A Real-Time Controlled Islanding and Restoration Scheme Based on Estimated States

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***Abstract*—Power system operators are facing major challenges today to keep the system operating at the admissible limits. Recent blackouts demonstrated the need for a systematic study and design of a comprehensive system control strategy. Intentional Controlled Islanding (ICI) has been proposed as an effective corrective control action of final resort to save the system from a partial or a complete blackout. ICI limits the occurrence and consequences of blackouts by splitting the power system into a group of smaller, stable, and sustainable subsystems, also called islands. After a controlled system separation, power system operators should resynchronize and reconnect each island to restore the system. In this sense, real-time knowledge of the operating condition of the islands is required. In this paper, a real-time ICI and restoration scheme is proposed. The proposed scheme consists of an ICI algorithm that finds islanding solutions with minimal power-flow disruption while considering power system restoration constraints (e.g., blackstart availability, sufficient generation capacity and observability), a real-time state estimator that monitors the system before and after the islanding, and a restoration process. The proposed ICI and restoration scheme is tested using the dynamic IEEE 39- and 118-bus test systems.**

***Index Terms*—Intentional Controlled Islanding; linear state estimator; PMU measurements; power system restoration.**

I. Introduction

POWER systems are being operated close to their physical limits due to the ever increasing electricity demand. On top of that, power systems experience unprecedented changes both in structure and operation due to the high penetration of renewable energy sources and the tendency of the electric utilities to follow the "smart grid" paradigm. This situation makes the power system vulnerable to severe contingencies. At the same time, the deregulated electricity market imposes a strong competition among the electric entities in which the "winner" is the one that provides reliable power to the end users with the minimum cost.

In this sense, the power systems should be resilient and robust in case of a severe disturbance, while the power system operators should be able to apply prompt mitigation measures to prevent the evolution of the disturbance. Although most of the disturbances are encountered effectively by either automated protection schemes or additional protective measures taken from the control center, severe blackouts have occurred in the last two decades due to cascading events. In 2003, the US-Canadian blackout affected 50 million people, while in the same year two major blackouts occurred in Sweden and Italy. A major blackout in Australia in 2007 resulted in the loss of 2.2 GW that affected 480,000 customers [1].

The catastrophic socio-economic consequences of these blackouts demonstrated the need for a systematic study and design of a comprehensive system control strategy. Intentional controlled islanding (ICI), also called system splitting or controlled system separation, is proposed as a corrective control action to limit these undesirable events [2]. ICI is aimed to be used as the last resort to prevent blackouts, usually after severe disturbances and when conventional control systems have failed to keep the system within stability margins. In practice, ICI determines in real-time (in a few seconds) a number of transmission lines to be disconnected in order to form sustainable islands [3], [4]. To create stable islands, the islanding solution must maintain together the coherent groups of generators resulting from the disturbance [5], [6], as well as other static and dynamic constraints.

After a successful system splitting, the system operators should reconnect each island to recover the integrity of the system as a whole. Hence, Parallel Power System Restoration (PPSR) always follows the ICI, sometimes hours after the splitting. The restoration of the power system is not an easy task given that it comprises several complex and time-consuming stages. Among these, synchronization of the islands to be connected is one major task. The synchronization requires the accurate knowledge of the operating condition of the islands to be connected (i.e., frequency of the islands and voltage magnitude and angles of the boundary buses) [7]. The contemporary process by the electric utilities to restore the system is to equip with synchroscopes the candidate substations for reconnection. A synchroscope allows the operator to visually observe the voltage difference between the two substations, as well as the frequency slip. The decision of the re-closure is based on the synchronizing conditions of the islands which are summarized in Section II-D of this paper [7]. If the conditions are satisfied, there will be little or no transfer of energy between the two islands when the breaker is closed. The main disadvantage of the contemporary procedure for power system restoration is that only the substations that are equipped with synchroscopes can be employed for

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synchronization. However, it is difficult to pre-specify such substations that cover all possible scenarios of system restoration. In other words, the number of synchronizing locations is limited. Furthermore, the re-closure requires the presence of crew field in the candidate substations to monitor the synchronization and perform the re-closure. This implies additional delay to the system restoration since the substations have no control effect on the island's frequency and voltage.

In the literature, several methods are reported to determine possible splitting strategies. In these methods, ICI is usually modelled as a combinatorial optimization problem with constraints. The objective function of this optimization problem is to minimize either the power-flow disruption or the power imbalance within islands, while the main constraints are the coherent generator groups [4], [8], [9]. The main drawback of the aforementioned methods is the lack of the PPSR planning stage. This disadvantage was attempted to be solved only by a few works [3], [10], [11]. The concept of novel schemes that provide real-time solutions for both ICI and power system restoration is still an unexplored research area.

The advent of the Synchronized Measurement Technology offers great flexibility to power system operators in several control and monitoring applications. PMU measurements (i.e., synchronized voltage and current phasors, frequency, and rate of change of frequency) can provide to the power system operators a real-time wide area visualization of the system operating condition. For instance, the installation of PMUs in an optimal way for rendering the power system fully observable by PMUs makes feasible the operation of a real-time state estimator that is based only on PMU measurements. Such a state estimator can estimate in real time (as the PMU measurements arrive to the control center) the states of the system (i.e., voltage magnitude and angle of the buses) and can track effectively power system transients [12]. Although the complete observability of the system by only PMUs is still not possible today, the trend of the electric utilities to install PMUs shows that such a case will be realistic in the near future. For instance, a recent report by the US DOE indicates that the PMUs in North America have increased from 166 in 2009 to 1700 in 2015 [13].

Crucially, in this work a real-time state estimator serves as the connection point between the controlled islanding and the power system restoration. In particular, this paper presents a real-time ICI and restoration scheme that consists of a sophisticated intentional controlled islanding algorithm, a real-time state estimator, and a power system restoration process. The main assumption in the paper is that the power system is observable by PMUs before the system splitting. In this sense, during the pre-islanding and the post-islanding stage, the state estimator provides the power system operating condition to the operators. This requires that all the formed islands are still observable by PMUs in the post-islanding stage; such condition is ensured by the ICI algorithm that is used in this paper. The real-time monitoring allows the reconnection of the islands in quasi real time, as soon as their synchronizing conditions are met, without the presence of any synchroscopes and crew in the substations. The proposed ICI and restoration scheme is tested and evaluated using the dynamic IEEE 39- and 118-bus test systems [14].

The rest of the paper is organized as follows: Section II provides the theory behind the intentional controlled islanding and the parallel power system restoration, as well as a brief description of the ICI algorithm used in this work. The proposed ICI and restoration scheme is thoroughly detailed in Section III while Section IV presents the simulation results from its testing. The paper concludes in Section V.

II. Intentional Controlled Islanding And Parallel Power System Restoration

A. ICI Problem Modeling

In graph theory, an undirected graph-model $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ can be used to describe an *m*-generator and *n*-bus power system. In this graph-model, the node set $\mathcal{V} = \{v_1, ..., v_n\}$ denotes the buses while the edge set $\mathcal{E}$ with elements $e_{ij}\,(i, j = 1, ..., n)$ denotes the transmission lines. The set $\mathcal{V}^{gen}$ is a subset of the node set $\mathcal{V}$ that contains only those buses with generators directly connected to them. The set $\mathcal{W}$, with elements $w_{ij}\,(i, j = 1, ..., n)$, is a set of edge weights representing the weight factors (power flow) associated with the lines. To accommodate network losses, w_{ij} is calculated as follows:

$$w_{ij} = \begin{cases} \dfrac{|P_{ij}| + |P_{ji}|}{2} & if\ e_{ij} \in \mathcal{E} \\ 0 & otherwise \end{cases} \tag{1}$$

where $|P_{ij}|$ and $|P_{ji}|$ represent the active power flow in the line from bus *i* to *j*, and from *j* to *i*, respectively.

A *cutset* $\mathcal{E}_{\mathcal{S}} \subset \mathcal{E}$ [15] is the set of edges to be removed to split $\mathcal{G}$ into $K \in \mathbb{Z}^+$ subgraphs $\mathcal{G}_k = (\mathcal{V}_k, \mathcal{E}_k)$, where $k \in \mathcal{K}$, $\mathcal{K} = \{1, \ldots, K\}$. For K islands, the sum of the weights of the edges within the cutset $\mathcal{E}_{\mathcal{S}}$ is called the cut, which is defined as,

$$\text{cut}(\mathcal{V}_h, \mathcal{V}_k) = \sum_{i \in \mathcal{V}_h,\, j \in \mathcal{V}_k} w_{ij}, \;\; h \neq k, \;\; h, k \in \mathcal{K} \tag{2}$$

In the ICI problem for minimal power-flow disruption, $\mathcal{E}_{\mathcal{S}}$ consists of the edges that represent the transmission lines in the system to be disconnected to create the islands. The value of the cut corresponds to the power-flow disruption in the islands.

It is likely that a formed island could collapse after system splitting. In such cases, the particular island should be restored since the main objective is the complete system restoration. This can be achieved through PPSR. Therefore, it is critical to study ICI and PPSR under the same framework.

When determining the optimal points for system separation, the following PPSR constraints should be taken into account [7]:

- Sufficient blackstart (BS) units should be available in a formed island.
- Sufficient generation capacity should be available in a formed island to satisfy the load demand.
- Adequate voltage control capabilities within the islands to maintain voltage stability.

- All boundary buses of the islands must be synchronized with adjacent boundary buses of other islands.
- Data collection in each island should be feasible.

B. Extended MILP ICI Algorithm

An exact ICI algorithm for solving effectively the ICI problem while considering power system restoration has been proposed in [11]. The proposed algorithm is based on a Mixed Integer Linear Programming (MILP) formulation [16]. It is capable of directly finding an islanding solution with minimal power-flow disruption for any given number of islands, while maintaining the generator coherencies in each island. Furthermore, it excludes any transmission lines that should not be disconnected (e.g., a line that contains a transformer), allows the control of the size of the islands and ensures the connectivity inside the islands. At the same time, the aforementioned algorithm guarantees that a PPSR is planned in case of any eventuality. This is achieved through the incorporation of additional restoration constraints to the MILP formulation. More specifically, assuming a completely observable power system at normal operating conditions, the extended MILP ICI algorithm creates islands that are also completely observable by PMUs, includes at least one BS unit within each island and guarantees sufficient generation capacity to match the load consumption within each island.

1) MILP formulation to solve the ICI problem

Consider an undirected, connected graph $\mathcal{G}=(\mathcal{V},\mathcal{E})$ and a matrix $W\in\mathbb{R}^{|\mathcal{V}|\times|\mathcal{V}|}$ for the edge weights $w_{i,j},(i,j)\in\mathcal{E}$, with $w_{i,j}=w_{j,i}$. The objective is to partition the graph into K subgraphs indicating the islands, while a) minimizing the weight of the edges that are not included in any subgraph (partitioning cost) which is described by the objective function:

$$\text{Partitioning Cost}=\min_{z}\sum_{(i,j)\in\mathcal{E}}\frac{1}{2}(1-z_{i,j})w_{i,j} \tag{3}$$

b) controlling the size of subgraphs, and c) ensuring that each produced subgraph is connected. In addition, the resulting subgraphs $\mathcal{G}_k=(\mathcal{V}_k,\mathcal{E}_k)$ with $\bigcup_k\mathcal{V}_k=\mathcal{V},k\in\mathcal{K}$ must follow a minimum cardinality restriction as $|\mathcal{V}_k|\geq M,k\in\mathcal{K}$, where $M\in\mathbb{N}^+$. Variables $z_{i,j},(i,j)\in\mathcal{E}$ are defined as the decision variables where $z_{i,j}=1$ if the edge is included in any subgraph and $z_{i,j}=0$ otherwise. It is noted that a detailed description of the aforementioned MILP formulation can be found in [16].

2) Additional restoration constraints

(i) Observability: Assuming that at normal operating conditions the system is completely observable by PMUs, the additional observability constraint incorporated in the MILP formulation can be defined as [11],

$$\sum_{j\in\mathcal{V}}z_{i,j}r_j+r_i\geq1,\quad i\in\mathcal{V}, \tag{4}$$

where r_i (i=1,…,n) are binary elements defined as:

$$r_i=\begin{cases}1, & \text{if there exists a PMU at bus } v_i\\ 0, & \text{otherwise}\end{cases} \tag{5}$$

The above observability constraint ensures that each node bus v_i is observable either by at least one of its neighboring buses or by itself. This leads to the formation of islands that are also completely observable.

(ii) Blackstart availability: Assuming that sufficient BS units are available, this constraint includes at least one BS unit within each island.

(iii) Sufficient generation capacity and unit commitment preservation: Assuming that the generators are able to operate at full rated power, the constraint of sufficient generation capacity and unit commitment preservation is as follows [11]:

$$\sum_{i\in\{1,\dots,n_k^{gen}\}}Pgen_{i,k}^{\max}\geq\sum_{i\in\{1,\dots,n_k^{load}\}}Pload_{i,k},\quad k\in\mathcal{K} \tag{6}$$

$$\sum_{i\in\{1,\dots,n_k^{gen}\}}Pgen_{i,k}^{\min}\leq\sum_{i\in\{1,\dots,n_k^{load}\}}Pload_{i,k},\quad k\in\mathcal{K} \tag{7}$$

where $Pgen_{i,k}$ and $Pload_{i,k}$ are the generation and load consumption in bus i of island k respectively. Equation (6) guarantees sufficient generation capacity to match the power demand in the formed islands. At the same time, (7) avoids the unnecessary shut down of generators just to achieve the load-generation balance. Hence, both the cost of disconnecting a generator from the system and the time delay of reconnecting it afterwards are negated.

C. Synchronizing Islands

When a controlled system separation occurs, the system operator must often perform a PPSR to reconnect the islands, and therefore, restore the whole power system. The sooner the islands are interconnected, the better they can withstand any additional disturbances [7]. The process of connecting islands involves synchronizing. Several conditions must be met before two islands can be synchronized. These conditions are measured at the point of reconnection.

Traditionally, synchronization is conducted within the interconnection substations and generating plants substations equipped with synchroscopes and/or synchronizing relays. At the circuit breaker (CB), where islands will be synchronized, the following three conditions should be considered [7]:

- The voltage magnitudes on the two sides of the CB should be as close as possible to one another. A rule of thumb would be to close the circuit breaker with no more than 2-5% voltage difference between the two islands.
- The frequencies of the two islands must be close to identical. Under abnormal conditions, a system may tolerate up to a 0.1 Hz frequency difference.
- The voltage phase angle between the two sides of the CB must be within allowable tolerance levels, as defined by the system engineers for the specific area where the synchronizing will occur (typically ± 20 degrees).

III. Proposed Islanding – Restoration Scheme

The proper restoration of the power system requires real time information from the islands. In this work, a linear state estimator is employed for providing the state of each island during the pre-islanding and post-islanding stage; therefore, the presence of synchroscopes and field crew is not required at the substation. For completeness, the theory behind the linear state estimator is first provided in this Section, while the proposed islanding and restoration scheme is thoroughly described next.

A. Real-time state estimator

With the advent of the Synchronized Measurement Technology and the installation of PMUs in the power system measurement layer, the concept of a real-time state estimator is feasible. The execution of a real-time state estimator implies a PMU observable system; therefore, the real-time state estimator is solely based on PMU measurements and is able to track the transients in case of fault [12]. The linear state estimator in this work is formulated in a Weighted Least Squares (WLS) framework and processes the real and imaginary parts of the current and voltage phasor measurements provided by the PMU. Therefore, the measurement model is formulated as,

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{e} = \begin{bmatrix} \mathbf{V}_r^{meas} \\ \mathbf{V}_i^{meas} \\ \mathbf{I}_r^{meas} \\ \mathbf{I}_i^{meas} \end{bmatrix} = \begin{bmatrix} \partial\mathbf{V}_r/\partial\mathbf{V}_r & \partial\mathbf{V}_r/\partial\mathbf{V}_i \\ \partial\mathbf{V}_i/\partial\mathbf{V}_r & \partial\mathbf{V}_i/\partial\mathbf{V}_i \\ \partial\mathbf{I}_r/\partial\mathbf{V}_r & \partial\mathbf{I}_r/\partial\mathbf{V}_i \\ \partial\mathbf{I}_i/\partial\mathbf{V}_r & \partial\mathbf{I}_i/\partial\mathbf{V}_i \end{bmatrix} \begin{bmatrix} \mathbf{V}_r \\ \mathbf{V}_i \end{bmatrix} + \mathbf{e}, \quad (8)$$

where $\mathbf{z}$ is a vector containing the measurements, $\mathbf{H}$ is the Jacobian matrix (relates the measurements to the states), $\mathbf{x}$ is a vector containing the system states, $\mathbf{e}$ is the Gaussian measurement noise, and $\mathbf{V_r}$, $\mathbf{V_i}$, $\mathbf{I_r}$, $\mathbf{I_i}$ are the real and imaginary parts of the bus voltage phasors and the line current phasors, respectively, when they are expressed in rectangular form. The WLS state estimation minimizes the square of the measurement residuals and is widely used in several control centers of different countries. Even if in the literature there are some works (e.g., [17], [18]) where the authors have proved that the WLS square state estimation minimizes only the detectable error and not the undetectable, without losing generality and being consistent to what is currently used in the control center today, the WLS state estimation is used in this work.

It should be noted that the real and imaginary parts of the current phasor measurements are expressed in relation to the states of the system.

Based on the WLS formulation the state vector $\mathbf{x}$ can be obtained by minimizing the function $J(\mathbf{x})$,

$$Min\ J(\mathbf{x}) = [\mathbf{z} - \mathbf{H}\mathbf{x}]^T \mathbf{R}^{-1} [\mathbf{z} - \mathbf{H}\mathbf{x}], \quad (9)$$

where $\mathbf{R}$ is the measurement error covariance matrix and its elements are used as weights of the measurements. By minimizing the objective function in (9) the state vector $\mathbf{x}$ can be estimated (without any iterative procedure) as,

$$\hat{\mathbf{x}} = (\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{R}^{-1} \mathbf{z}\ . \quad (10)$$

B. A real-time scheme for system islanding and restoration

Fig. 1 illustrates the general concept of the proposed ICI and restoration scheme based on estimated states. As it is shown in Fig. 1, in this work it is implicitly assumed that PMUs were optimally placed to make the system observable. This allows the execution of a linear state estimation directly from the control center. Following the determination of the necessity to split the system, the main steps for executing the scheme are:

Step 1: Use the extended MILP ICI algorithm to find the optimal islanding solution.

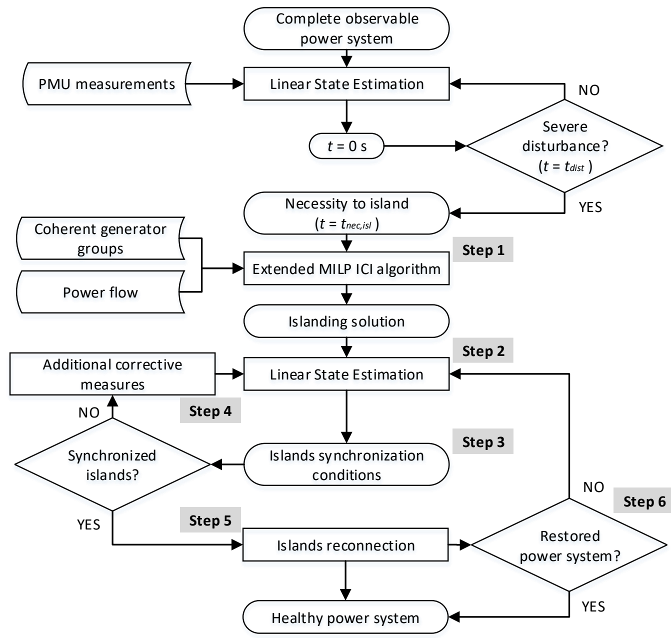

Fig. 1: Flowchart of the proposed real-time controlled islanding and restoration scheme based on estimated states

Step 2: After system splitting, perform a linear state estimation at the control center.

Step 3: Use the estimated states to assess the status of the islands' boundary buses and their synchronization.

Step 4: If there are any islands that are in synchronism, reclose the CBs of their boundaries to reconnect them. Otherwise, apply additional corrective measures while assessing the boundary status through state estimation until the synchronizing conditions of some islands are met.

Step 5: Reconnect the synchronized islands.

Step 6: Repeat Steps 4-5 until all the islands are reconnected and the system is restored.

IV. Simulation Results

To demonstrate the effectiveness of the proposed real-time ICI and restoration scheme, both a small-scale and a large-scale power system (the IEEE 39-bus and 118-bus test systems) are used. The dynamic data of the machine models along with the data for the controllers (i.e., AVR and governors) are provided in [14]. Moreover, it is assumed that an optimal placement of PMUs has been previously performed for complete observability of these test systems at normal conditions. This allows the execution of a linear state estimation directly from the control center. In addition, the loads of the test systems are assumed to be voltage dependent while the effect of the loads' voltage dependency on the system response is captured from the real-time state estimator through the PMU measurements. All times quoted are based on simulations in Matlab software (a PC with 3.10 GHz dual core CPU and 4 GB RAM).

A. IEEE 39-bus Test System

The single-line diagram of the IEEE 39-bus test system is presented in Fig. 2. This system has 10 synchronous generators, 34 transmission lines, 12 transformers and 19 constant power

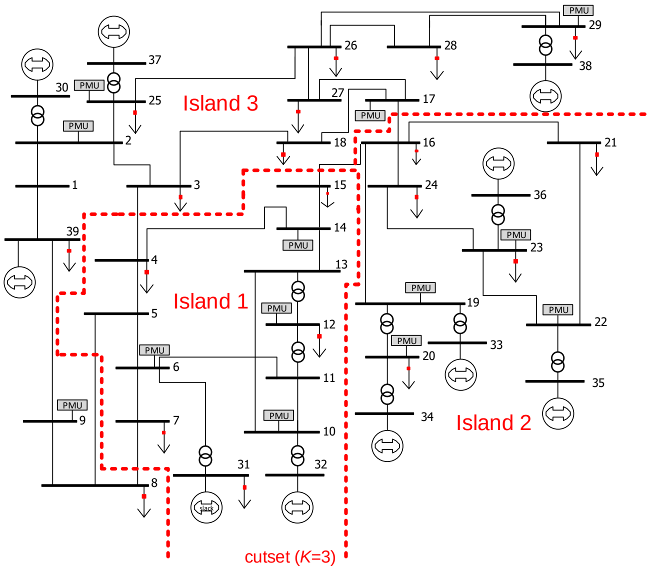

Fig. 2: Single-line diagram of IEEE 39-bus test system with optimal islanding solution

loads. The optimal PMU locations are shown in Table I [19]. This paper considers generators 30, 32, 34 and 39 as BS units.

Test case description: At time $t = 1$ s, a three phase to ground fault occurs at bus 2 and is cleared 0.65 s later, at $t = 1.65$ s. Fig. 3 shows the swing curves of the generators. It can be noticed that, shortly after the fault is cleared, three groups of generators are formed: {G31, G32}, {G33, G34, G35, G36}, and {G30, G37, G38, G39}. Although these groups can be created through visualization of the generator rotor angle trends, algorithms to automatically identify coherent groups of generators (e.g., [20]) must be adopted in large-scale systems to ensure adequate generator grouping, and to further improve the islanding-restoration scheme proposed here. In addition, as Fig. 3 depicts, if the system is not separated into three islands, the speed of the generators increases and their terminal voltages significantly reduce. Thus, a blackout is unavoidable even if the fault is removed. In this case, the necessity to split the system is considered to be at 1.7 s. As the proposed ICI and restoration scheme is adaptive and considers the actual topology and state of the system, the information (power flow and topology) at $t = 1.7$ s is used.

The scheme identifies the optimal solution (for minimal power-flow disruption) to open the lines 3-4, 5-8, 7-8, 15-16 and 16-17 (red dotted line in Fig. 2). The solution was found in approximately 0.021 s (Table II). Hence, system separation was performed at $t = 1.721$ s. Fig. 4 shows the generator swing curves after the solution is applied. As noticed, three stable groups are created. Moreover, the frequencies of Island 1, Island 2, and Island 3 are 1.001 p.u., 1.001 p.u., and 0.981 p.u. respectively (Fig. 4). Voltages also recover close to their nominal values (Fig. 4). Since the system separation successfully recovers the frequency and the voltages of the islands within admissible limits, it can be concluded that the proposed ICI and restoration scheme separated the system in a controlled manner, preventing the blackout.

The load and generation in each island, as well as the

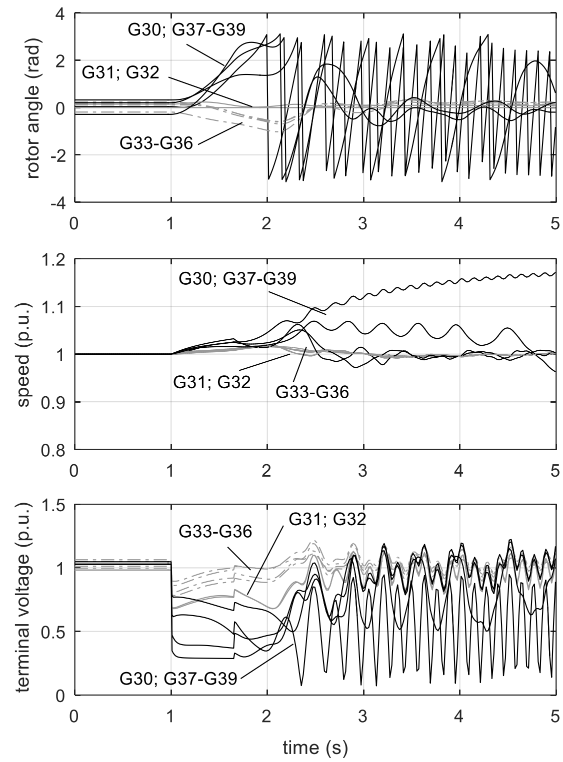

Fig. 3: IEEE 39-bus test system: Electrical behavior without islanding

TABLE I
OPTIMAL PMU PLACEMENT FOR THE IEEE 39-BUS TEST SYSTEM

	Optimal PMU locations	***Optimal Number***
Normal operating conditions	2, 6, 9, 10, 12, 14, 17, 19, 20, 22, 23, 25, 29	13

TABLE II
EXACT ISLANDING SOLUTION FOR THE IEEE 39-BUS TEST SYSTEM

No. of Islands (K)	***Cutset***	***Cut (MW)***	***Time (s)***
3	3-4, 5-8, 7-8, 15-16, 16-17	1027.21	0.021

TABLE III
LOAD AND GENERATION WITHIN EACH ISLAND FOR THE IEEE 39-BUS TEST SYSTEM SPLIT INTO THREE ISLANDS (K=3)

Island number	***ΣPload (MW)***	***ΣPgen (MW)***	***Generation capacity (MW)***	***Available BS units (bus no)***	***Observable?***
1	1143.88	1169.9	1670	32	YES
2	1787.1	2350	3340	34	YES
3	3323.9	2620	4036	30, 39	YES

generation capacity, BS availability and observability status of each island (i.e., the PPSR constraints included in the splitting strategy) are presented in Table III. As it can be noticed, at least one BS unit and sufficient generation capacity to match the load consumption are available in each island. In addition, it is important to understand that the proposed ICI scheme has ensured the creation of completely observable islands, and therefore, the continuous execution of the linear state estimation at the control center. In other words, the scheme has enabled the system operator to assess both the status of the islands' boundary buses during the post-islanding stage and their resynchronization using estimated system states.

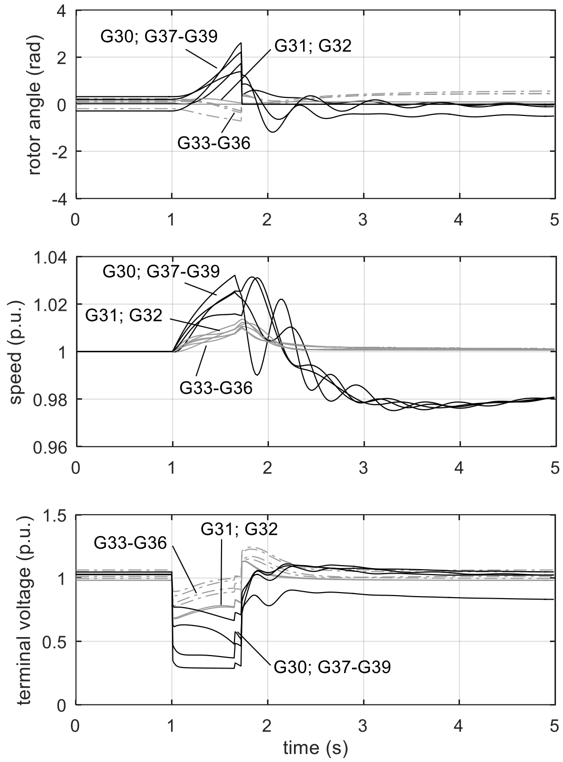

Fig. 4: IEEE 39-bus test system: Electrical behavior with islanding

TABLE IV
CORRECTIVE MEASURES FOR ISLAND SYNCHRONIZATION OF THE IEEE 39-BUS TEST SYSTEM

Time (s)	***Corrective measure***
11	Reclose CB of transmission line 16-17
40	30% load shedding of loads 8 and 39
97	Reclose CB of transmission lines 5-8 and 7-8
115	Change tap position of transformers 25-37 and 2-30 from 1 to -4
130	Reclose CB of transmission line 3-4
150	Change tap position of transformer 10-32 from 2 to 5
150	Change tap position of transformer 23-36 from 0 to -5
170	Reclose CB of transmission line 15-16

In this sense, the voltage magnitude and angle difference of boundary buses based on the estimated states available at the control center are shown in Fig 5. Fig. 6 further illustrates the frequency difference of the islands. It is noted that the frequency of each island is available by the PMUs in each island. Based on Fig. 5 and 6, a few seconds after the system separation, none of the boundaries satisfies all three conditions for island synchronization. Therefore, additional corrective measures (e.g., generation rescheduling, load shedding and transformer tap change) are needed to achieve island synchronization and thus to complete system restoration. In this case, the corrective measures required to resynchronize the islands are summarized in Table IV. Note that the synchronizing status of the islands' boundary buses during the application of these corrective measures is shown in Figs. 5-6. As it can be noticed, Island 2 and Island 3 are synchronized approximately 9 seconds after the splitting strategy is carried out and are reconnected at time t = 11 s by reclosing the CB of transmission line 16-17 (ideal time based on the simulation). In the real field, a system operator may need more time before

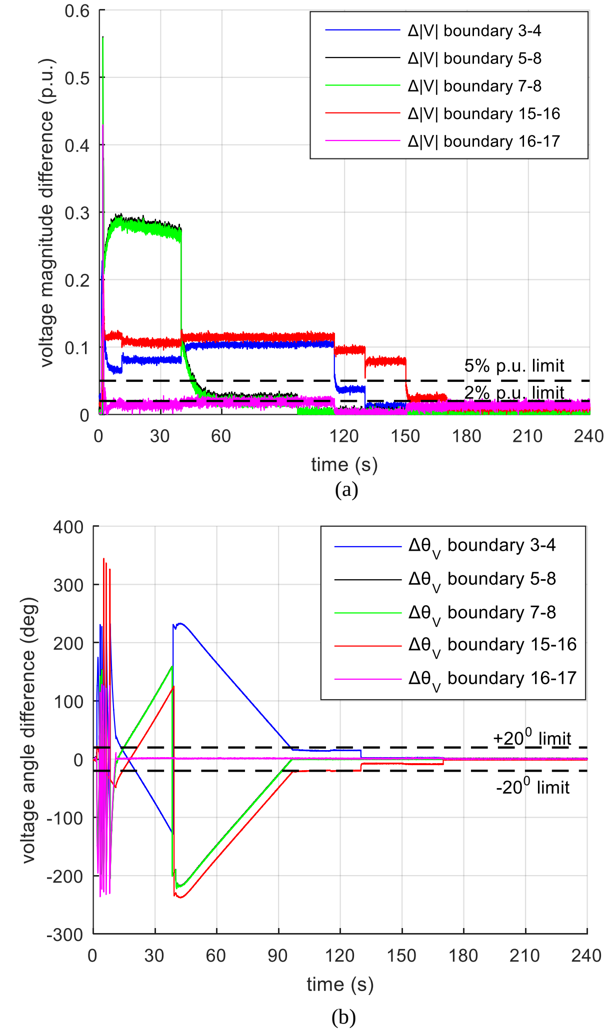

Fig. 5: IEEE 39-bus test system: (a) Voltage magnitude and (b) Angle difference of islands boundary buses during their resynchronization

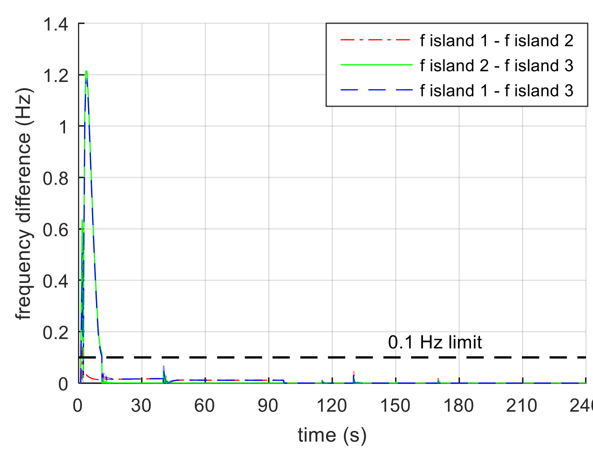

Fig. 6: IEEE 39-bus test system: Islands frequency difference during their resynchronization

taking such a decision. The restoration of the whole power system is completed at time t = 170 s. It is important to clarify that the choice by the authors of the appropriate corrective measure to be applied at each time was based on some operating tips for synchronizing islands provided by NERC [7]. For instance, according to NERC, if the frequencies of the two islands are different, the frequency of the smaller island should

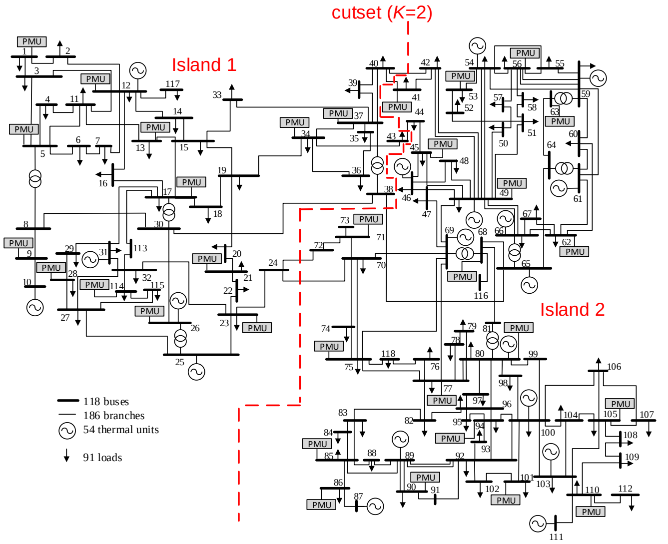

Fig. 7: Single-line diagram of IEEE 118-bus test system with optimal islanding solution

TABLE V
OPTIMAL PMU PLACEMENT FOR THE IEEE 118-BUS TEST SYSTEM

	Optimal PMU locations	*Optimal Number*
Normal operating conditions	1, 5, 9, 12, 13, 17, 21, 23, 26, 28, 34, 37 41, 45, 49, 53, 56, 62, 63, 68, 71, 75, 77, 80, 85, 86, 90, 94, 101, 105, 110, 114	32

TABLE VI
EXACT ISLANDING SOLUTION FOR THE IEEE 118-BUS TEST SYSTEM

No. of Islands (*K*)	Cutset	Cut (MW)	Time (s)
2	24-70, 24-72, 38-65, 40-41, 40-42, 43-44	89.918	0.112

TABLE VII
LOAD AND GENERATION WITHIN EACH ISLAND FOR THE IEEE 118-BUS TEST SYSTEM SPLIT INTO TWO ISLANDS (*K*=2)

Island number	*ΣPload (MW)*	*ΣPgen (MW)*	*Generation capacity (MW)*	*Available BS units (bus no)*	*Observable?*
1	1233	1076	1530	25	YES
2	3009	3300.1	4615	69, 87, 89	YES

be adjusted to match the frequency of the larger island. Hence, an appropriate corrective measure is to shed some loads in the smaller island in order to increase its frequency and match it to the frequency of the larger island. Again, in the real field, the corrective measures applied may vary based on the experience and knowledge of the system operator.

B. *IEEE 118-bus Test System*

The second test system used to demonstrate the efficiency of the proposed ICI-restoration scheme is the IEEE 118-bus test system. The topology of the system is shown in Fig. 7. This test system contains 19 synchronous generators, 177 transmission lines, 9 transformers and 91 constant power loads. The optimal PMU locations for this test system are shown in Table V [21]. This paper considers generators 25, 69, 87 and 89 as BS units.

Test case description: At time $t = 1$ s, a three phase to ground fault occurs at bus 30 and is cleared 0.4 s later, at $t = 1.4$ s, by

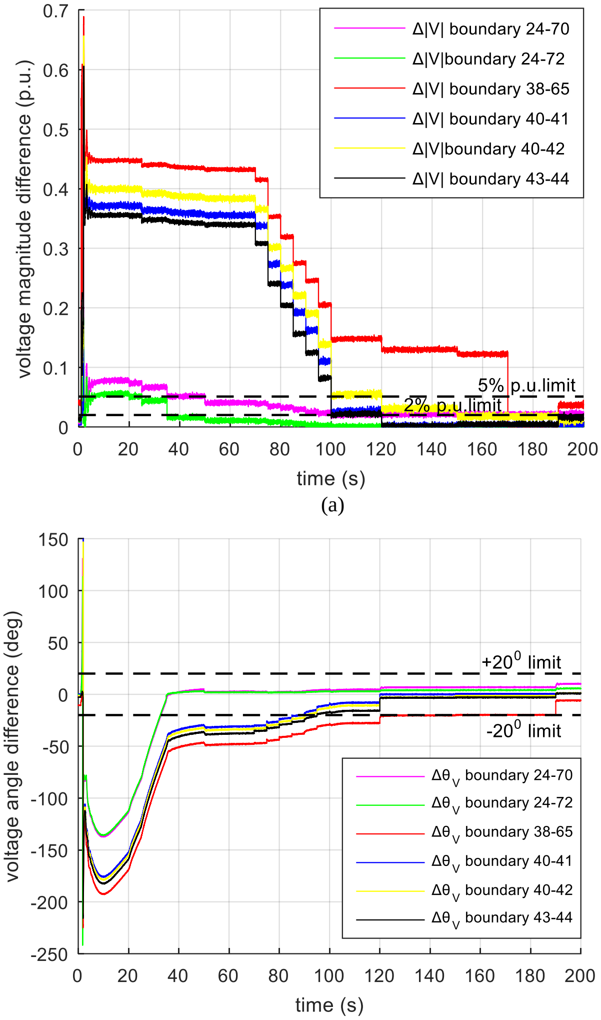

Fig. 8: IEEE 118-bus test system: (a) Voltage magnitude and (b) Angle difference of islands boundary buses during their resynchronization

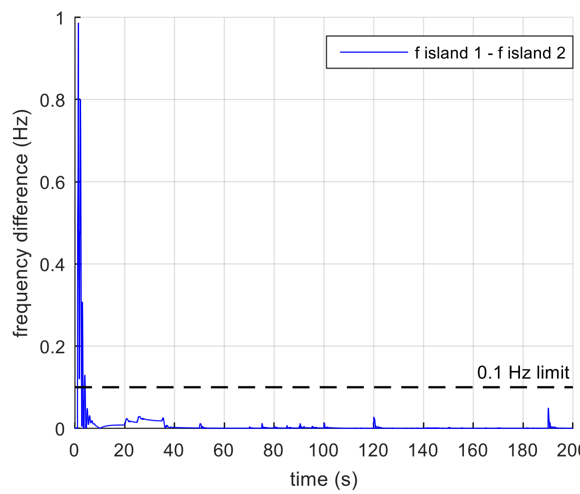

Fig. 9: IEEE 118-bus test system: Islands frequency difference during their resynchronization

disconnecting all the transmission lines that are directly connected to bus 30 (i.e., 8-30, 17-30, 26-30, and 30-38). It is assumed that bus 30 needs to be repaired since the fault caused a permanent damage to it. Shortly after the fault, a group of 5

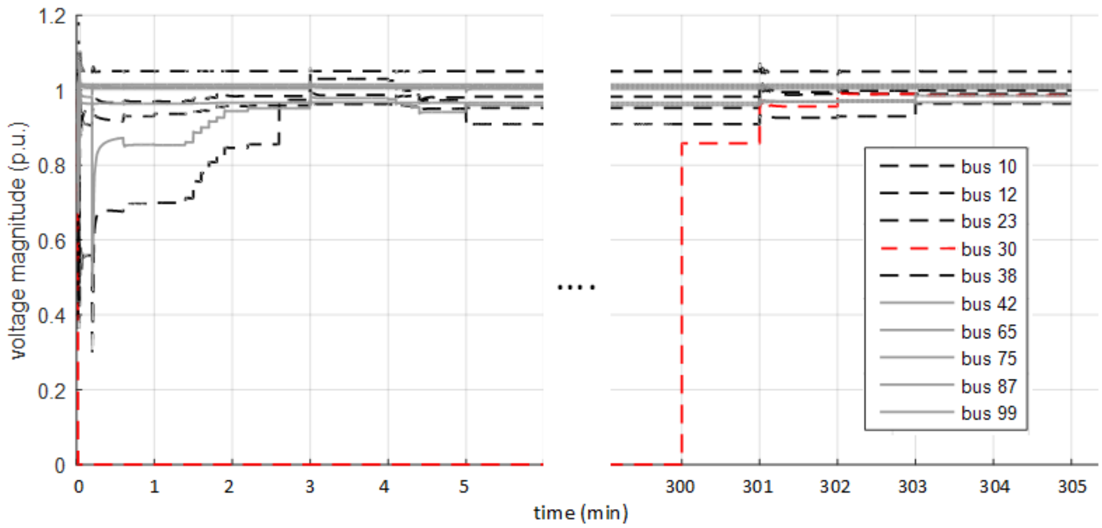

Fig. 10: IEEE 118-bus test system: Voltage magnitudes for selected buses during power system restoration

TABLE VIII
CORRECTIVE MEASURES FOR ISLAND SYNCHRONIZATION OF THE IEEE 118-BUS TEST SYSTEM

Time (s)	*Corrective measure*
20-25	Shed loads 20, 21, 22, and 23
35	Reclose CB of transmission line 24-72
50	Reclose CB of transmission line 24-70
70 - 100	Shed loads 43, 34, 35, 36, 19, 39, and 40
120	Reclose CBs of transmission lines 40-41 and 43-44
150	Reclose CB of transmission line 40-42
170	Change tap position of transformer 37-38 from 1 to -1
190	Reclose CB of transmission line 38-65

generators swing together and the rest ones swing apart. Two groups are created: {G10, G12, G25, G26, G31} and {G46, G49, G54, G59, G61, G65, G66, G69, G80, G87, G89, G100, G103, G111}. Moreover, the generator speeds are increased, while the generator terminal voltages are significantly low. Thus, it can be concluded that the system needs to be split if the blackout is to be avoided. Here, the necessity to split the system is considered to be at 1.8 s. Hence, considering the information of the system (power flow and topology) at $t = 1.8$ s, the ICI and restoration scheme is used to find the optimal splitting solution (Fig. 7). The information about the splitting strategy found, the value of the cut and the execution time are presented in Table VI. The post-islanding behavior of the islands, which is quite similar to the one of the previous case study, highlights that the proposed ICI and restoration scheme successfully prevents the power system blackout. Table VII presents the PPSR constraints included in the strategy. As it can be seen, the ICI scheme has ensured the creation of completely observable islands. In addition, at least one BS unit and sufficient generation capacity to match the load consumption are available in each island. Since these constraints have been included in the strategy, a PPSR is planned in case of any eventuality which can be carried out at the control center with the use of the linear state estimator. In this sense, the corrective measures applied to synchronize the islands in this test system are summarized in Table VIII, while the synchronizing status of their boundaries is illustrated in Figs. 8-9. As it can be observed, to re-close the first two boundary lines, it was necessary to shed some loads in Island 1 during the first minute. Next, to re-close the rest boundary lines, more load shedding was needed in both islands. The last boundary line was able to reconnect during the third minute. Note that the loads that were shed have been reconnected after the reclosure of the boundaries (between 3rd and 5th minute) (Fig. 10). Five hours later, the electric utility was able to repair the damaged bus 30 and to successfully reconnect the transmission lines that are directly connected to it (Fig. 10). This led to the restoration of the whole power system. Finally, it is highlighted that all the changes in the voltage magnitudes of selected buses from the occurrence of the fault (t=1 s) until the restoration of the whole power system can be seen in Fig. 10 (buses of Island 1 and Island 2 and the damaged bus 30 are marked with black dashed line, solid grey line and red dashed line respectively).

V. DISCUSSION

The simulation results presented in this work indicate that the proposed controlled islanding and restoration scheme is able to provide real-time solutions for both ICI (that are also optimal) and PPSR. In general, to find an optimal constrained islanding solution in real-time (within a few seconds in practice) is a demanding problem (NP-hard problem [15]) that may also have convergence problems. On the other hand, the constraints of the ICI problem pose no problem for the MILP and may actually speed up the convergence process by reducing the size of the feasible region. For instance, the MILP ICI algorithm used in the paper maintains both static (i.e., transmission line availability) and dynamic constraints (i.e., generator coherencies), as well as restoration constrains (i.e., observability, blackstart availability, sufficient generation capacity and unit commitment preservation). This large set of constraints contributes significantly to the reduction of the search space of the MILP and the overall complexity of the problem. Therefore, the convergence problems associated with the ICI problem are avoided even in the case of large-scale power systems.

Furthermore, as mentioned in Section III-A, the state estimator of the proposed scheme uses only PMU measurements and no SCADA measurements. This is mainly for two reasons: 1) The severe disturbance on the system that will trigger the islanding scheme should be detected timely. This requires measurements that will be reported in real time (i.e., milliseconds) for capturing the system dynamics. The reporting rate of the SCADA measurements is within 2-5 seconds; hence they can be used only for monitoring the steady state operating conditions of the system. On the other hand, the high reporting rate of the PMUs (i.e., 100 phasor measurements per second) is suitable for such an application; 2) The restoration process of the proposed scheme requires measurements/estimated states with high synchronization accuracy. The conventional measurements through SCADA (i.e., power injections and flows) are not reported in a synchronized fashion, and therefore the synchronization of islands is in most cases not feasible. Unlike the conventional measurements, PMU measurements can be reported in a synchronized way, giving the operator the flexibility to monitor the behavior of the islands at the same time frame and thus to resynchronize and reconnect them.

Consequently, it is obvious that any PMU measurement anomalies will negatively impact the accuracy of the proposed scheme. This is because the performance of the state estimator would be deteriorated, providing inaccurate information to the power system operators. In this sense, a scheduled routine can be performed [22] during the steady state operation of the system for avoiding the presence of PMU anomalies during the execution of the proposed ICI and restoration scheme.

An interesting extension of the work in this paper is to consider different cases encountered in practice. For instance, given that in a transmission system might exist different operators distinguished as grid operators and generation operators, the communication between them should be taken into consideration both for islanding and restoration purposes. Furthermore, the actual generation capabilities of the different entities of the system and their dynamic behavior under grid disturbances may be taken into consideration.

VI. Conclusion

In this paper the Intentional Controlled Islanding (ICI) and Parallel Power System Restoration (PPSR) are combined under the same framework, and thus, a compete scheme (called "ICI and restoration scheme") is proposed that is capable of providing real-time solutions for both ICI and PPSR. The proposed scheme consists of an ICI algorithm, a real-time linear state estimator and a restoration process. Following the necessity to split the system, the MILP ICI algorithm firstly determines an exact islanding solution with minimal power-flow disruption while ensuring that each resulting island contains only coherent generators. At the same time, it creates islands that are also completely observable, includes at least one BS unit within each island, and guarantees sufficient generation capacity to match the power demand of the islands. The aforementioned constraints can be viewed as a power system restoration planning stage. Since system observability is guaranteed, the real-time state estimator can continuously provide to the system operator the operating conditions of the power system before and after its splitting. This gives the operator the flexibility to monitor the islands during the post-islanding stage. Hence, the reconnection of the islands can be achieved in quasi real time, as soon as their synchronizing conditions are met, leading to the restoration of the whole power system.

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