ABSTRACT Inter-area oscillations and cascading failures are the most significant threats to power system security. In case of unstable inter-area oscillation or progressive cascading failure, the system will be faced uncontrolled islanding. The establishment of uncontrolled islands with a deficiency in load-generation balance is the main reason for system blackout. In this respect, for reducing the risk of blackout, controlled islanding has been considered as a preventive strategy. In this paper, based on the coherency and nearest electrical distances between loads and coherent groups of generators, a new algorithm for applying the strategy of controlled islanding is proposed. In this method, first based on the correlation coefficients between generators and the DBSCAN clustering algorithm, coherent generators as the main core for controlled islands are identified. Then by using mixed-integer linear-programming around each coherent group, the sub-networks are established. Then, non-linear programming is used to construct the stable sub-networks associated with islands satisfying load-generation balance, voltage limits, and transmission limits. The proposed scheme is implemented on the IEEE 39-bus system as a small system and Iran power network as a large-scale realistic power system. The results show the ability of the proposed method for implementation in a real power system.

INDEX TERMS Intentional Islanding, Generator coherency, Electrical distances, DBSCAN algorithm, Dijkstra algorithm, non-linear programming

I. INTRODUCTION Power systems are naturally under the risk of uncontrolled islanding following a severe disturbance by two mechanisms, namely 1-progressive cascading failure and 2-unstable inter-area oscillations [1]. Cascading failure is a complicated process consisting of a sequence of events that take place due to the local function of protection relays. Progressive cascading failure gradually weakens network connectivity, which finally disintegrates the whole power system into uncontrolled islands [2]. Unstable inter-area oscillations can be triggered due to unstable coherent groups of generators following a severe disturbance. An anti-phase oscillation of generators in different coherent groups with negative damping is the leading cause of unstable inter-area oscillations. It can lead to loss of synchronism between two areas of power system and final separation of whole power network into uncontrolled islands [3]. Both mechanisms can finally split the power system into islands with a significant mismatch of active and reactive power in load-generation balance. This mismatch is the leading cause of voltage/frequency instability which propels power systems toward blackout [4]. For avoiding the uncontrolled separation of the power network and reduce the risk of a blackout, a controlled islanding strategy has been considered a preventive defense strategy [5]. Intentional islanding is a controlled splitting strategy in which by opening proper boundary branches and performing additional corrective actions, the power system can be separated into stable controlled islands. To successfully apply the splitting strategy, all islands should be able to satisfy load-generation.
balance, transient stability, voltage stability, frequency stability, and transmission line capacity. However, for executing a controlled islanding strategy, deciding the proper boundary branches satisfying all constraints is challenging [6]. Regarding intentional islanding of power systems as the final defence strategy against uncontrolled separation, three critical issues namely “When”, “Where” and “How” to split power system, should be carefully dealt with sequentially[7].

1. When: recognizing the time at which applying intentional splitting is inevitable for avoiding uncontrolled islands.
2. Where: identifying the proper boundary lines for establishing stable intentional islands.
3. How: implementation of the islanding scenario in the correct way without any dynamic and transient consequence[7].

The above tasks can be categorized into three consecutive subproblems referred to as “when to separate,” “where to separate,” and “how to separate”[8].

Determining the island boundary is regarded as a graph partitioning problem, which is a very complicated and time-consuming problem, especially for real power systems with extremely huge searching space. For this purpose, more sophisticated techniques should be applied to handle the problem at the right time [9]. Identifying coherent groups is vital for power system stability assessment and designing the appropriate countermeasures for maintaining transient stability of islands. There are two main approaches available in the literature for coherency identification; model-based (offline)[10] and measurement-based (online) [11]. Some of the prominent model-based techniques include the Weak Links Method [12], coherent clustering method based on state-space [13], Krylov subspace method [14], and relation factor method [15]. These methods are based on a system linearized model, in which the resulting analysis is valid only for a particular equilibrium point and suffers from modeling inaccuracies and parametric uncertainties. Following a change in system operating conditions, network configuration, or fault pattern, the groups of coherent generators tend to vary. In other words, when the system operating condition varies or the network topology changes, one coherent group may separate into smaller groups or the contrary, multiple groups may combine to a bigger coherent group. Therefore, involving online operating data for identifying system coherency is more efficient than using offline data [16]. Both measurement-based and model-based methods have been used in controlled islanding. The model-based methods have been widely considered in controlled islanding in the literature [17-19]. However, the above-mentioned deficiencies make the model-based methods not suitable for online uses such as controlled islanding in a profoundly disturbed power network. Therefore, an efficient measurement-based method has been considered in this paper. The slow coherency method is used in [8, 17, 20-22].

In [23], a new slow coherency grouping-based approach using minimal cut sets is presented for controlled islanding. In [24], the analytical basis for applying slow coherency theory for designing an islanding scheme is investigated, in which the analysis is conducted under varying networks and loading conditions. The results indicate that the slow coherency-based grouping is almost insensitive to locations and severity of the initial faults; in other words, this method is almost fault independent and mostly relies on grid topology. In the literature, various methods have been proposed to determine the location of islands based on islanding constraints. In addition to slow coherency-based methods, some of the prominent approaches include graph theory, heuristic algorithms, and optimization-based approaches. In [25], an intrinsic relationship between the power grid’s physical topology and its graph representation is explored to develop an algebraic-graph method (hybrid method) for fast identification of islanding. In [26, 27], by developing an integrated cut-set identification algorithm for large power systems and based on the slow coherency, a controlled islanding scheme is proposed in which a large-scale power system is represented as a graph, and a simplification algorithm is used to reduce the complexity of the system. In [6], a spectral clustering method is used for a two-step controlled islanding algorithm. The weak point of this method is applying the admittance matrix in the calculation process of dynamic coupling between subsystems, which makes it unpractical in the event of severe faults. Constrained spectral clustering with minimal power flow disruption across boundaries of islands and generator coherency is proposed as a real time controlled islanding algorithm [6, 28-31]. In [32], based on identifying vulnerable areas of transmission system to islanding following a branch outage, a method denoted as one-line remaining algorithm is proposed which can recognize potential islands formation. As heuristic methods, in [7], a new algorithm based on ant search mechanism is proposed for identifying controlled islanding scenarios. In [33], the issue “where to island” is addressed, and for this purpose, a decision tree based tool is proposed to recognize conditions existing in the system that warrant controlled islanding. Based on the OBDD algorithm, a two-phase method [34] and a three-phase method [35] is used for searching proper splitting strategies in a medium scale and large-scale power systems respectively.

In recent years, optimization-based methods have been considered for controlled islanding. In [36], a flexible optimization method is proposed for controlled islanding in which a mixed-integer linear programming (MILP) formulation is used for simultaneous decision on the boundaries of islands and generators adjustment, constrained to load shed minimization. In [37], based on the mixed-integer programming technique and considering the restoration process within each island, a network partitioning algorithm is presented. In [38], a linear programming formulation problem is presented for controlled islanding, which determines an islanding solution for large-scale power
networks with minimal power-flow disruption. In [39], a mixed-integer second-order cone programming relaxation with dynamic simulation is intended for power system controlled islanding.

In this paper, in order to preserve transient stability of islands after intentional islanding, a new approach based on the coherency feature of oscillating generators is proposed. This approach is mainly based on the real-time voltage phase angle oscillation data provided by the wide-area measurement system (WAMS). WAMS is able to provide distributed and synchronized data from all over the network which makes it more suitable for wide-area phenomena like inter-area oscillation. In addition to communication facilities, phasor measurement units (PMU) are the main components of WAMS for providing such data. [40]. Using data provided by WAMS, the Correlation Coefficients (CCs) for all pairs of generators are evaluated as real-time indices based which for each pair an equivalent electrical distance is introduced. Using DBSCAN clustering algorithm and equivalent electrical distance between generators, coherent group of generators are identified as the backbone of controlled islands. Then, based on the shortest electrical distance between coherent generators and load buses and using MILP, the sub-network of island is identified. Finally, for each island by means of non-linear programming (NLP), the operational feasibility of islands are satisfied. Therefore, compared with the recently reported works [17, 39, 41] which attempted to handle all the process in one step, this paper presents an efficient three-steps approach for controlled islanding which can be more flexible. In this approach, although some optimal solutions may be ignored, but contrary to the previous works it always guarantees a feasible solution. The proposed approach is implemented on the IEEE 39-bus system as a small system and Iran power grid as a large-scale realistic power system. The results show the ability of the proposed method for implementation in a real power system.

II. PROPOSED METHOD

In this approach, for preserving the stability of the separated islands, based on the coherency of generators and minimum electrical distance between coherent generators and load buses a three-steps algorithm is proposed for controlled islanding as follows.

**STEP1- IDENTIFICATION OF COHERENT GENERATORS**

The ability of real-time identification of coherent groups of generators based on the measured oscillation data is one of the most vital issues in the strategy of controlled islanding. In power networks, following occurrence of various faults, there is a potential for forming coherent groups of generators in different patterns. Therefore, taking a pre-designed fixed pattern for the structure of coherent groups may lead to a mismatch with the actual pattern of coherent group which may result in an inappropriate defensive strategy against uncontrolled islanding [17, 18]. Therefore, following an event, a real-time measurement-based method for coherency identification is necessary. Generally, the measurement-based methods are based on two fundamental tasks: 1- coherency measuring and 2-clustering algorithm. In this paper, CC between generators is adopted as coherency measure and DBSCAN as online clustering algorithm.

A. CALCULATION OF CC

In this approach, coherent groups of generators are identified as the central core for the controlled islands in which each coherent group stands as the backbone of a controlled island. For real-time identification of coherent generators, the CCs between generators are used. The CC between rotor oscillations of two generators is a measure for the strength of similarity and linear association between two generators. It is worth noting that there is a strong correlation and similarity between rotor angle oscillation and terminal phase angle oscillation of generators. Regarding this fact, in contrast with other works [28, 42-44], in this paper for the sake of availability of data, CCs between generators are calculated based on the terminal phase angle oscillation of generators. The CC between two generators i and j is evaluated based on the generator's terminal phase angle oscillations provided by PMU within a moving time window consisting n sample points using Eq.(1) [44].

\[
CC_{ij} = \frac{n \sum_{k=1}^{n} (\theta_i(k) \theta_j(k)) - (\sum_{k=1}^{n} \theta_i(k)) (\sum_{k=1}^{n} \theta_j(k))}{\sqrt{n (\sum_{k=1}^{n} \theta_i^2(k)) - (\sum_{k=1}^{n} \theta_i(k))^2} \sqrt{n (\sum_{k=1}^{n} \theta_j^2(k)) - (\sum_{k=1}^{n} \theta_j(k))^2}}
\]

(1)

Where \( \theta_i(k) \) and \( \theta_j(k) \) are terminal phase angle of generators i and j respectively for sample k. The value of \( CC_{ij} \) lies within the range (+1.0 ~ -1.0), where the extreme value +1.0 refers to in-phase oscillations of unit i and j with perfect coherency whereas the extreme value -1.0 refers to anti-phase oscillations with no coherency. For this purpose, phase angle oscillation data for all terminal generators should be measured synchronously within a moving time window by WAMS. Using these data the CC between all pairs of generators can be consecutively evaluated. Based on the CC between two generators i and j, an equivalent electrical distance \( Ed_{ij} \) is defined by Eq. (2), which can be used as a criterion for clustering the coherent generators.\( Ed_{ij} = d_{max} \times \frac{1 - CC_{ij}}{2} \)

(2)

Where, \( d_{max} \) represents the maximum distance corresponding to anti-phase oscillations. In fact, Eq. (2) maps inversely the CCs (+1 ~ -1) to distance (0 ~ \( d_{max} \)) respectively.

B. DBSCAN Clustering Algorithm

The key idea of the proposed DBSCAN based clustering algorithm for generators is based on the equivalent electrical distance of generators from each other. Here, a short distance is a representative of the coherency of two generators.

In contrast to clustering algorithms used in recent papers such as Hierarchical clustering [45], K-means [16], Koopman Mode Analysis [46], Fuzzy C-means, and Kernel
Principal Component Analysis [47], which are dependent on a priori knowledge about the number of groups, the proposed algorithm does not need to specify the number of coherent groups a priori. In other words, it determines the coherent group adaptively based on online operating condition after disturbance. Also, calculation time of clustering algorithms is a key problem which can make them unsuitable for online controlled islanding, especially for large-scale power systems [48]. An interesting feature of the proposed DBSCAN algorithm is high-speed calculation ability which compared to [41, 42] takes only fraction of second for Iran power grid with more than 400 generators. Therefore, the proposed DBSCAN algorithm excellent efficiency on large power systems.

The DBSCAN algorithm requires two parameters $\varepsilon$ and $\text{minGs}$. The parameter $\varepsilon$ represents the radius of a neighborhood around each generator [49, 50]. In order to apply DBSCAN algorithm for generator clustering, for a given threshold distance $\varepsilon > 0$, based on the equivalent distance of generators, for each generator $G_i$ an $\varepsilon$-neighborhood is defined and the number of generators locating in the neighborhood is calculated by Eq. (3).

$$N_{\varepsilon}(G_i) = \{G_j \in D_i \mid \text{Ed}_{ij}(G_i, G_j) \leq \varepsilon\}$$

Where $G_i$ is regarded as the core of the $\varepsilon$-neighborhood, and $D_i$ contains all generators within the $\varepsilon$-neighborhood of $G_i$.

The process of DBSCAN clustering algorithm for finding a coherent group of generators can be explained through the following simulates.

1- Adopt a minimum number of generators (minGs) as a criterion for establishing an $\varepsilon$-neighborhood.

2- For all generators, corresponding $\varepsilon$-neighborhood and associated $N_{\varepsilon}(G)$ are calculated.

3- List all generators according to their $N_{\varepsilon}(G)$ from max to min.

4- Select the top unvisited generator with $N_{\varepsilon}(G)$
   - If $N_{\varepsilon}(G) < \text{minGs}$ and $G_i$ does not belong to a prior established cluster, it will constitute a new cluster
   - If $N_{\varepsilon}(G) < \text{minGs}$ and $G_i$ belongs to a prior established cluster, $D_i$ will be combined with the prior cluster
   - If $N_{\varepsilon}(G) < \text{minGs}$ and $G_i$ belongs to a prior established cluster then $D_i$ remained uncombined

5- If all generators are examined the process will be terminated otherwise;

6- Eliminate the unvisited generators from the list and go to step 4

Fig. 1 shows a conceptual illustration of DBSCAN clustering algorithm.

**STEP2- ESTABLISHMENT OF SUB-NETWORK**

To find the sub-network associated with each controlled island, each coherent group of generators is regarded as backbone of a sub-network. The minimum electrical distance between load buses and generators of coherent groups are determined. By performing a MILP, the sub-networks associated with controlled islands consisting of coherent generators and nearest load buses are constructed.

Fig. 1. Conceptual illustration of DBSCAN clustering algorithm

**A. MINIMUM ELECTRICAL DISTANCE OF LOAD BUSES TO GENERATORS**

For finding the sub-networks of the controlled islands, by using the Dijkstra algorithm (DA) [51], the minimum electrical distance between all load buses and generators are evaluated. According to DA, the power network is considered as a graph in which buses and branches are regarded as nodes and edges of the graph, respectively. Each branch is weighted by its reactance as its electrical length. By using DA, the shortest electrical path and distance in terms of the number of nodes and reactance are calculated for all pairs of generator and load buses as follows:

$$\text{SEP}_{ij} = \text{Shortest electrical path between nodes } i \text{ and } j \text{ in term of number of nodes}$$

$$\text{LED}_{ij} = \text{Least electrical distance between nodes } i \text{ and } j \text{ in terms of reactance}$$

All distances are calculated offline. However, if network structure changes due to a line outage, the algorithm modifies the distances only for those paths affected by the outage. After evaluating the least electrical distances, for representing the backbone of each potential island, all generators of each coherent group are merged into an equivalent generator (EG). Fig. 2 shows the process of merging a coherent group consisting of three generator nodes (1, 2, 3), five load nodes (5, 6, 7, 8, 9) and a null node (4). The process of merging coherent generators into one equivalent generator is explained as follows.

1- The shortest paths between coherent generators are found, as shown by the bold lines in Fig. 2-a.

2- All coherent generators, including the nodes in the shortest path (i.e., 5, 6, 8, 9), are merged, consisting a new equivalent generator $J$, as shown by the dashed circle in Fig. 2-b.

3- All other nodes remain as nodes with the modified distances from $J$ as follows.

$$\text{SED}_{ij}^{\text{new}} = \min\{\text{SED}_{ij}||J \in \text{Coherent Generator } J\}$$

4- The generation power of the equivalent generator $J$ corresponding to the $J$th coherent group is evaluated as follows;
\[ P_{GJ} = \sum_{i \in J} (P_{Gi} - P_{Li}) \]  

(5)

At the end of this process, all generators are merged into equivalent generators with a reduced network.

\[ \text{Fig. 2. The process of merging the generators of a coherent group} \]

**B. FINDING THE SUB-NETWORK OF ISLANDS**

After constructing equivalent generators as the backbones of islands, the sub-networks around equivalent generators corresponding to islands are identified by performing an optimization algorithm. The main criteria for constructing sub-networks is the connection of load buses to the nearest equivalent generator constrained to preserving load-generation balance, which can be formulated as a MILP as follows:

\[
\min: f = \sum_{i=1}^{N_b} \sum_{j=1}^{N_f} C_{ij} \cdot X_{ij} 
\]

(6)

Subject to:

\[
P_{DJ} = \sum_{i=1}^{N_b} C_{ij} \cdot P_{di} \leq 1.1 P_{GJ} \quad \forall J = 1 \ldots N_f
\]

(7)

\[
P_{DJ} = \sum_{i=1}^{N_b} C_{ij} \cdot P_{di} \geq 0.9 P_{GJ} \quad \forall J = 1 \ldots N_f
\]

(8)

\[
\sum_{j=1}^{N_f} C_{ij} = 1 \quad \forall i = 1 \ldots N_b
\]

(9)

Where:

- \( N_b \): Number of non-generator nodes in the reduced network
- \( N_f \): Number of EGs representing coherent groups
- \( X_{ij} \): Total reactance of the shortest electrical path between node \( i \) and \( EG_j \)
- \( C_{ij} \): Connectivity of node \( i \) to \( EG_j \) such that:
  - \( C_{ij} = 1 \) if node \( i \) is located in the island \( J \).
  - \( C_{ij} = 0 \) if node \( i \) is not located in the island \( J \).
- \( P_{Di} \): Total generation (MW) of \( EG_i \).
- \( P_{DJ} \): Total load (MW) in the sub-network associated with \( EG_j \).

Eqs. (7) and (8) guarantee load-generation balance in each potential island regarding 10% generation reserve (0.9PGJ < PDJ < 1.1PGJ). Eq. (9) Guarantees the connection of each non-generator node \( i \) to only one island \( J \). At the end of this process, the sub-networks with their corresponding buses and lines will be identified.

**STEP 3- OPERATIONAL FEASIBILITY OF SUB-NETWORK ISLANDS**

After constructing sub-networks, in order to make each sub-network operable with respect to line overloading and voltage drop, the available remedial actions such as generation rescheduling and load shedding within the permissible capacities are used. These operational constraints could be modeled using AC or DC power flow equations. Because, as a result of ignoring voltage and reactive power, the DC power flow-based islanding strategies [18, 41] may be inaccurate. Therefore, AC power flow is considered in recent papers. As time is of the essence, some algorithms employ linearized AC power flow equations to reduce system models and calculations [17, 39]. It is noted that linearized models are not capable to capture the actual behavior of a profoundly disturbed power network, such as controlled islanding conditions. Therefore, to improve accuracy of controlled islanding, AC equations are used so that without linearization, acceptable computational efficiency is satisfied. In order to use minimum generation rescheduling and minimum load shedding, the problem for each island \( J \) can be handled by the NLP algorithm formulated by Eqs. (10)-(20). It is worth noting that all load buses are equipped with load shedding with a capacity of 20% of their nominal load.

\[
\min : \sum_{i=1}^{N_g} \left( \frac{P_{g_i}^R}{\max} \right)^2 + \alpha \sum_{j=1}^{N_f} P_{dj}^S \quad J = 1, 2, \ldots, N_f
\]

(10)

Subject to:

\[
\sum_{i=1}^{N_g} P_{g_i}^R - \sum_{j=1}^{N_f} P_{dj}^S = f_p(\theta, V)
\]

(11)

\[
\sum_{i=1}^{N_g} Q_{g_i}^S - \sum_{j=1}^{N_f} Q_{dj}^S = f_q(\theta, V)
\]

(12)

\[
P_{dj}^S = 0.8 P_{dj}^R + P_{dj}^{Sh}
\]

(13)

\[
Q_{dj}^S = K_{Fj} P_{dj}^S + K_{Qj} P_{dj}^S
\]

(14)

\[
P_{g_i}^R = P_{g_i}^0 + f_{Pg}(\theta, V)
\]

(15)

\[
0 \leq P_{dj}^S \leq 0.2 P_{dj}^R
\]

(16)

\[
-0.1 P_{g_i}^\max \leq P_{g_i}^S \leq 0.1 P_{g_i}^\max
\]

(17)

\[
Q_{g_i}^S \leq Q_{g_i}^\max
\]

(18)

\[
F_{lk}(\theta, V_{im}) \leq Q_{g_i}^\max
\]

(19)

\[
\nu_{i}^\min \leq \nu_{i} \leq \nu_{i}^\max
\]

(20)

Where:

- \( N_g \): Number of generators in island \( J \)
- \( N_f \): Number of loads in island \( J \)
\( p_{G_i}^{R}, p_{G_j}^{S} \): Amount of generation rescheduling and load shedding at bus \( i \) and \( j \) respectively
\( Q_{G_i}, Q_{G_j}^{\text{max}} \): Amount of reactive generation and maximum active generation at bus \( i \)
\( \alpha \): Weighting factor showing the contribution of load shedding for operational feasibility of islands
\( p_{G_i}^{R}, p_{G_j}^{S} \): Active generation at bus \( i \) before and after rescheduling respectively
\( p_{G_i}^{R}, p_{G_j}^{S}, Q_{G_i}^{\text{max}} \): Active and reactive loads at bus \( j \) before and after load shedding respectively
\( F_{Lk}, F_{k}^{\text{max}} \): Apparent power flow and maximum power flow of line \( k \) respectively
\( v_i, v_i^{\text{min}}, v_i^{\text{max}} \): Voltage magnitude and its lower and upper limits at bus \( i \) respectively
\( K_D = \tan(\cos^{-1}(\varphi)) \): the ratio of reactive load to active load at bus \( i \)

Eqs (11) and (12) represent active and reactive power flow equations respectively, and superscripts \( R \) and \( S \) refer to the situation after rescheduling and load shedding, respectively. Eqs (13) and (14) show active and reactive power after load shedding and generation rescheduling, respectively. Eq. (15) Moreover, (16) represent limits on load shedding and generation rescheduling, respectively. Eq. (19) Furthermore, (20) represent limits on line flows and bus voltage magnitudes.

III. SIMULATION STUDY

In order to demonstrate the effectiveness and ability of the proposed algorithm for finding controlled islanding, the algorithm has been applied to the IEEE 39-bus test system illustrated in Fig. 3-a and Iran 522-bus power network as a bulk power system illustrated in Fig. 9-a and simulation results are presented.

A. Simulation Results for IEEE 39-bus Network

In this scenario, a three-phase fault occurs on line 2-3 near to bus #2 at \( t=5 \) s, and by outage of the line is cleared after 160 ms. As a consequence of fault condition, at \( t=8.7 \) s, line 26-27 is tripped due to power oscillation. Following these events, the inter-area oscillation between coherent groups of generators is excited. Finally, without any control, the network is separated into two uncontrolled islands at \( t=19.9 \) s. Fig. 3-b shows the rotor angle oscillation of all generators following the event until the point of out of step.

In order to apply the proposed control strategy, by using PMU installed at the terminal of generators, voltage phase angles and line currents are measured by sampling time of 10 ms. Based on the measured data, a moving time window of 1 s including 100 samples with updating time interval of 10 ms is constructed. Then by using Eqs. (1) and (2), CCs and electric distance between all pairs of generators are determined consecutively.

For DBSCAN clustering algorithm, the values of \( d_{\text{max}}, \varepsilon, \) and \( \text{MinGs} \) are set to 10, 0.6 and 3, respectively. All generators are categorized into two coherent groups, as shown in Table i and depicted in Fig. 3. Table ii shows the time required for identification of coherent generators with DBSACN compared to [42-44]. As can be seen, DBSCAN algorithm is much faster. This supremacy is more evident on the Iran power grid which makes DBSCAN more efficient for controlled islanding.

Using DA, the minimum path between all nodes and generators are calculated. In Fig. 4-a, bold lines show the shortest paths between generators of each coherent group. In Fig. 4-b, EG\(_1\) and EG\(_2\) show the equivalent generators for two coherent groups, respectively, with their associated shortest routes merged into them. In this figure, the backbone of the sub-network associated with each coherent group is presented. After finding equivalent generators, the shortest distances of all remained nodes from equivalent generators are modified by Eq.(4). The generation power of each
equivalent generator (EG) is evaluated by Eq. (5). The initial sub-networks associated with islands are identified by performing the optimization algorithm of step 2-B, as shown in Fig. 5-a. Fig. 5-b shows the whole topology of sub-networks with original nodes and branches. The boundary lines which should be opened for controlled islanding are; 26-27, 2-3, 6-7, and 5-8.

By applying the NLP algorithm of step 3, the operational feasibility of the islands is checked. In the previous works [17] it is assumed that all loads are available to be shed up to their maximum values. For the sake of simplicity, it is assumed that immediately after network splitting, the power balance of each island is satisfied by the simultaneous execution of all control actions. However, these simplified assumptions may not hold in practice. Furthermore, due to inherent delay in performing load shedding and generation change, it is expected to have a specific power imbalance in each island for a short time. Therefore, in this paper, the actual amount of load shedding capacity of network equipped with the under-frequency relay and free governor capacity of network is considered for the allowable mismatch of each island. Therefore, for preserving load-generation balance in islands, 10% of each generator’s nominal capacity is considered as a controllable reserve, and 20% of each load is allocated for load shedding. Table iii shows the load-generation balance in the islands after optimization. The strategy of controlled islanding is carried out at t=19.5 s by opening boundary lines 6-7 and 5-8. Fig. 6-a shows rotor angle oscillations after controlled islanding, and as shown, all oscillations are damped.

| Island No. | Gen. | Generation (MW) Before Islanding | Generation (MW) After Islanding | Total generation (MW) Before Islanding | Total generation (MW) After Islanding | Generation rescheduled (MW) After Islanding | Total Load (MW) Before Shedding | Total Load (MW) After Shedding | Load shedding (%) |
|------------|------|----------------------------------|----------------------------------|---------------------------------------|---------------------------------------|------------------------------------------|-------------------------|-------------------------|------------------|
| A (Blue)   | 30   | 294.4                            | 264.9                            |                                       |                                       |                                          | 3269.7                  | 3396                    | +3.86            |
|            | 37   | 640.5                            | 576.5                            |                                       |                                       |                                          | 3277                    | 3471                    | 3.15             |
|            | 38   | 952.0                            | 890.3                            |                                       |                                       |                                          | 3277                    | 3471                    | 1.15             |
|            | 39   | 1105.3                           | 1042                             |                                       |                                       |                                          | 3277                    | 3471                    | 1.48             |
| B (Red)    | 31   | 119.6                            | 125.6                            |                                       |                                       |                                          | 2992.3                  | 2774                    | -7.29            |
|            | 32   | 700.7                            | 723.5                            |                                       |                                       |                                          | 2717                    | 2676                    | 1.48             |
|            | 33   | 671.0                            | 694.8                            |                                       |                                       |                                          | 2717                    | 2676                    | 1.48             |
|            | 34   | 533.9                            | 557.5                            |                                       |                                       |                                          | 2717                    | 2676                    | 1.48             |
|            | 35   | 650.0                            | 674.1                            |                                       |                                       |                                          | 2717                    | 2676                    | 1.48             |
|            | 36   | 594.6                            | 618.5                            |                                       |                                       |                                          | 2717                    | 2676                    | 1.48             |

In order to show the role of coherency in preserving transient stability of islands after controlled islanding, another islanding scenario is examined in which with preserving load-generation balance, coherency of generators is not preserved completely. For this purpose, by opening line 1-39, generator 39 is separated from its red group (30, 37, 38) and located in the blue group (31, 32, 33, 34, 35, 36, 39). Fig. 6-b shows unstable rotor angle oscillations of the generators after islanding with incoherent groups.

In this case, Iran power grid as a realistic large-scale power system, with the specification shown in Table iv is adopted for examining the proposed approach. All time-domain dynamic simulation studies are carried out for the
whole system consisting of 413 generating units.

### TABLE IV.
Specification of Iran power grid

| HV Buses (kV) | HV Transmission Lines (kV) | Generating Unit | Load |
|---------------|---------------------------|-----------------|------|
| 230           | 400                       | 230             | 400  |
| 319           | 203                       | 553             | 193  |

An event including a short-circuit on line BE906 at t=9s is applied, which is cleared by the outage of the line after 100 ms. Following this line trip, some generators will become out of step at t=19.7s. Fig. 7-a shows rotor angle oscillation for all generators following the event. The generators with the same type located in one power station with full coherent oscillations are replaced with an equivalent generator whose rotor angle and inertia are evaluated using Eq.(21).

\[
\delta_{eq} = \frac{1}{H_{eq}} \sum_{i}^{N_g} H_i \cdot \delta_i
\]

\[
H_{eq} = \frac{\sum_{i}^{N_g} H_i \times S_i}{\sum_{i}^{N_g} S_i}
\]

Where, \( \delta_i \), \( H_i \) and \( S_i \) are rotor angle, constant inertia and rating power of generating unit \( i \) locating in a power station, and \( N_g \) is the number of generating units of the power station, and \( \delta_{eq} \) and \( H_{eq} \) are rotor angle and constant inertia of the equivalent generator for the power station.

By this way, the number of generators is reduced to 115 equivalent units. Fig. 7-b shows rotor angle oscillation for 115 equivalent generators. As the first step of the proposed approach, CCs between all 115 equivalent generators are evaluated consecutively within a moving time window with a length of 4s. Based on the CCs and using the DBSCAN clustering algorithm, all generators are categorized into two coherent areas denoted as East area and CW area.

### TABLE V.
Regions constructing coherent areas

| Group No. | Coherent Area | Regions constructing coherent area | Number of Equivalent Gen. | Total generation (MW) |
|-----------|---------------|-----------------------------------|---------------------------|------------------------|
| 1         | East          | Khorasan, Sistan, Semnan & Golestan | 22                        | 7513                   |
| 2         | CW            | Center & West                     | 93                        | 39227                  |

As the second step, by using DA, minimum routes between every two equivalent generators of the Iran power graph are calculated. Fig. 9-a shows the shortest paths between generators of each area by bold lines. The generators of each coherent area with their associated shortest routes are embedded and represented by one equivalent generator constructing the backbone of the islands.

After backbone construction, by performing the optimization algorithm of step 2-B, the sub-networks associated with coherent areas are identified as initial sub-networks, as illustrated in Fig. 9-b. The load-generation situation is shown in Table vi. After finding two islands, the lines connecting two islands are recognized as the inter-area lines, as shown in Table vii. The operational feasibility of the islands is checked by the non-linear optimization algorithm of step 3. For this purpose, the capacity of generation reserve and load shedding are defined as 10% and 20% of total

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generation and load, respectively. The result of the optimization is shown in Table VIII.

By opening inter-area lines, the islanding strategy evaluated by the proposed approach is implemented on Iran power network at $t=19$ s before happening uncontrolled separation of two areas. Fig. 10 shows rotor angle oscillations of all generators after applying controlled islanding. Fig. 10-a illustrates rotor angle oscillations of East area and Fig. 10-b illustrates rotor angle oscillations of CW area.

**TABLE VI.** Load-generation condition for areas East & CW in Iran power grid before islanding (STEP 2-B)

| Area | Total generation (MW) | Total Load (MW) | Load-Gen. mismatch (MW) | Generation reserve (10%) | Load Shedding Capacity (20%) |
|------|-----------------------|----------------|------------------------|--------------------------|-----------------------------|
| East | 7513                  | 7172           | 341                    | 751                      | 1434                        |
| CW   | 39227                 | 39068          | 159                    | 3923                     | 7813                        |
| Sum  | 46740                 | 46240          |                        |                          |                             |

As can be seen by applying the strategy of controlled properly all generators in two islands East and CW are remained stable with damped oscillation.

**TABLE VII.** Inter-area lines between two islands of Iran power grid

| No  | Branch Name | From (Area A) | To (Area B) |
|-----|-------------|---------------|-------------|
| 1   | AL806B      | HEZARSANGAR   | Alamdeh     |
| 2   | AM800       | Bam           | AnbarAbad   |
| 3   | BM824       | Bam           | KermanCC    |
| 4   | BR806       | Iranshahr     | Halil       |
| 5   | CV809c      | SavadKuh      | FiruzKuh    |
| 6   | EM812       | Bam           | Shahab      |
| 7   | FW933       | Narivaran     | HasanKif    |
| 8   | GL929       | Golshan       | Nakhlestan  |
| 9   | HM828       | Semnan        | Garmser     |
| 10  | KR810b      | Delgan ToT    | Kahunj      |
| 11  | LN926       | ShahidSalimi  | Jalal       |

**TABLE VIII.** Generator rescheduling and load shedding

| Island | Total generation Before Islanding | Total generation After Islanding | Generation rescheduled | Total Load Before Shedding | Total Load After Islanding | Load shedding |
|--------|----------------------------------|----------------------------------|-------------------------|----------------------------|----------------------------|---------------|
| East   | 7512                             | 7189                             | -323                    | 7172                       | 7103                       | 70            |
| CW     | 39227                            | 39233                            | 6                       | 39068                      | 38673                      | 395           |

Fig. 10. Rotor angle oscillation of all generators (a) in island East (b) in island CW

In order to have a global comparison between the proposed approach with other works, TABLE IX shows the ability and features of the proposed approach compared to other methods. According to TABLE IX, the ability of an approach can be evaluated from different point of views, including on-line, off-line, number of coherent groups, AC/DC load flow calculation and load shedding constraint. As it can be seen the proposed approach is an on-line method without any knowledge about number of coherent groups which uses AC load flow
calculation. All these features make it powerful for fast handling the strategy of controlled islanding in a realistic large-scale power system.

| Proposed  | TABLE IX. | \(\text{COMPARISON OF THE PROPOSED APPROACH WITH THE PREVIOUS WORKS}  
| Ref. | coherency identification | prior knowledge for NO. of clusters | Load flow equations | Load shedding constraint | Real limitations | Bulk power system |
|------|--------------------------|-------------------------------------|---------------------|-------------------------|------------------|------------------|
| [17] | ✓                        | -                                   | ✓                   | ✓                       |                  |                  |
| [18] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [19] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [46] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [47] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [48] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [39] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |
| [41] | ✓                        | ✓                                   | ✓                   | ✓                       |                  |                  |

IV. CONCLUSION

In this paper, for preserving the rotor angle stability of controlled islands, based on the coherency feature of generators and the shortest electrical distance, an algorithm for controlled islanding is proposed. The coherency of generators is identified by CCs between generators using real-time oscillation data provided by the WAMS. Based on the CC between generators, an equivalent electrical distance is introduced from which by using DBSCAN clustering algorithm, a fast method for coherency identification is proposed. DBSCAN is very fast compared to other algorithms and its speed is independent of the size of the network. The effect of coherency on the rotor angle stability of separated controlled islands is demonstrated well and it is shown that without considering coherency of generators there is no guarantee for stability of islands. The proposed scheme is implemented on the IEEE 39-bus system as a small system and Iran power grid as a large-scale realistic power system. The results show the ability of the proposed method for implementation in a real size power system.

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