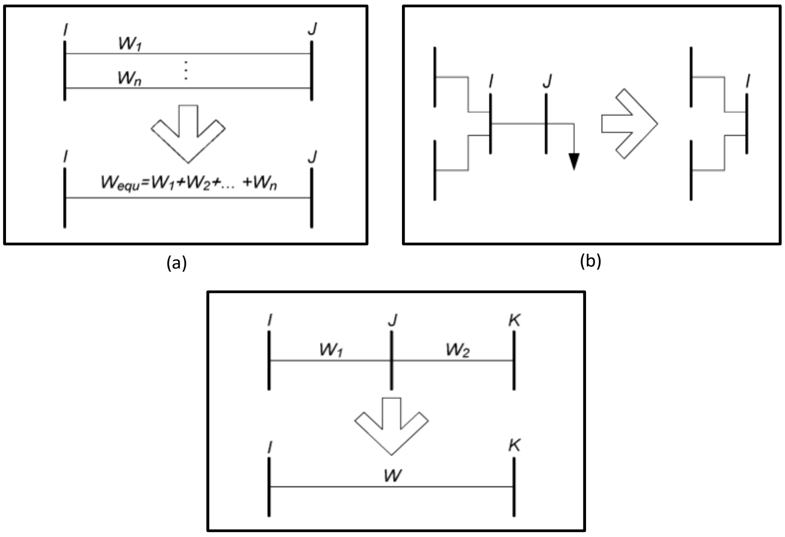


(a) (b)

(c)

Figure 5. Simplification method used in [32] : (a) remove vertices of degree one, (b) contract energy conserving vertices of degree two and (c) tree node collapsing

Authors in [34] proposed Krylov projection method to group the generators and buses in different coherent groups as primary islanding scheme in the first step. In the second step, minimum spanning tree based on breadth first search (BFS) algorithm is used to balance and reduce the net flow between the islands tie lines during splitting execution. This method considers both steady state and dynamic constraints. This algorithm is applied when instability of the system is detected due to any outage and the interrupted line is removed.



(a) (b)

(c)

Figure 6. Simplification method used in [33] : (a) parallel line equivalent, (b) removal of degree one node (c) removal of degree two nod

4. DISCUSSION ON INTENTIONAL ISLANDING METHODS

It is observed that methods reviewed in this paper do not carry out appropriate contingency analysis to determine the critical lines which can initiate the cascading failure. This is important because occurrences of outages are uncertain and not all outages lead towards cascading failures and blackout scenarios. Therefore, highlighting the critical lines and providing its intentional islanding solution within some specified time interval continuously might help the power system operation to avoid severe cascading events in future. Other than that, discrete optimization with robust mutation technique can be used in future research for this topic. It is expected that robust mutation technique using discrete value will speed up the convergence process and can produce optimal intentional islanding solution.

5. CONCLUSION

tabtableThis paper reviewed numerous methods proposed by previous researchers on intentional islanding solution. The basic concepts and objective function used in each method have been described in detail.

The two common objective functions used to find the best intentional islanding solution are minimal power imbalance and minimal power flow disruption. The intentional islanding methods can be classified into five groups which are analytical, numerical, heuristic, meta-heuristic or hybrid approach. All methods have their own concepts and assumptions in order to determine the best intentional islanding solution. Methods reviewed in this paper can be improved and analysed for better intentional islanding solution in future.

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