نهمین کنفرانس بین المللی
توسعه فناوری در مهندسی برق
9th International Conference on
Technology Development in Iranian Electrical Engineering

# Controlled Intelligent Islanding of Power System: Concept, Methods, and Applications

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**ABSTRACT**

Recent blackouts have shown that the power system is greatly vulnerable to high-risk disturbances. While the power systems seem more reliable than before, wide area cascading outages frequently occur. In this paper, a comprehensive literature survey on the theory, development, and application of controlled islanding in power systems against wide area blackouts is provided. Several implemented methods for different stages of islanding schemes, including where, when, how, and what to do, are reviewed thoroughly. The concept of intelligent controlled islanding based on WAMPAC (Wide Area Monitoring, Protection and Control) structure to form islands in the power system is also highlighted aiming at establishing an adaptive optimal scheme.

**Keywords:** wide area blackout, cascading outages, controlled islanding, intelligent islanding, WAMPAC

## 1. INTRODUCTION

The incidents of recent blackouts, which are mainly the result of uncontrolled widespread outages, reveal the fact that cascading failures are frequently occurring across the power system [1-7]. There are many reasons for cascading outage initiation, such as weather conditions, outage of major components, failure of control and protection systems, improper alarm systems, power system instability and human errors [7-12]. The operation of power systems close to security limits imposed by power market competition, economic and environmental constraints make these systems more vulnerable to large disturbance [13-14]. Successive unpredictable outage of equipment under stressed condition for a very short period of time makes the prediction and prevention of cascading failures a challenging task [12-16].

Meanwhile, it has been proved that the conventional SIPS (system Integrity protection system) installed in the form of SPS (special protection system) or RAS (remedial action systems) are unable to keep the system integrity at all unpredicted and complicated disturbances [1-13]. Therefore, controlled islanding of the power system is considered as the last automatic protection action designed to prevent disturbance propagation and wide area blackouts. One solution is to separate interconnected power system into stable self-healing islands to cease instability propagation and to save system from uncontrolled separation [17-21].

Moreover, recent advances in synchronized measurement technology make it possible to have wide information of the whole system [22-23]. These real-time data give the ability to assess the wide-area stability and to perform the islanding process more effectively [23-24].

In this paper, the necessity of adopting a practical design for controlled islanding is verified through a brief investigation of recent blackouts. The main steps in the proposed islanding design are thoroughly discussed considering different constraints. The distinct applied methods are reviewed comprehensively and their performance and effectiveness are demonstrated. Finally, the advantage of an intelligent islanding concept based on WAMPAC structure is indicated.

## 2. MOTIVATION FOR CONTROLLED ISLANDING

Power system disturbances have a progressive behavior to spread into the whole network through weak interconnected lines [25-26]. Mis operation of local relays in tripping healthy equipment under stressed conditions and failure of system controllers such as automatic generation control (AGC) may accelerate the initiation of cascading outages [27-29]. Some major blackouts around the world, listed in Table 1, show the lack of an ultimate preventive plan [1-10].

**Table 1.** *Recent major blackouts around the world*

| Location | Date | Scale | Collapsed time | Restoration time |
|---|---|---|---|---|
| 1. US-West [1-2] | 7/2/1996 | 11.8 GW | 36 sec | Several hours |
| 2. US-West [2-3] | 8/10/1996 | 30.5 GW | >6 min | Up to 9 hours |
| 3. Brazil [4] | 3/11/1999 | 25 GW | 30 sec | Up to 4 hours |
| 4. Iran [5] | 2/20/2001 | 35 GW | >15 min | Several hours |
| 5. North US [6] | 8/14/2003 | 11.8 GW | >1 hour | Up to 4 days |
| 6. Italy [7] | 9/28/2003 | 27.7 GW | 27 min | Up to 19 hours |
| 7. UCTE [8] | 11/4/2006 | - GW | - | Up to 2 hours |
| 8. India [9] | 7/30/2012 | 36GW | - | Up to 16 hours |
| 9. India [9] | 7/31/2012 | 48GW | - | Up to 8 hours |
| 10 Pakistan [10] | 2/25/2013 | >30 GW | - | Several hours |

In July 1996, in WSCC, a number of critical lines and generation units were successively tripped following an initial short circuit fault [1-2]. Then, the network split into five uncontrolled electrical islands with considerable load and generation outage and finally a blackout occurred in southern Idaho. In 2001, in Iran, a preliminary line fault initiated the outage of several interconnected tie-lines because of circuit breaker failure [5]. The overload and unstable power swings led to tripping the rest of the tie-lines and system splitting. Finally, the uncontrolled constructed islands were collapsed due to generator outages and insufficient under frequency load shedding in different areas [5]. The 2003 NERC blackout is another example, where the initial disturbance become a wide-area instability problem. The initial outage due to deficiency of reactive power led to voltage collapse and then wide-area cascading outage resulted in different forms of rotor, frequency and voltage instability [6, 11].

These events show that blackouts are complicated phenomena and may not be avoided by the present corrective actions or load shedding [1-8]. Therefore, controlled islanding should be taken into consideration as the last effective defense plan to keep the system integrity. The network is separated at proper locations and time to reach stable islands that may be interconnected together as soon as possible [30-32]. Basically, the main reasons for performing the controlled islanding scheme in power systems can be summarized as follows [30-36]:

1) Preventing widespread cascading outage,
2) Avoiding the spread of local disturbances that may cause global instability,
3) Isolating the faulted area from other areas to cope with disturbance propagation,
4) Forming stable islands that can be reconnected as soon as possible.

In order to design a practical islanding scheme, the following main questions should be responded to:

a) In which locations islanding should be performed?
b) When should the islanding be executed?
c) How to perform controlled islanding?
d) What should be done in the islands?

## 3. DETERMINING THE POINTS OF ISLANDING

To perform islanding scheme and to split large interconnected networks to self-healing islands, several transmission lines should be disconnected at suitable locations [30-40].

### 3.1 Islanding criteria

To have stable islands for both transient and steady state frames, several static and dynamic criteria must be satisfied, which are given as follows;

a) Active power balance
Normally, minimizing the active power mismatch between the load and the generation in each island is the first criterion in boundary determination [30-38].

b) Equipment loading
The loading of power system components such as transmission lines and transformers should meets steady-state stability limits [31-40].

c) Transient stability
The synchronism of generators in each island must be guaranteed [30-33]. The generators in each island should be also in the same coherent group at the time of islanding [33-35].

d) Voltage magnitude
The voltage magnitude of all buses must be in the acceptable range to avoid the islanding collapse [37-38]. Therefore, the static and dynamic reactive power capability of the islands should be considered [39].

e) Restoration criteria
Because of the blackout possibility, there must be at least one black-start generator in each island to perform restoration [40]. It is not practical to consider all of the above-mentioned criteria together in one single objective function. However, a feasible solution can be reached by selecting some of these criteria [30-40].

### 3.2 Graph representation

The power system structure is composed of buses, loads, generators and transmission lines. It is convenient to model the power system as a weighted directed or undirected graph which consists of edges (lines) between nodes (buses) [32-38]. The graph representation has been applied extensively in power system studies such as coherency analysis, islanding design and restoration planning [41-43]. For the case of islanding scheme, the boundary determination is converted into finding a proper cut-set with respect to the objective function and constraints [31-37]. The cut-set consists of disconnected transmission lines to form islands.

### 3.3 Generator coherency

The initial concern to achieve a good islanding scheme is to ensure that the generators in each island belong to the same coherent group to satisfy transient stability constraint [30-36]. The time domain simulation [44], frequency domain [45-46], modal analysis [47], electrical distance [48], fuzzy [49] and slow coherency [50] approaches have been used to determine the generators coherency.

### 3.4 Determining islanding boundary

There are some methods to determine the location of controlled islanding boundary in large interconnected power systems. The slow coherency (S.C) graph based [50-57] and order binary decision diagram (OBDD) [58-63] are two main methods applied in many studies.

#### *3.4.1 S.C graph-based method*

In the S.C graph-based method, the objective is to minimize the active power imbalance considering the coherency of generators [50-56]. For coherency determination, the two-time scale concept has been adopted where the system with n states has r slow and n-r fast states [52-53]. The r slowest modes represent r slow coherency groups of generators. The S.C approach is based on the characteristics of the network structure and, therefore, the classical model of generators has been considered [51-52]. Also, the generators coherency is assumed to be independent of the size of disturbance magnitude and, therefore, a linear model is utilized [54-56].

**a) Network graph structure**

In the S.C method, after determining the coherent generators, the directed graph of the network is constructed [51]. Since the initial graph of a power system is normally large, the original graph is reduced to speed up finding a feasible solution. Then, all possible cut-sets to partition the network to the desirable islands are determined. The optimum solution is the cut-set with minimum load/generation imbalance and disconnected lines [50-55]. This method has been applied effectively in very large networks such as the WECC network [52]. The effectiveness of the S.C graph-based controlled islanding has been verified to avoid the 2003 NERC blackout [57].

**b) Graph partitioning**

The graph partitioning has been applied directly to split the graph-based structure of the power system into k islands. In k-way partitioning of the graph G = (V, E, W), in which |V| = n is the number of nodes, E and W are the edge set and edge weight respectively, V is divided into k disjoint subsets, V1, V2, …, Vk such that Vi∩Vj =ϕ; for i≠j, |Vi|=n/k (balanced constraint), and Ui Vi =V [64]. The objective is to minimize the sum of the edge weights of Ec (cut-set) whose incident nodes belong to different subsets. The objective function of graph partitioning into two islands is given as follows [64]:

$$min\ \ cut\ (\mathbf{V_1}, \mathbf{V_2}) = min \sum_{i \in \mathbf{V}_1, j \in \mathbf{V}_2} w_{ij} \tag{1}$$

where $w_{ij}$ is the edge weight [63]. The k-way partitioning, multilevel recursive bisection, multi-level kernel k-means, and spectral clustering are several popular methods used for graph partitioning [56, 64-67].

*3.4.2 Order binary decision diagram (OBDD)*

The OBDD method has been used in many islanding studies considering following constraints [58-63]:

- Asynchronous groups of generators should be separated (SSC)
- Active power balance constraint at each island should be satisfied (PBC)
- Loading of equipment at islands should be in the specified range (RLC)

Unlike the S.C method, the nodes weights are considered in OBDD by using balanced graph partition technique.

a) Balanced graph partition method

In undirected, connected and node-weighted graph **G (V, E, W)** considering $\mathbf{V_{GA}}$ and $\mathbf{V_{GB}}$ as two asynchronous groups, the problem is to find a subset of **E** as $\mathbf{E_c}$ to split the network into two connected sub-graphs $\mathbf{G_1}$ **(**$\mathbf{V_1}$**,** $\mathbf{E_1}$**,** $\mathbf{W_1}$**)** and $\mathbf{G_2}$ **(**$\mathbf{V_2}$**,** $\mathbf{E_2}$**,** $\mathbf{W_2}$**)** considering the following constraints [59]:

$$V_{GA} \square V_1,\ V_{GB} \square V_2 \ (\text{SSC}) \tag{2}$$

$$\left\|\sum_{v_k \in V_1} w_k\right\| \le d,\ \left\|\sum_{v_k \in V_2} w_k\right\| \le d \ (\text{PBC}) \tag{3}$$

where $w_k = P_G^k - P_L^k$ is the weight of vk which is the difference between injected active generation and active load power at bus k.

In the OBDD method, the node weighted graph model of the network is created with respect to generations and loads of the nodes. Then, the balanced graph partitioning algorithm is applied to find sub-graphs to satisfy PBC constraint. At the second phase, the loading of equipment constraint (RLC) at each sub-graph is investigated by performing load flow for islands [60-61]. In OBDD, all edges in the graph can be candidates to be removed and, therefore the problem is converted into an NP-complete problem, which is solved by the symbolic model verifier (SVM) tool [60]. The basic OBDD method is time-consuming and, therefore, to solve this drawback, the DC load flow is usually used to check the RLC constraint [59-60].

b) Three-step OBDD

To increase the efficiency of the OBDD approach while decreasing the computation time, a new initial phase was added. At this phase, the initial node weighted graph is reduced based on the graph theory and SSC consideration to accelerate the calculation for real-time application [60-61]. Parallel computation structure is also another way to increase the speed of computations [62].

c) Transient stability consideration

The transient stability of formed islands has not been addressed in OBDD method directly. To overcome this drawback, "Threshold Value Constraint (TVC)" as a new criterion has been applied to consider the severe effect of the disturbance with respect to loadings of disconnected lines before islanding [63]. It has been shown that with the TVC application, some of previous determined boundaries by OBDD method are not feasible anymore [63].

*3.4.3 Intelligent-based Algorithm*

There are some intelligent-based approaches that can be utilized to optimize the objective function of graph partitioning, such as genetic algorithm (GA), ant search, tabu search and particle swarm optimization (PSO) [68-71]. In these methods, the location of islanding is determined with respect to the assigned multi-objective function. In GA algorithm, the edge weighted graph corresponding to electrical distance is constructed based on Jacobian matrix [68]. To find the clusters (islands), the objective function consists of the electrical coherence index (ECI), between clusters connectedness index (BCI), clusters size, cluster connectedness and cluster count indexes [68]. In [69], ant search algorithm with probable mechanism is applied to graph partitioning considering static constraints including load/generation balance and lines loadings. In [71], the PSO evolutionary algorithm has been used to obtain proper (not optimal) sub-graphs with the purpose of maximizing the loading supply at each island. The main limitation of these methods is generators coherency. Also, because of random nature of these algorithms, the final solution may diverge or contain isolated buses.

In [72-73], the fuzzy C-mediod (FCMdd) algorithm is proposed for partitioning a large power system to coherent groups for dynamic vulnerability assessment. The performance of the FCMdd approach in network partitioning is demonstrated by fuzzy c-means algorithm in Hydro-Quebec power network. It is shown that the power system is partitioned efficiently with minimum cut-sets while the area-wise PMU configuration is obtained [73].

#### *3.4.4 Heuristic approaches*

In [74], a two-stage method that consists of mixed-integer linear programming (MILP) is proposed and load shedding minimization is performed. At the first step, the feasible solutions based on the MILP optimization framework are determined by using DC load flow. At the next step, to achieve a feasible AC solution, the new objective function based on AC load flow is utilized to minimize the load shedding for determined islands [74]. It has been shown that many feasible solutions using DC load flow may not be acceptable for AC load flow [75]. To overcome this drawback, the piecewise linear approximation of AC power flow is developed and is used for MILP formulation. Basically, minimizing load shedding is the main objective of these approaches [76-78]. In some power systems, islanding location choices are very limited and are obtained experimentally with respect to the simple network structure and previous occurred events [79-80].

### 3.5 Special consideration

There are two main objective functions to find a feasible boundary solution based on active power consideration as follows:

#### *3.5.1 Minimal power imbalance*

The objective here is to minimize the active power imbalance between active power of the load and generation at individual islands. The algebraic sum of active power flow in the weighted graph is accounted to minimize the amount of load or generation to be disconnected. This objective function is applied in the S.C graph-based method, OBDD and many other heuristic approaches [50-62]. The objective function used to form islands V1 and V2 based on graph V is:

$$\min_{\mathbf{V}_1,\mathbf{V}_2\in\mathbf{V}} \left| \sum_{i\in\mathbf{V}_1,\, j\in\mathbf{V}_2} P_{ij} \right| \tag{4}$$

#### *3.5.2 Minimal power flow disruption*

The objective here is to disconnect the lines with minimum power flow prior to network splitting without considering flow direction [40, 56, 81]. The advantage of this method is to minimize the power flow direction changes after islanding. This will help to avoid disconnection heavy loaded lines, which is possible in the minimal power imbalance method. Here, the objective function to form islands V1 and V2 from graph V is:

$$\min_{\mathbf{V}_1,\mathbf{V}_2\in\mathbf{V}} \sum_{i\in\mathbf{V}_1,\, j\in\mathbf{V}_2} \left| P_{ij} \right| \tag{5}$$

The main methods for determining the islanding locations are summarized in Table 2. As can be seen, in few studies, the reactive power criterion is considered, while the coherency analysis is ignored.

**Table 2.** *Applied methods for islanding locations*

| Ref. No | Applied Method | | | | | R.P | C.A | Active Power | |
|---|---|---|---|---|---|---|---|---|---|
| | S.C | OBDD | Intelligent | Heuristic | G.B.A | | | M.P.F | M.P.I |
| [18] | ✓ | - | ✓ | - | - | ✓ | - | - | - |
| [21] | ✓ | - | ✓ | - | ✓ | - | - | - | - |
| [30-32] | ✓ | - | ✓ | - | ✓ | - | - | - | - |
| [37-38] | ✓ | - | - | ✓ | ✓ | - | - | - | - |
| [40, 43] | - | ✓ | ✓ | - | ✓ | - | - | - | ✓ |
| [50-57] | ✓ | - | ✓ | - | ✓ | - | - | - | ✓ |
| [58-63] | ✓ | - | ✓ | - | - | - | - | ✓ | - |
| [69-71] | ✓ | - | - | - | - | - | ✓ | - | - |
| [72-73] | ✓ | - | ✓ | - | - | - | ✓ | - | - |
| [74-76] | ✓ | - | - | - | - | ✓ | - | - | - |
| [78-80] | ✓ | - | ✓ | - | | ✓ | - | - | - |
| [81] | - | ✓ | ✓ | - | ✓ | - | - | - | ✓ |

G.B.A: Graph Based Approaches (Multi level and Spectral clustering), *R.P: Reactive Power, *C.A: Coherency Analysis, M.P.F: Minimal Power Flow, *M.P.I: Minimal Power Imbalance.

## 4. WHEN SHOULD ISLANDING BE EXECUTED?

Unnecessary or wrong islanding execution can be a more severe disturbance than the initial events. Besides, the late execution of islanding has dangerous consequences. The islanding command must be sent at the time when it is necessary [53-59]. In this regard, the following methods have been frequently used to determine the islanding time.

### 4.1 Local out-of step (O.S) protection

The out-of-step function of local distance relays sends a trip signal when unstable or large power swings are detected [82]. In many studies, R-Rdot relays are installed at the predetermined transmission lines to execute controlled islanding. The operation time of these relays are based on the local measurement of line resistance and depends on the relay settings [53-55].

### 4.2 Wide-area out-of-step protection

In this plan, the data of wide-area measurement systems (WAMS) are used to send tripping signal directly to the breakers when unstable swings are detected [83-84]. In [85], the Prony analysis is applied to real-time swing curves between coherent groups of generators to calculate the oscillation damping and to detect unstable swings. In another method, the first and second derivative of phase angle difference between bus voltages at two endpoints of each line are considered to detect stable swings from unstable ones [79]. Frequency and the change in voltage angle are two other wide-area measurement-based criteria used for islanding detection [86].

### 4.3 Decision Tree (DT)

The DT approach has been widely used in dynamic security assessment of power system operation [87-91]. In [92], DT is trained offline based on numerous simulations at different disturbances to detect unstable swings between coherent groups, which may lead to global instability and uncontrolled separation [93-94]. The number of DTs is assigned for stability assessment of each coherent group. The islanding decision is made considering the confidence level of all specified DTs [95]. In [96], a modified DT structure with islanding module is proposed based on real-time data. By using the depth first method, locations of islands as well as stability estimation are determined online. However, it is shown that the DT performance is affected by a considerable variation in loadings and structure of the system. This is due to changing the coherency of generators and the time when instability appears [97].

### 4.4 Lyapunov method

The Lyapunov method is used to identify unstable swings and also to assess short-term voltage stability by using the classical model of generator [98-101]. At this method, the post-fault system trajectory is monitored to evaluate the stability of the system following any disturbances. The maximal Lyapunov exponent (MLE) of the nonlinear system trajectory is calculated based on the provided data from WAMS over a finite appropriate time interval [99]. A negative value of MLE represents the convergence of the nearby system trajectory, while the positive value indicates system instability [100-101].

### 4.5 Intelligent systems

Intelligent systems, such as Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Interface System (ANFIS), are widely used for stability assessment [103-110]. In [111], ANN has been utilized to discover stable and unstable swings to perform corrective actions such as load and generation shedding and controlled islanding. Nevertheless, the main problem of ANN algorithm is to determine which corrective actions should be performed for detected unstable cases [111]. In [112], the ANFIS structure is used to investigate the defined stability indexes for frequency and voltage stability assessment of the system. The performance of these intelligent methods highly depends on different parameters such as input/output selection, training data, algorithms and fuzzy set in ANFIS structure [112].

### 4.6 Heuristic approaches

In these methods, the advantage of real-time stability assessment is used for providing early warning and performing corrective actions [113-116]. In some methods, the WAMS data are employed to monitor the characteristics of inter-area oscillations such as frequency, mode shape and damping between coherent groups to detect asynchronous oscillations by investigating assigned indexes [117-119]. In [120], the proposed wide-area severity indices considering voltage, frequency and center of inertia have been investigated for short-term post-disturbance stability analysis. In another method, the center of inertia of rotor angles has been used for transient stability between areas to detect wide-area asynchronous oscillations [121].

## 5. WHAT SHOULD BE DONE IN CONSTRUCTED ISLANDS?

After splitting the network into different islands, the main concern is to keep the stability of islands. In doing so, different corrective actions should be applied at islands, such as under-frequency load shedding (UFLS) or generation rejection [50-62]. Because of neglecting the reactive power criteria in islanding boundary determination, using UVLS in islands may also be necessary.

### 5.1 UFLS scheme

Different UFLS methods including conventional and adaptive techniques have been applied in power systems to keep system stability and to avoid the islands collapse [122-124]. The conventional UFLS is based on local frequency relays with fixed predetermined load shedding at different steps [122]. However, it is shown that it may not operate properly if the system encounters wide-area severe disturbances and unanticipated outages [123]. In the proposed adaptive UFLS methods, the settings are changed adaptively based on the disturbance magnitude to stop fast frequency decay and to recover the frequency properly with minimum load shedding [124]. The rate of change of frequency (df/dt) is used as the clue of disturbance magnitude [122-125]. The effectiveness of adaptive UFLS schemes to keep system stability for the case of having large power outages has been demonstrated by conventional UFLS scheme [125].

### 5.2 Undervoltage load shedding (UVLS)

Basically, there are two local and wide-area-based UVLS schemes that have been implemented by both centralized and decentralized structures [126-127]. There are many considerations in UVLS scheme design, such as excitation system and its limiter operation, load model, transformer tap-changer and local protection systems [128]. The UVLS application in islanding scheme should be coordinated with UFLS to avoid having unnecessary load disconnection that may lead to overvoltage and over-frequency problems. Similar to Section 3, different distinct approaches related to determining the time of islanding and the necessary actions in constructed islands are summarized in Table 3. The O.S operation in Table 3 contains both local and wide-area O.S protections due to out-of-step oscillations.

**Table 3.** *Applied methods for the time of islanding and what should be done in constructed islands*

| | When | | | | | What | |
|---|---|---|---|---|---|---|---|
| Ref. No. | O.S Operation | DT | MLE | Intelligent | Heuristic | UFLS | UVLS |
| [82-86] | ✓ | - | - | - | - | - | - |
| [89-94] | - | ✓ | - | - | - | - | - |
| [94-100] | - | - | ✓ | - | - | - | - |
| [101-108] | - | - | - | ✓ | - | - | - |
| [109-115] | - | - | - | - | ✓ | | - |
| [116-125] | - | - | - | - | - | ✓ | - |
| [126-129] | - | - | - | - | - | | ✓ |

## 6. HOW CAN ISLANDING BE APPLIED?

The islanding is performed locally or based on wide-area systems. In the local case, the lines to be disconnected to form islands are equipped with R-Rdot relays [50-54]. To perform islanding at correct locations and to avoid mis-operation of other O.S tripping, a supervised algorithm like DT is employed to arm installed local relays and to block O.S relays of the other line [90-92]. In wide-area methods, tripping signals are sent directly to circuit breakers of the lines that are supposed to be disconnected [93-100].

## 7. INTELLIGENT ISLANDING

Intelligent islanding design is one of the main challenges in power system protection area in modern power systems. In this design, the boundaries of islands should be adaptive according to the network topology, loading condition, coherent groups of generators and disturbance location. To do this, the coherent group of generators and the number of necessary islands to be formed should be determined based on real-time data of the system. The islanding should be realized at the correct time considering all possible wide-area instability problems. Also, the operation of corrective UFLS and UVLS schemes should be performed adaptively to stabilize the islands with minimum load and generation shedding. To achieve the response-based intelligent islanding, the real-time data of the system is a necessary tool. This can be achieved by using WAMPAC system [129, 130].

## 8. WIDE-AREA MONITORING, PROTECTION AND CONTROL (WAMPAC)

WAPMAC is an integrated real-time system which utilizes both wide-area and local information to perform optimal and adaptive response-based corrective control and protection actions [131-133]. The main contributions of WAMPAC system in intelligent islanding design are the capability of monitoring disturbance propagation and having wide-area protection and control function.

The real-time data from WAMPAC system is used to detect disturbance location and to change the islanding boundaries adaptively with respect to the real-time data of active and reactive power flow. The real-time wide-area information received from WAMPAC system gives the opportunity to perform the real time stability assessment in the system to identify the correct islanding time. Also, the tripping signal could be sent to proper locations after decision making, which increases the islanding system reliability [133, 134].

## 9. CONCLUSIONS

In this paper, a comprehensive literature survey about the power system-controlled islanding in large-scale power systems was given. The necessity of the controlled islanding as the last defense plan against catastrophic blackouts was shown by reviewing the recent major blackouts. The concept of main steps for practical islanding design including where, when, how and what to do were thoroughly explained. There were some important aspects that should to be considered at each step of the islanding design.

**Where:** Different criteria for determining the island cut-sets were investigated. It was shown that the coherency analysis is the vital aspect to build stable islands. The main objective in islanding was to split the network into islands with minimum active power imbalance or minimal power flow disruption. Different methods for islanding boundary determination including graph based, intelligent and heuristic approaches were reviewed.

**When:** It was shown that the time of islanding execution was dependent on wide-area stability at severe disturbances. With respect to the previous research, the performance of different applied methods including local and wide-area O.S relays, DT, Lyapunov, intelligent and heuristic approaches were investigated.

How: It was shown that the operation of local relays or sending trip commands to circuit breakers of lines by wide-area systems are the two distinct methods used for islanding execution.

**What to do:** The UFLS and generation rejection are two main necessary corrective actions which may be applied to balance the load and generation in islands after network splitting. It was shown that the UVLS may be necessary at islands with insufficient reactive power reserves and low voltage magnitude. Finally, by demonstrating the performance of various methods, it was concluded that intelligent islanding with adaptive performance at different steps is the optimal design of islanding scheme. It was shown that to have an intelligent islanding scheme, the WAMPAC application is necessary to have the real-time data of the entire power system.

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