

Controlled islanding schemes for interconnected power systems based on coherent generator group identification and wide-area measurements



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Abstract A reasonable islanding strategy of a power system is the final resort for preventing a cascading failure and/or a large-area blackout from occurrence. In recent years, the applications of wide area measurement systems (WAMS) in emergency control of power systems are increasing. Therefore, a new WAMS-based controlled islanding scheme for interconnected power systems is proposed. First, four similarity indexes associated with the trajectories of generators are defined, and the weights of these four indexes are determined by using the well-developed entropy theory. Then, a coherency identification algorithm based on hierarchical clustering is presented to determine the coherent groups of generators.

Secondly, an optimization model for determining controlled islanding schemes based on the coherent groups of generators is developed to seek the optimal cutset. Finally, a 16-generator 68-bus power system and a reduced WECC 29-unit 179-bus power system are employed to demonstrate the proposed WAMS-based controlled islanding schemes, and comparisons with existing slow coherency based controlled islanding strategies are also carried out.

Keywords Wide area measurement system, Coherent generators, Controlled islanding, Trajectory clustering algorithm, Entropy weight

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1 Introduction

Due to the ever-increasing energy demand, power systems are now operating closer to their operation limits, and the growing complexity of power systems and the inevitable uncertainties in power system operation introduced by fast penetration of renewable stochastic generation (such as wind and solar) increase the possibility of power system failures [1, 2]. Power system islanding [3–5] is one of the solutions to preventing cascading failures and/or wide-area blackouts, which could maintain the stability of power systems under contingencies [6].

Several methods have been proposed to split a power system into several islands [7–12], and some controlled islanding schemes are based on the coherent groups of generators in a given power system. In [11], the weak coupling among generators is employed to cluster the generators with slow coherency, and then the spectral clustering scheme presented to split the power system into controlled islands. An integrated WAMS-based adaptive controlled islanding scheme is presented, in which the improved Laplacian eigenmap algorithm is employed to identify the

coherent generators [12]. An identification algorithm of the controlling group of generators is presented and a new power system islanding scheme is proposed based on the unified stability control framework in [13]. In [14], two wide-area protection schemes both on synchrophasor measurements are presented for controlled islanding of the Uruguayan electrical power system. An approach for identifying coherent generators of power systems is presented in [15] by using spectrum analysis of the generators velocity variations. In [16], an algorithm based on principal component analysis is presented for identifying coherent generators of an interconnected power system by using the measured data sets of generator speeds and bus angles. In [17], the independent component analysis method is applied for coherency identification of interconnected power systems with WAMS. The Fourier analysis method is proposed in [18] to identify the coherent groups of generators by analyzing the generator speed sets measured by WAMS. In [19], a method based on non-negative matrix factorization is presented to identify the coherent generators from the measured high-dimensional generator speeds. A new unified synchrophasor-based controlled separation scheme, which is strategically implemented in three time stages (i.e., offline analysis stage, online monitoring stage and real-time control stage) is proposed, and the synchrophasors are employed to study “where” and “when” to island [20]. In [21], two islanding detection methods based on bus voltage phase angles and frequencies measured by a frequency monitoring network (FNET) is presented and applied to the North American power grid.

Based on the above survey, it can be seen that the current research publications on power system islanding schemes mainly focus on the islanding methods or algorithm based on the given power system topology and the coherency identification methods or algorithms based on the measured generator speeds or bus angles. However, the swing curves of generators after a disturbance consist of many swing parameters, such as generator angles, speeds and swing directions, so there should be many hidden characteristics to be investigated. Thus, all the generator angles, speeds and swing directions of swing generator curves should be fully considered in the identification of coherent generator groups.

Therefore, a comprehensive study on the swing curves of generators measured by the WAMS is performed in this paper. First, four indexes, i.e., the angle deviation similarity, swing direction similarity, rotating speed deviation similarity, and corner deviation similarity, are defined for identifying the coherency of generators based on the swing curves or trajectories of generators. Then, four indexes are combined into a synthesized index by using the entropy weight theory, which could take most of the characteristics of generator trajectories into consideration in identifying the coherent generator groups. For a given power system, each generator can be considered as a cluster, and the generators with

highest coherency can be clustered into one group. Thus, the agglomerative method of the hierarchical clustering which could be used to build a hierarchy of clusters is employed to identify the coherent groups of generators. Then, the optimization model of controlled islanding schemes based on the coherent group of generators is developed to seek the optimal cutset. Finally, a 16-generator 68-bus power system and the reduced WECC 29-unit 179-bus power system are used for demonstrating the effectiveness of the proposed WAMS-based islanding schemes.

2 Coherency identification of generators

Given a set of trajectories $T = \{T_{r1}, T_{r2}, T_{r3}, \dots, T_{rm}, \dots, T_{rM}\}$ ($1 \leq m \leq M$) of all generators in a given power system, which is measured by phase measurement units (PMUs) with a fixed time interval. An angle or speed trajectory T_{rm} of one generator is defined as a sequence of multi-dimensional points. M is the total number of the generators in the power system. $T_{ri} = \{P_{m,1}, P_{m,2}, P_{m,3}, \dots, P_{m,n}, \dots, P_{m,N}\}$ ($1 \leq n \leq N$), where $P_{m,n}$ is the n^{th} sampling point of the m^{th} generators measured by PMUs and represented by a point $(T_n, \delta_{m,n}$ or $\omega_{m,n})$ on the coordinate axis. N is the total number of the sampling points; T_n is the time of the n^{th} sampling point; $\delta_{m,n}$ and $\omega_{m,n}$ are the generator angle and rotating speed of the m^{th} generator measured by PMUs at the n^{th} sampling point (i.e. T_n), respectively.

2.1 Trajectory similarity for coherency identification

In this section, four indexes for identifying the coherency of generators are introduced [22].

1) Angle deviation similarity

The angle deviations between any two generators are widely employed to determine the coherency of generators in actual power systems. Therefore, it should be considered in selecting the indexes for identifying the coherency of generators. The angle deviation similarity is defined to reflect the relative distance between any two angle trajectories. Thus, the index of the angle deviation similarity between the i^{th} and j^{th} generators can be formulated as

$$I_L(i, j) = \sqrt{\sum_{n=1}^N [(\delta_{i,n} - \delta_{i,1}) - (\delta_{j,n} - \delta_{j,1})]^2} \quad (1)$$

where $\delta_{i,n}$ and $\delta_{j,n}$ are the angles of the i^{th} and j^{th} generators at the sampling point n ; $\delta_{i,1}$ and $\delta_{j,1}$ are the angles of the i^{th} and j^{th} generators at the starting sampling point. It can be seen that $I_L(i, j)$ could well measure the deviation between the i^{th} and j^{th} angle trajectories.



2) Swing direction similarity

The swing direction similarity is used to reflect the deviation degree of the overall swing directions between the i^{th} and j^{th} generator angle trajectories. The index of swing direction similarity between generator i and generator j is formulated as

$$I_D(i, j) = \arccos \left(\frac{\overrightarrow{P_{i,1}P_{i,N}} \overrightarrow{P_{j,1}P_{j,N}}}{\| \overrightarrow{P_{i,1}P_{i,N}} \| \| \overrightarrow{P_{j,1}P_{j,N}} \|} \right) \quad (2)$$

where $\overrightarrow{P_{i,1}P_{i,N}}$ and $\overrightarrow{P_{j,1}P_{j,N}}$ are the vectors from the starting sampling point $(T_1, \delta_{i,1})$ to the ending sampling point $(T_N, \delta_{i,N})$ of the i^{th} and j^{th} generator trajectories.

3) Rotating speed deviation similarity

When a disturbance occurs in a power system, the power flow will be redistributed and then the generation outputs will change. Then the rotating speeds of generators will be increased or decreased. The rotating speed deviation between the measured speed and the synchronized speed should be considered in the coherency identification. With the rotating speed deviation considered, it would be helpful to identify the coherency of generators quickly and correctly. Thus, the rotating speed deviation similarity is defined as an index to check the difference between the i^{th} and j^{th} speed trajectories of generators, which is represented as

$$I_S(i, j) = \sqrt{\sum_{n=1}^N (\omega_{i,n} - \omega_{j,n})^2} \quad (3)$$

where $\omega_{i,n}$ and $\omega_{j,n}$ are the rotating speed of the i^{th} and j^{th} generators at the sampling point n .

4) Corner deviation similarity

For a power system under disturbances, the angles of different generators will oscillate towards different direction, which will impact on the coherency of generators. So the inner direction changes of angle trajectories at different sampling points should be considered. The inner direction changes of an angle trajectory can be represented by the angle deviation of two neighboring sampling intervals, and is denoted as

$$\theta_{i,n} = \begin{cases} \arccos \left(\frac{\overrightarrow{P_{i,n-1}P_{i,n}} \overrightarrow{P_{i,n}P_{i,n+1}}}{\| \overrightarrow{P_{i,n-1}P_{i,n}} \| \| \overrightarrow{P_{i,n}P_{i,n+1}} \|} \right) & \delta_{i,n-1} + \delta_{i,n+1} \geq 2\delta_{i,n} \\ -\arccos \left(\frac{\overrightarrow{P_{i,n-1}P_{i,n}} \overrightarrow{P_{i,n}P_{i,n+1}}}{\| \overrightarrow{P_{i,n-1}P_{i,n}} \| \| \overrightarrow{P_{i,n}P_{i,n+1}} \|} \right) & \delta_{i,n-1} + \delta_{i,n+1} < 2\delta_{i,n} \end{cases} \quad (4)$$

where $\overrightarrow{P_{i,n-1}P_{i,n}}$ and $\overrightarrow{P_{i,n}P_{i,n+1}}$ are the vectors from the sampling points $(T_{n-1}, \delta_{i,n-1})$ and $(T_n, \delta_{i,n})$ to the sampling

points $(T_n, \delta_{i,n})$ and $(T_{n+1}, \delta_{i,n+1})$ of the i^{th} generator trajectory. If $\delta_{i,n+1} - \delta_{i,n} \geq \delta_{i,n} - \delta_{i,n-1}$ (i.e. $\delta_{i,n-1} + \delta_{i,n+1} \geq 2\delta_{i,n}$), $\theta_{i,n}$ is a positive value of the intersection angle of vectors $\overrightarrow{P_{i,n-1}P_{i,n}}$ and $\overrightarrow{P_{i,n}P_{i,n+1}}$; otherwise, $\theta_{i,n}$ is a negative value of the intersection angle of vectors $\overrightarrow{P_{i,n-1}P_{i,n}}$ and $\overrightarrow{P_{i,n}P_{i,n+1}}$.

Based on the above inner direction changes of the angle trajectories, an index for reflecting the corner deviation similarity of two angle trajectories can be defined to measure the difference of internal oscillation degree between the i^{th} and j^{th} generators. The index of corner deviation similarity is represented as

$$I_C(i, j) = \sum_{n=2}^{N-1} \frac{1}{N-2} |\theta_{i,n} - \theta_{j,n}| \quad (5)$$

where $\theta_{i,n}$ and $\theta_{j,n}$ are inner direction changes of the i^{th} and j^{th} angle trajectories at the sampling point n .

It can be seen from the definition of four similarity indexes that there are four index values for each pair of generators, and these four indexes will reflect the coherency of generators to some extent. Given a power system with M generators, there exist four $M \times M$ matrices for all generators, which are I_L , I_D , I_S and I_C where $I_L = [I_L(i, j)]_{M \times M}$, $I_D = [I_D(i, j)]_{M \times M}$, $I_S = [I_S(i, j)]_{M \times M}$ and $I_C = [I_C(i, j)]_{M \times M}$. It can be seen that all the matrices of four indexes are symmetric matrices, and all their diagonal elements are equal to zero.

It can be seen from (1)–(3) and (5) that four similarity indexes cannot be compared with each other directly because they have different measurement units. So these four indexes should be normalized before integrating them. The four matrices are translated to $I'_L = [I'_L(i, j)]_{M \times M}$, $I'_D = [I'_D(i, j)]_{M \times M}$, $I'_S = [I'_S(i, j)]_{M \times M}$, $I'_C = [I'_C(i, j)]_{M \times M}$, which are calculated by

$$I'_L(i, j) = \frac{I_L(i, j)}{\max_{i, j \in \{1, 2, \dots, M\}} \{I_L(i, j)\}} \quad (6)$$

$$I'_D(i, j) = \frac{I_D(i, j)}{\max_{i, j \in \{1, 2, \dots, M\}} \{I_D(i, j)\}} \quad (7)$$

$$I'_S(i, j) = \frac{I_S(i, j)}{\max_{i, j \in \{1, 2, \dots, M\}} \{I_S(i, j)\}} \quad (8)$$

$$I'_C(i, j) = \frac{I_C(i, j)}{\max_{i, j \in \{1, 2, \dots, M\}} \{I_C(i, j)\}} \quad (9)$$

For a given pair (i, j) of generators, four indexes after normalization will have different values, so it would be difficult to identify the different coherent groups of generators because all four indexes for one pair of generators might not be better than that for the other

pairs. As a result, a synthesized similarity index for identifying the coherency of generators should be given to solve this issue. Therefore, the weighting method is employed to generate the following $M \times M$ synthesized similarity matrix.

$$\mathbf{I}_{\text{Coherency}} = W_1 \mathbf{I}'_L + W_2 \mathbf{I}'_D + W_3 \mathbf{I}'_S + W_4 \mathbf{I}'_C \quad (10)$$

where W_1, W_2, W_3, W_4 are the weights of the angle deviation similarity $I'_L(i, j)$, swing direction similarity $I'_D(i, j)$, rotating speed deviation similarity $I'_S(i, j)$ and corner deviation similarity $I'_C(i, j)$, respectively. Equation (10) is used to find the coherent and equivalent generators based on the aggregation method [22, 23] which is also employed in DYNRED (Dynamic reduction program of EPRI, USA) [20, 25–27]. Theoretical details could be found in [22, 23]. If the trajectories of two generators i and j are similar, which means that these two generators are within one coherent group, the value of the synthesized similarity index $I_{\text{Coherency}}(i, j)$ would be relatively small; otherwise, it would be relatively large. Therefore, the coherency of generators could be identified by the elements of the synthesized similarity index matrix $\mathbf{I}_{\text{Coherency}}$. The synthesized similarity matrix $\mathbf{I}_{\text{Coherency}}$ is also symmetrical, i.e., $\mathbf{I}_{\text{Coherency}}(i, j) = \mathbf{I}_{\text{Coherency}}(j, i)$, which means that the coherency between the i^{th} and j^{th} generators is identical to the one between the j^{th} and i^{th} generators. Thus, there is $M(M - 1)/2$ pairs of generators for identifying their coherency.

2.2 Coherency evaluation based on entropy weight

It can be seen from (10) that the synthesized similarity index matrix $\mathbf{I}_{\text{Coherency}}$ is impacted by four similarity matrices $\mathbf{I}'_L, \mathbf{I}'_D, \mathbf{I}'_S$ and \mathbf{I}'_C , which are calculated by the PMU sampling values of generator trajectories, and four index weights W_1, W_2, W_3 and W_4 , which is to be determined. If different weights are selected, different coherency identification results will be obtained. So how to select the appropriate weights for four indexes will impact on the accuracy of coherency identification.

In practice, the relative importance (i.e. weight) of each evaluating index (or attribute) was also considered in multi-attribute decision-making. A direct and simple method for determining weights is to set each index with a value by power experts based on their knowledge and experience. However, the experts who is unfamiliar the power systems will give the incorrect weights for four similarity indexes, and then will impact the correctness of coherency identification of generators.

In thermodynamics, entropy can be employed to measure the disorder. According to information theory, the disorder of the obtained information (i.e. the sampling

points of generator trajectories in this paper) can also be measured by entropy [24]. The values of the sampling points of generator trajectories are disorder, so it can be deduced from some closely related indexes based on the entropy. Thus, an objective weight, which is denoted as the entropy weight, can be deduced from the entropy of the parameters of the sampling points of generator trajectories in this paper.

In order to determine the weights of four indexes by using the entropy theory, the problem of coherency identification of generators in (10) can be transferred into a decision-making problem with four evaluating indexes and the Q schemes to be evaluated, where Q is equal to $M(M - 1)/2$ and each pair of two generators is regarded as a scheme. The evaluating matrix of this decision-making problem can be represented as

$$\mathbf{R} = (r_{uq})_{U \times Q} \quad (11)$$

where r_{uq} is the q^{th} element above the diagonal elements of the u^{th} index matrix. U is the number of the similarity indexes. In this paper, U is equal to 4.

Thus, the entropy H_u of the u^{th} similarity index is defined as

$$H_u = -k \sum_{q=1}^Q f_{uq} \ln f_{uq} \quad u = 1, 2, \dots, U \quad (12)$$

where $f_{uq} = r_{uq} / \sum_{q=1}^Q r_{uq}$; $k = 1 / \ln Q$. $f_{uq} \ln f_{uq}$ would be set to zero if f_{uq} is equal to zero. So, the entropy weight W_u of the u^{th} similarity index is defined as

$$W_u = \frac{1 - H_u}{U - \sum_{u=1}^U H_u} \quad (13)$$

It can be concluded from the definitions of entropy and entropy weight that there is $0 \leq W_u \leq 1$ ($i = 1, 2, \dots, U$) and $\sum_{u=1}^U W_u = 1$. The entropy may be relatively small if the values of the u^{th} similarity index of all the pairs of generators are greatly different from one another, but its entropy weight may be relatively large. It means that some available information is provided by this index. So, the index should be given particular considerations if its values are significantly different. It should be pointed out that the entropy weight is not the coefficient reflecting the actual importance of the index, but the coefficient reflecting the relative important degree of the index in the competition with all the given indices of all the pairs of the generators.

With the obtained entropy weights of the similarity indexes, the synthesized similarity values of each pair of the generators can be determined by (10). Then, the coherency and its ranking of all the pair of the generators can be obtained.



2.3 Coherency identification based on hierarchical clustering algorithm

Hierarchical clustering is a clustering analysis method which seeks to build a hierarchy of clusters. In general, hierarchical clustering methods consist of the agglomerative one, which is a “bottom up” approach, and divisive one, which is a “top down” approach, and the dendrogram is employed to demonstrate the clustering results [22].

For power systems, each generator can be considered as a cluster, and the generators with highest coherency can be clustered into one group first. Furthermore, Equation (10) is used to find the coherent and equivalent generators based on the aggregation method. Thus, the agglomerative method is employed to identify the coherent groups of generators in this paper. The steps of hierarchical clustering method for coherency identification are presented as follows.

Step 1: Set the number C_G of the coherent groups of generators as 0.

Step 2: Set each generator as a cluster. There are M clusters for the power system with M generators.

Step 3: Acquire the generator angles and rotating speeds data from WAMS, and then obtain M trajectories of the generator angles and rotating speeds respectively.

Step 4: Calculate the values of four similarity indexes in (1)–(3) and (5) based on the obtained trajectories of the generator angles and rotor speeds, and form the four similarity matrices I_L , I_D , I_S and I_C .

Step 5: Normalize I_L , I_D , I_S and I_C to I'_L , I'_D , I'_S and I'_C for comparison using (6)–(9), respectively.

Step 6: Transfer four similarity matrices I'_L , I'_D , I'_S and I'_C into a decision-making problem with four evaluating indexes and the Q schemes to be evaluated.

Step 7: Calculate the entropy and entropy weights of four evaluating indexes by (12) and (13), respectively, and W_1 , W_2 , W_3 and W_4 in (10) can be obtained.

Step 8: Calculate the synthesized similarity matrix in (10), and obtained the synthesized similarity value of each pair of any two generators.

Step 9: Rank all the pairs of generators based on their synthesized similarity values.

Step 10: Seek and select a pair of the generators with minimum value of synthesized similarity index. If there exist any coherent groups, check whether any of two generators of the selected pair with minimum similarity index value are in any coherent group. If two generators in the pair are all in one coherent group, discard the selected pair of generators. If only one generator in the pair is in one coherent group, merge the generator not in coherent group into the coherent group where the other generator located. If both generators in the pair are not

included in the same coherent group, then set a new coherent group to include these two generators in the pair, and hence the number C_G of coherent groups increases by one.

Step 11: Remove the value of the selected pair of the generators from the ranking lists. Repeat Step 9 until there are no generators in a cluster alone.

Step 12: Obtain the C_G groups of coherent generators clustered and the clustering dendrogram.

3 Optimization model of islanding schemes based on coherent generators

After the coherent groups of generators are determined from the trajectories monitored by WAMS, the next step is to search for an optimum cut set to split the power systems into several subsystems. There are many possible methods to do that such as minimal cutset, minimal cutest with minimum net flow, K -means technique, K -way partitioning, multi-way balanced graph partitioning and angle modulated particle swarm optimization. In this paper, the minimal cutset method is presented with the obtained coherent generator groups considered, in which minimal power flow disruption is selected as the optimization objective. Thus, for an M -generator B -bus power system with L branches, the optimization objective for optimizing the controlled islanding schemes can be represented by

$$\min O = \sum_{l=1}^L |(1 - a_l)F_l^P| \quad (14)$$

where F_l^P is the actual active power of transmission line l before islanding; a_l is the operating state of transmission line l . If the transmission line l is disconnected in the islanding schemes, $a_l = 0$; otherwise, $a_l = 1$. The optimization objective of (14) is to construct islands with minimum change from the pre-disturbance power flow pattern, which is for improving transient stability of the split islands and reducing the overloading possibility of transmission lines within each island [3]. Furthermore, it would maintain a good power balance to some certain extent, which is for reducing the amount of load shedding and maintaining the frequency in each island within the permitted ranges.

The optimization model is based on the coherency identification, so the coherency constraint should be satisfied for the islanding schemes. The coherency constraint is that all the coherent generators in one group should be split into one island, and any two non-coherent generators cannot be split into one island. It is assumed that there are C_{CG} coherent groups of generators in the power system;

and the power system is split into C_{CG} islands. The coherency constraint can be represented by

$$\begin{cases} \Omega_{CG,e} \in \Omega_{Island,f} & e = f \\ \Omega_{CG,e} \cap \Omega_{Island,f} = \emptyset & e \neq f \end{cases} \quad (15)$$

where $e, f \in \{1, 2, \dots, C_{CG}\}$; $\Omega_{CG,e}$ is the set of the generators in the e^{th} coherent group; $\Omega_{Island,f}$ is the set of the nodes in the f^{th} island.

After the power system has been split, the following constraints should also be respected.

1) Power flow constraints

For any bus $x \in \{1, 2, \dots, B\}$, there exist

$$F_{Gx}^P - F_{Lx}^P - V_x \sum_{y \in \Omega_x} V_y (G_{xy} \cos \delta_{xy} + B_{xy} \sin \delta_{xy}) = 0 \quad (16)$$

$$F_{Gx}^Q - F_{Lx}^Q - V_x \sum_{y \in \Omega_x} V_y (G_{xy} \sin \delta_{xy} + B_{xy} \cos \delta_{xy}) = 0 \quad (17)$$

where Ω_x is the set of nodes which are connected with node x in the power system after islanding; F_{Gx}^P and F_{Gx}^Q are the real and reactive power generation in node x after islanding; F_{Lx}^P and F_{Lx}^Q are the real and reactive power of the loads in node x ; V_x and V_y are the voltage amplitude of nodes x and y after islanding; G_{xy} and B_{xy} are the real and imaginary elements in the x^{th} row and y^{th} column of bus admittance matrix; δ_{xy} is the voltage phase difference between bus x and bus y after islanding.

2) Generation output constrains

$$F_{Gm}^{P,\min} \leq F_{Gm}^P \leq F_{Gm}^{P,\max} \quad \forall m \in \{1, 2, \dots, M\} \quad (18)$$

$$F_{Gm}^{Q,\min} \leq F_{Gm}^Q \leq F_{Gm}^{Q,\max} \quad \forall m \in \{1, 2, \dots, M\} \quad (19)$$

where F_{Gm}^P and F_{Gm}^Q are the active and reactive power outputs of generator m after islanding; $F_{Gm}^{P,\min}$, $F_{Gm}^{P,\max}$, $F_{Gm}^{Q,\min}$ and $F_{Gm}^{Q,\max}$ are the maximum active power, minimum active power, maximum reactive power and minimum reactive power of generator m , respectively.

3) Constrains of bus voltage magnitudes

$$V_x^{\min} \leq V_x \leq V_x^{\max} \quad \forall x \in \{1, 2, \dots, B\} \quad (20)$$

where V_x is the voltage amplitude of node m after islanding; V_x^{\min} and V_x^{\max} are the minimum and maximum amplitude of the voltage of node x .

4) Constrains of transmission line capacities

$$|F_l^P| \leq F_l^{P,\max} \quad \forall l \notin L_s \quad (21)$$

where L_s is the set of transmission lines which are disconnected in the islanding strategy; $F_l^{P,\max}$ is the active power transmission capacity of transmission line l .

5) Connectivity constraints

$$\begin{cases} \prod_{l \in L_{x \leftrightarrow y}} a_l = 1 & \forall x, y \in \Omega_{Island,e} \\ \prod_{l \in L_{x \leftrightarrow y}} a_l = 0 & \forall x \in \Omega_{Island,e}, y \in \Omega_{Island,f}, e \neq f \end{cases} \quad (22)$$

where $L_{x \leftrightarrow y}$ is the set of the transmission lines of the electrical paths connecting node x with node y .

Thus, the optimization model of controlled islanding schemes based on WAMS is formulated as follows.

$$\begin{aligned} \min O &= \sum_{l=1}^L |(1 - a_l) F_l^P| \\ \text{s.t.} & \end{aligned}$$

$$\begin{aligned} \Omega_{CG,e} &\in \Omega_{Island,f} & e = f \\ \Omega_{CG,e} \cap \Omega_{Island,f} &= \emptyset & e \neq f \end{aligned}$$

$$F_{Gx}^P - F_{Lx}^P - V_x \sum_{y \in \Omega_x} V_y (G_{xy} \cos \delta_{xy} + B_{xy} \sin \delta_{xy}) = 0$$

$$F_{Gx}^Q - F_{Lx}^Q - V_x \sum_{y \in \Omega_x} V_y (G_{xy} \sin \delta_{xy} + B_{xy} \cos \delta_{xy}) = 0$$

$$F_{Gm}^{P,\min} \leq F_{Gm}^P \leq F_{Gm}^{P,\max} \quad \forall m \in \{1, 2, \dots, M\}$$

$$F_{Gm}^{Q,\min} \leq F_{Gm}^Q \leq F_{Gm}^{Q,\max} \quad \forall m \in \{1, 2, \dots, M\}$$

$$V_x^{\min} \leq V_x \leq V_x^{\max} \quad \forall x \in \{1, 2, \dots, B\}$$

$$|F_l^P| \leq F_l^{P,\max} \quad \forall l \notin L_s$$

$$\prod_{l \in L_{x \leftrightarrow y}} a_l = 1 \quad \forall x, y \in \Omega_{Island,e}$$

$$\prod_{l \in L_{x \leftrightarrow y}} a_l = 0 \quad \forall x \in \Omega_{Island,e}, y \in \Omega_{Island,f}, e \neq f \quad (23)$$

Then, the proposed optimization model of controlled islanding schemes can be solved by the minimal cutset method.

4 Case studies

A 16-generator 68-bus sample power system is employed to demonstrate the proposed WAMS-based islanding scheme and the traditional slow coherency based islanding schemes in which the coherent groups of generators are determined by modal analysis [25–27]. Furthermore, the reduced WECC 29-unit 179-bus power system [28] is also employed to demonstrate the proposed WAMS-based islanding scheme, and the traditional slow coherency based islanding schemes is taken from [20].

4.1 16-generator 68-bus sample power system

In the 16-generator 68-bus power system, the 4th-order generator model was used for all the generators. The



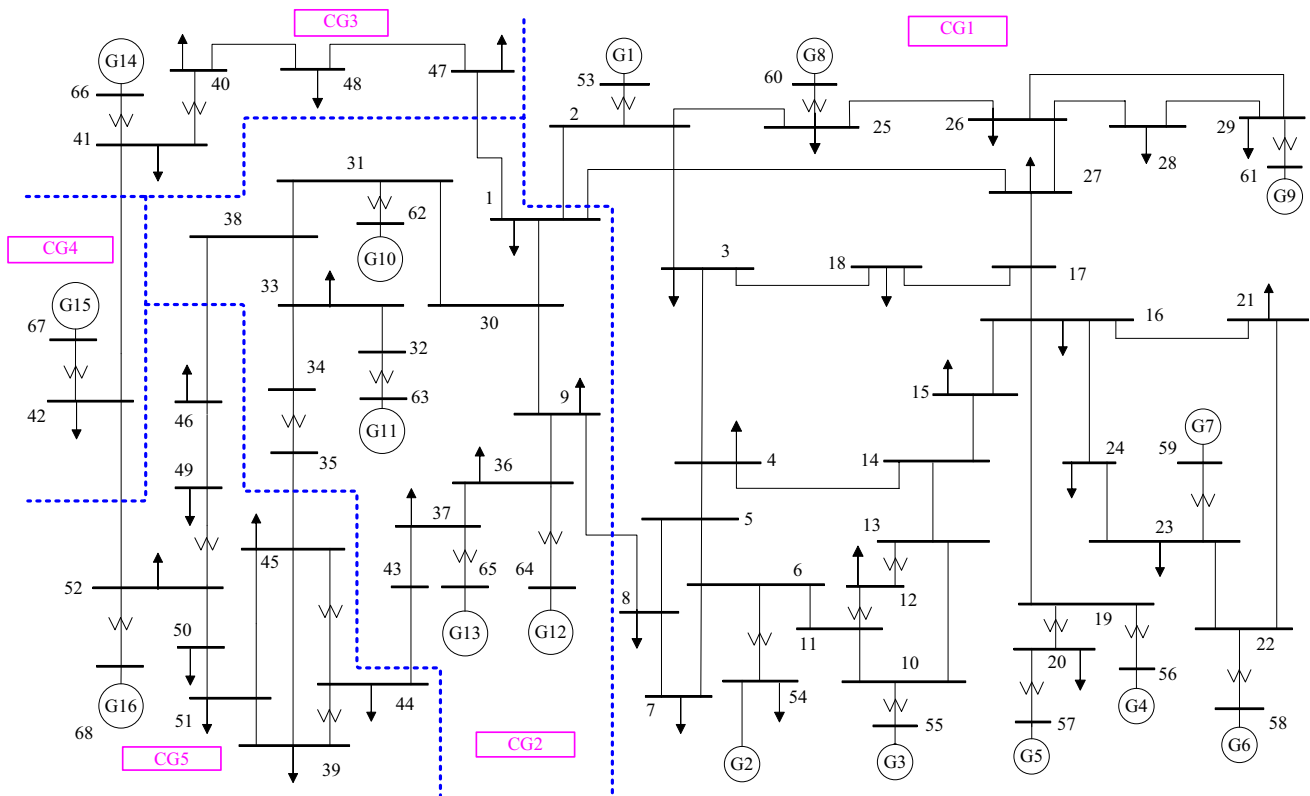


Fig. 1 Islanding strategy based on slow coherency in traditional method

detailed data associated with this power system can be found in [25, 29].

For traditional slow coherency based islanding schemes, 16 generators are divided into five coherent groups which are as follows: $CG1 = \{G_1, G_2, \dots, G_9\}$, $CG2 = \{G_{10}, G_{11}, G_{12}, G_{13}\}$, $CG3 = \{G_{14}\}$, $CG4 = \{G_{15}\}$ and $CG5 = \{G_{16}\}$. The optimized islanding strategy is obtained and shown in Fig. 1. The optimal cutsets among five coherent groups of generators are $\{L_{1-2}, L_{1-27}, L_{8-9}, L_{1-47}, L_{38-46}, L_{35-45}, L_{43-44}, L_{41-42}, L_{42-52}\}$. Thus, the optimal islanding strategy obtained by the traditional method is to split the power system into 5 islands, and the power flow disruption of the optimized islanding strategy is equal to 6.925 p.u.

For the proposed WAMS-based islanding schemes, it is assumed that each generator bus is equipped with one PMU, so the generator angles and rotating speeds of 16 generators can be sampled and acquired by WAMS with coordinated universal time. The following two cases are presented for demonstration.

Case 1: A fault at bus 16 for 0.16 s

A fault at bus 16 is applied to the power system and is cleared after 0.16 s for simulating the measured data of generator angles and rotating speeds of 16 generators by PMUs. The curves of the generators' angles are shown in

Fig. 2. It would be difficult to determine the coherent groups of generators based on the swing trend of the curves. Thus, the proposed coherency identification method based on the hierarchical clustering algorithm is applied to identify the coherent groups for the swing curves measured by WAMS. First, the four similarity matrices L_L , L_D , L_S and L_C are calculated and normalized, and then the entropy weights of four evaluating indexes, i.e., W_1 , W_2 , W_3 and W_4 , are obtained and equal to 0.3810, 0.1288, 0.3187 and 0.1715, respectively. It can be seen that the weights of the angle deviation similarity and rotating speed deviation similarity are greater than these of swing direction similarity and corner deviation similarity. The synthesized similarity matrix is obtained, and the clustering dendrogram is plotted and shown in Fig. 3. It can be seen from Fig. 3 that the generators are clustered as three coherent groups which are denoted as $CG1'$, $CG2'$ and $CG3'$. $CG1' = \{G_1, G_2, \dots, G_9\}$, $CG2' = \{G_{10}, G_{11}, G_{12}, G_{13}\}$, and $CG3' = \{G_{14}, G_{15}, G_{16}\}$. The generators in the same coherent group are connected each other, and there is no connection among the generators in different coherent groups.

To demonstrate whether the proposed WAMS-based method is suitable for actual measurements in a noise condition, a white Gaussian noise is added to the measured data of generator angles and rotating speeds for simulating

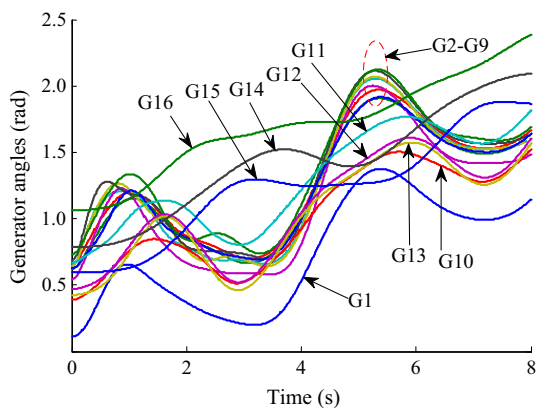


Fig. 2 Swing curves of generators' angles in Case 1

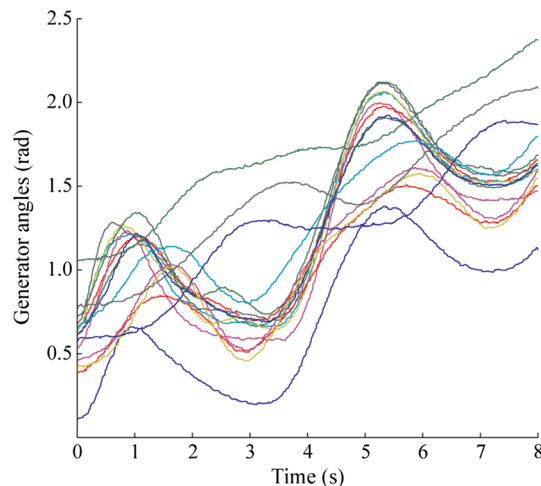


Fig. 5 Swing curves of generators' angles after filtering in Case 1

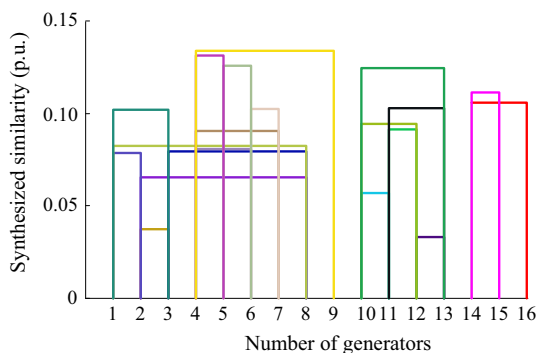


Fig. 3 Clustering dendrogram for Case 1

the measuring noise. The curves of the angles of generators with the white Gaussian noise are shown in Fig. 4. Then, the median filter algorithm is employed to pre-filter the white Gaussian noise from the measured data. Figure 5 shows that swing curves of the angles of generators after filtering. It can be seen from Fig. 5 that the white Gaussian

noise in the measured data is reduced to some extent. Finally, the proposed WAMS-based method is applied to identify the coherent groups based on the swing curves in which the white Gaussian noise is pre-filtered in Fig. 5. The clustering dendrogram is attained and shown in Fig. 6. It can be seen from Figs. 3 and 6 that the division result of the coherent groups for Case 1 with white Gaussian noise considered is the same with that without considering the white Gaussian noise, and this means that the division result of the coherent groups is not affected by the noise in the measured data for Case 1.

Finally, the islanding strategies is optimized based on the obtained three coherent groups of generators and the proposed model. The optimal cutset is obtained as $\{L_{1-2}, L_{1-27}, L_{1-47}, L_{8-9}, L_{35-45}, L_{38-46}, L_{43-44}\}$, and the power flow disruption is equal to 4.827 p.u.. It can be seen that there are seven transmission lines disconnected by the

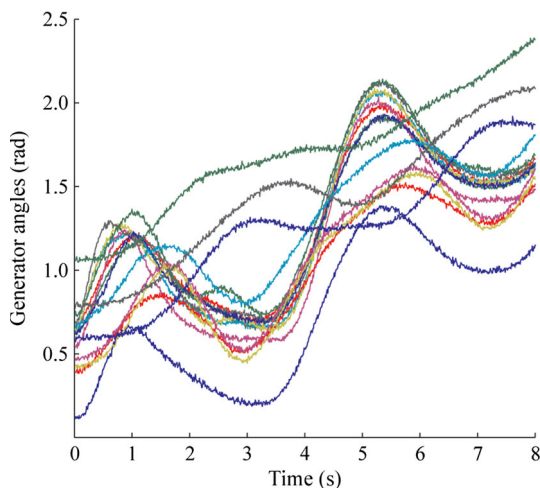


Fig. 4 Swing curves of generators' angles with white Gaussian noise in Case 1

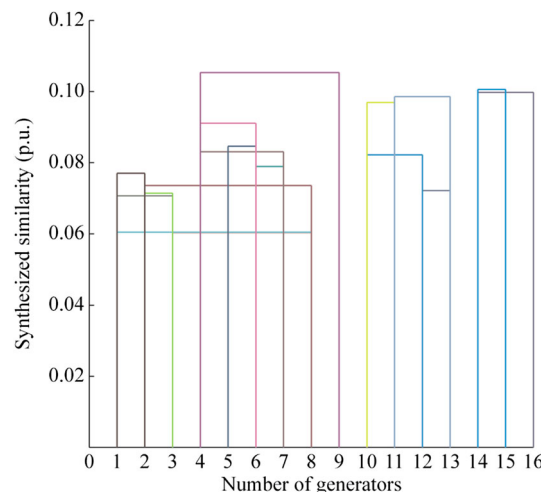


Fig. 6 Clustering dendrogram for Case 1 considering white Gaussian noise



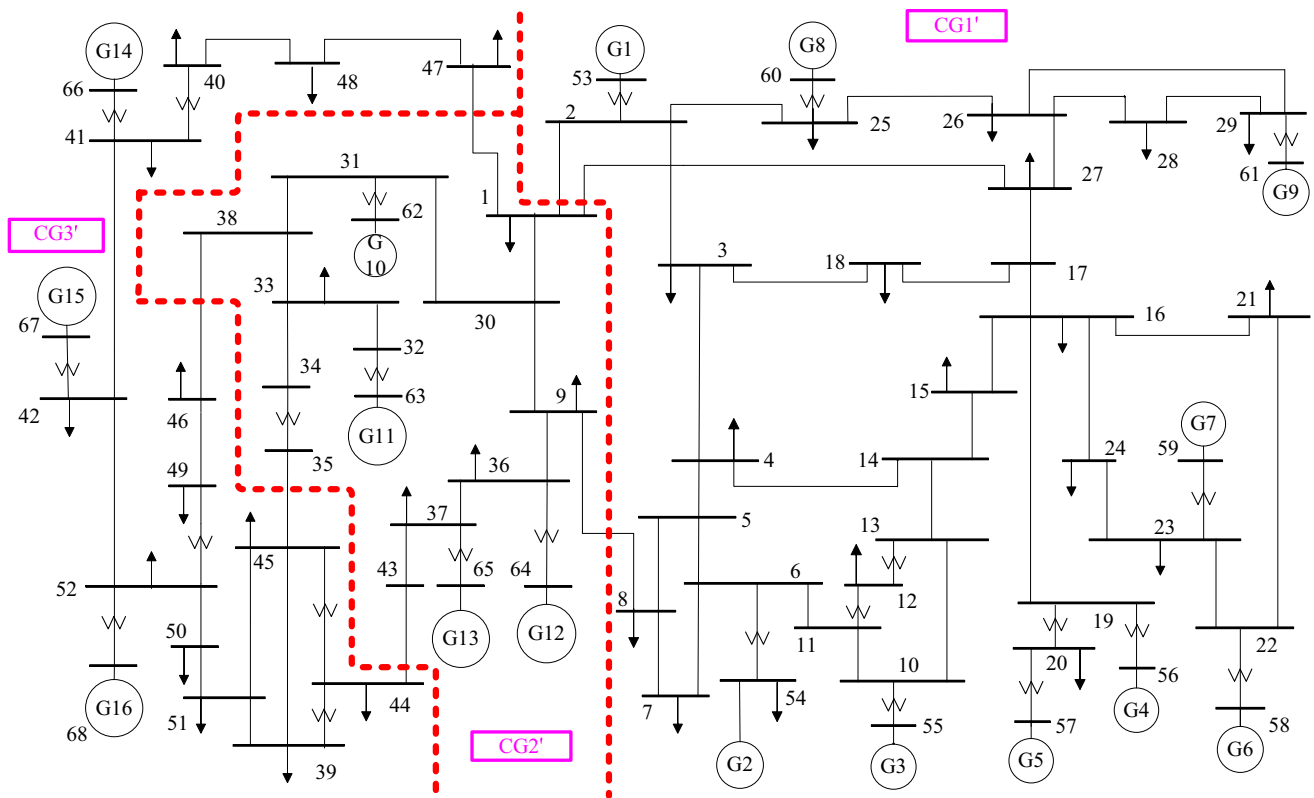


Fig. 7 Islanding strategy based on WAMS for Case 1

islanding scheme. The optimized islanding strategy is shown in Fig. 7.

Case 2: A fault at bus 45 for 0.60 s

A fault at bus 45 is applied to the power system and is cleared after 0.60 s for simulating the measured data of generator angles and rotating speeds of 16 generators by PMUs. The curves of the generators' angles are shown in Fig. 8. It would be difficult to determine the coherent groups of generators based on the swing trend of the curves. Thus, the proposed the coherency identification method based on hierarchical clustering algorithm is applied to identify the coherent groups for the swing curves measured by WAMS. The entropy weights of four evaluating indexes, i.e., W_1 , W_2 , W_3 and W_4 , are obtained and equal to 0.3459, 0.1713, 0.2821 and 0.2007, respectively. The clustering dendrogram is plotted and shown in Fig. 9. It can be seen from Fig. 9 that the generators are clustered as two coherent groups which are denoted as CG1'' and CG2''. $CG1'' = \{G_1, G_2, \dots, G_{13}\}$, and $CG2'' = \{G_{14}, G_{15}, G_{16}\}$. The generators in the same coherent group are connected each other, which means that these generators are strongly coherent. For example, the generators G_1, G_2, \dots, G_{13} in the coherent group CG1'' are connected with numerous coherent lines, thus it can be concluded that the

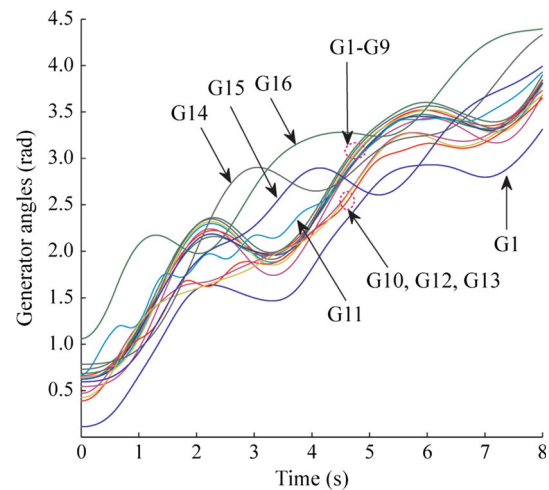


Fig. 8 Swing curves of generators' angles in Case 2

generators G_1, G_2, \dots, G_{13} are strongly coherent each other.

For checking whether the proposed WAMS-based method is suitable for real measurement in a noise condition, a white Gaussian noise is added to the measured data of generator angles and rotating speeds for simulating the measuring noise. The curves of the generators' angles with

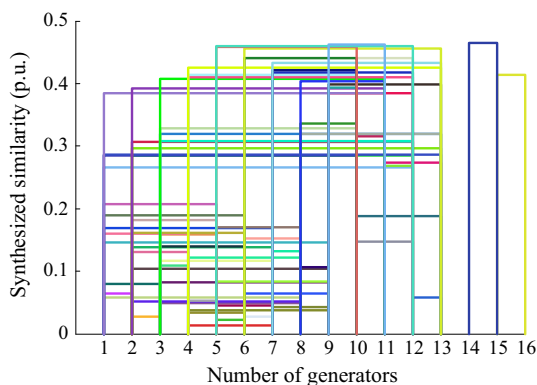


Fig. 9 Clustering dendrogram for Case 2

white Gaussian noise are shown in Fig. 10. Then, the median filter algorithm is employed to pre-filter the white Gaussian noise from the measured data. Figure 11 shows that swing curves of the generators' angles after filtering. It can be seen from Fig. 11 that the white Gaussian noise in the measured data is reduced to some extent. Finally, the proposed WAMS-based method is applied to identify the coherent groups based on the swing curves in which the white Gaussian noise is pre-filtered in Fig. 11. The clustering dendrogram is obtained and shown in Fig. 12. It can be seen from Figs. 9 and 12 that the division result of the coherent groups for Case 2 with white Gaussian noise considered is same to that without considering white Gaussian noise, which also means that the division result of the coherent groups is not affected by the noise in the measured data for Case 2.

Finally, the optimal cutset is obtained as $\{L_{1-47}, L_{35-45}, L_{38-46}, L_{43-44}\}$, and the power flow disruption is equal to 3.939 p.u.. It can be seen that there are four transmission

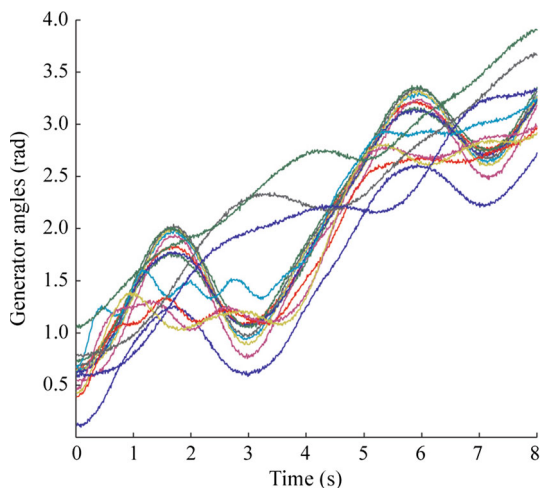


Fig. 10 Swing curves of generators' angles with white Gaussian noise in Case 2

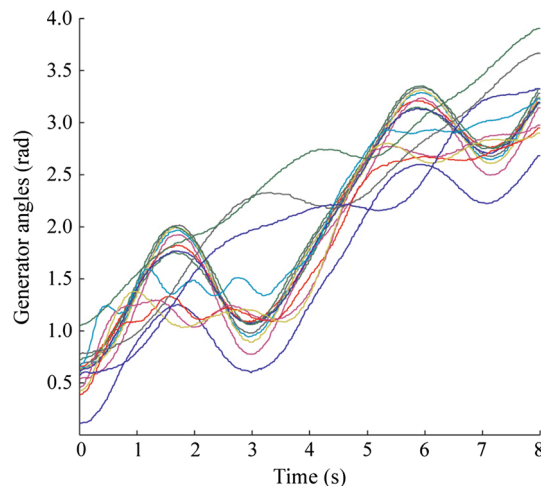


Fig. 11 Swing curves of generators' angles after filtering in Case 2

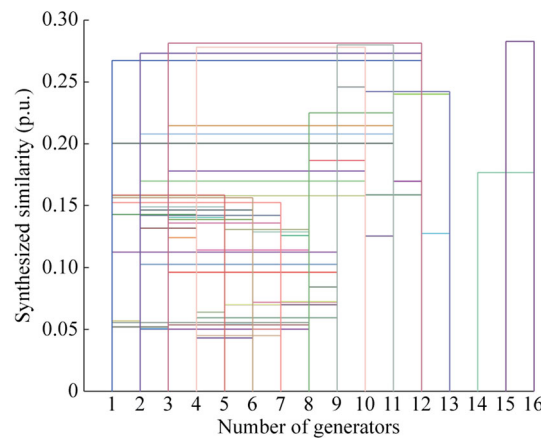


Fig. 12 Clustering dendrogram for Case 2 considering white Gaussian noise

lines are disconnected in the islanding strategy. The optimized islanding strategy based on WAMS for Case 2 is shown in Fig. 13.

In summary, the simulation results optimized by the proposed WAMS-based islanding schemes and the traditional slow coherency based islanding schemes are shown in Table 1.

It can be seen from Table 1 that the proposed WAMS-based islanding schemes divide the 16 generators into three and two coherent groups, and then split the 68-bus power system into three islands and two islands for Case 1 and Case 2, respectively. However, the traditional slow coherency islanding schemes divide the 16 generators into five coherent groups, and then split the power system into five islands. Compared to the traditional slow coherency islanding schemes, the proposed WAMS-based islanding schemes could split the power system into fewer islands



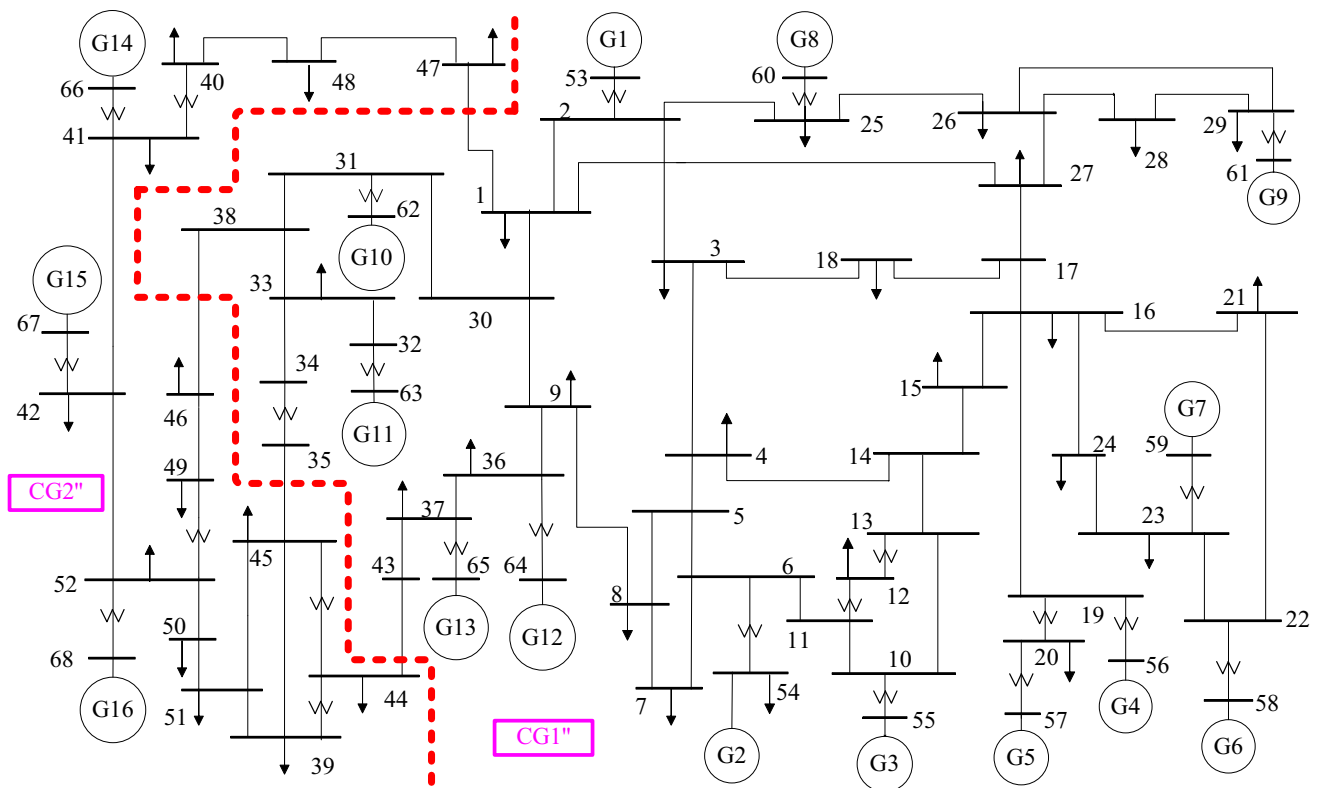


Fig. 13 Islanding strategy based on WAMS for Case 2

Table 1 Comparison of proposed WAMS-based and traditional slow coherency based islanding strategies for 16-generator 68-bus power system

Method	Coherent groups	Optimal cutsets	Power flow disruption
Traditional slow coherency method	{G ₁ , G ₂ , ..., G ₉ }, {G ₁₀ , G ₁₁ , ..., G ₁₃ }, {G ₁₄ }, {G ₁₅ }, {G ₁₆ }	L ₁₋₂ , L ₁₋₂₇ , L ₈₋₉ , L ₁₋₄₇ , L ₃₈₋₄₆ , L ₃₅₋₄₅ , L ₄₃₋₄₄ , L ₄₁₋₄₂ , L ₄₂₋₅₂	6.925
WAMS-based method proposed (Case 1)	{G ₁ , G ₂ , ..., G ₉ }, {G ₁₀ , G ₁₁ , ..., G ₁₃ }, {G ₁₄ , G ₁₅ , G ₁₆ }	L ₁₋₂ , L ₁₋₂₇ , L ₁₋₄₇ , L ₈₋₉ , L ₃₅₋₄₅ , L ₃₈₋₄₆ , L ₄₃₋₄₄	4.827
WAMS-based method proposed (Case 2)	{G ₁ , G ₂ , ..., G ₁₃ }, {G ₁₄ , G ₁₅ , G ₁₆ }	L ₁₋₄₇ , L ₃₅₋₄₅ , L ₃₈₋₄₆ , L ₄₃₋₄₄	3.939

and disconnect fewer transmission lines. Thus, the power flow disruptions of the proposed WAMS-based islanding strategies are reduced by 30.30% and 43.12% for Case 1 and Case 2, respectively, which means that the disturbance on the power systems could be alleviated. Furthermore, it can also be seen from Table 1 that the coherent groups identified by the proposed WAMS-based islanding schemes are similar to the coherent groups obtained by the traditional slow coherency islanding schemes. In Case 1, the first two coherent groups identified by traditional slow coherency method are maintained, but the last three coherent groups {G₁₄}, {G₁₅} and {G₁₆} are merged into one new coherent group {G₁₄, G₁₅, G₁₆}. In Case 2, the first two coherent groups identified by traditional method are merged into one new coherent group {G₁, G₂, ..., G₁₃},

and the last three coherent groups {G₁₄}, {G₁₅} and {G₁₆} are merged into one new coherent group {G₁₄, G₁₅, G₁₆}. It can be concluded that the proposed WAMS-based islanding schemes could merge part of strongly coherent groups of generators into a new coherent group according to different operation characteristic of power systems. As a result, the proposed WAMS-based islanding algorithm could reduce the number of coherent generation groups and disconnected transmission lines, and then a more reasonable and stable islanding strategies could be obtained.

4.2 Reduced WECC 29-unit 179-bus power system

For the reduced WECC 29-unit 179-bus power system, classical second-order differential model reflecting the

motion of the rotor was used for all the generators, and constant MVA model for all loads. The detailed data associated with this power system can be found in [28, 30].

For traditional islanding schemes based on slow coherency, 29 generators are divided into four coherent groups which are as follows: $CG1 = \{G_{30}, G_{35}, G_{65}, G_{70}, G_{77}, G_{79}\}$, $CG2 = \{G_{103}, G_{112}, G_{116}, G_{118}\}$, $CG3 = \{G_{13}, G_{15}, G_{40}, G_{43}, G_{47}, G_{138}, G_{140}, G_{144}, G_{148}, G_{149}\}$, and $CG4 = \{G_4, G_6, G_9, G_{11}, G_{18}, G_{36}, G_{45}, G_{159}, G_{162}\}$ [20]; the optimal cutsets among four coherent groups of generators are $\{L_{76-82}, L_{86-180}, L_{153-175}, L_{153-177}, L_{153-179}, L_{14-29}\}$. Thus, the optimal islanding strategy obtained by the traditional method is to split the power system into 4 islands, and the power flow disruption of the optimized islanding strategy is equal to 41.441 p.u.

For the proposed WAMS-based islanding schemes, it is assumed that each generator bus is equipped with one PMU, so the generator angles and rotating speeds of 29 generators can be sampled and acquired by WAMS with coordinated universal time.

A fault at bus 79 is applied to the power system and is cleared after 0.05 s for simulating the measured data of generator angles and rotating speeds of 29 generators by PMUs. For simulating the measuring noise, a white Gaussian noise is added to the measured data of generator angles and rotating speeds. The curves of the generators' angles with white Gaussian noise are shown in Fig. 14. It would be difficult to determine the coherent groups of generators based on the swing trend of the curves. Thus, the proposed coherency identification method based on the hierarchical clustering algorithm is applied to identify the coherent groups for the swing curves measured by WAMS.

It can be obtained that the generators are clustered as three coherent groups which are denoted as $CG1'$, $CG2'$

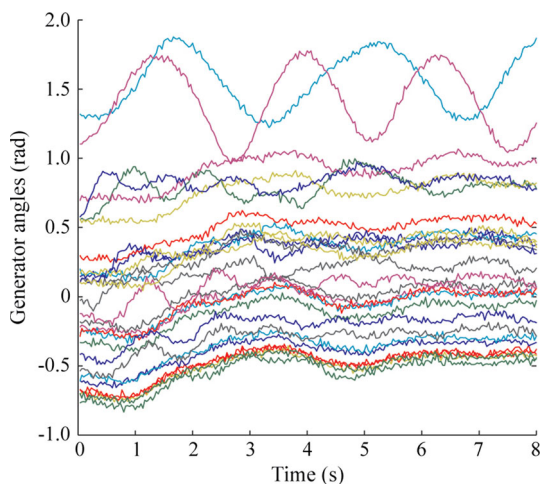


Fig. 14 Swing curves of generators' angles with white Gaussian noise in WECC power system

and $CG3'$. $CG1' = \{G_{13}, G_{15}, G_{30}, G_{35}, G_{40}, G_{43}, G_{47}, G_{65}, G_{70}, G_{77}, G_{79}, G_{103}, G_{112}, G_{116}, G_{118}, G_{138}, G_{140}, G_{144}, G_{148}, G_{149}\}$, $CG2' = \{G_4, G_6, G_9, G_{11}, G_{18}\}$, and $CG3' = \{G_{36}, G_{45}, G_{159}, G_{162}\}$. The optimal cutsets among three coherent groups of generators are $\{L_{86-180}, L_{8-163}, L_{5-160}, L_{14-29}\}$. Thus, the optimal islanding strategy obtained by the WAMS-based method is to split the power system into 3 islands, and the power flow disruption of the optimized islanding strategy is equal to 22.132 p.u.

In summary, the simulation results optimized by the proposed WAMS-based islanding schemes and the traditional slow coherency based islanding schemes are shown in Fig. 15 and Table 2.

It can be seen from Table 2 that the proposed WAMS-based islanding scheme could split the power system into less islands and disconnect less transmission lines, comparing to the traditional slow coherency islanding scheme. The power flow disruption of the proposed WAMS-based islanding strategy is reduced by 46.59% in this case, and this means that the disturbance on the given power system could be alleviated.

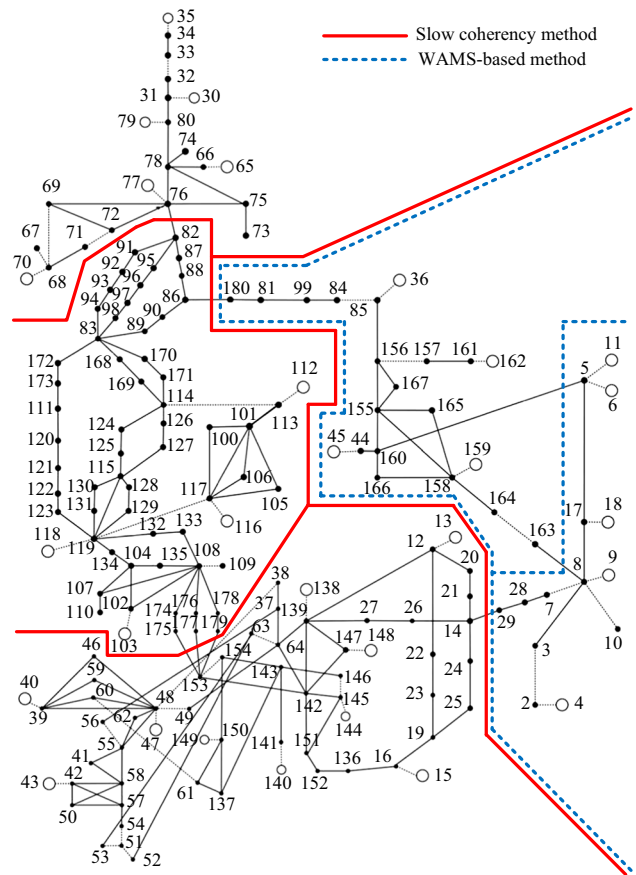


Fig. 15 Islanding strategies based on slow coherency and WAMS for WECC power system



Table 2 Comparison of proposed WAMS-based and traditional slow coherency based islanding strategies for WECC power system

Method	Coherent groups	Optimal cutsets	Power flow disruption
Traditional slow coherency method	{G ₃₀ , G ₃₅ , G ₆₅ , G ₇₀ , G ₇₇ , G ₇₉ }, {G ₁₀₃ , G ₁₁₂ , G ₁₁₆ , G ₁₁₈ }, {G ₁₃ , G ₁₅ , G ₄₀ , G ₄₃ , G ₄₇ , G ₁₃₈ , G ₁₄₀ , G ₁₄₄ , G ₁₄₈ , G ₁₄₉ }, {G ₄ , G ₆ , G ₉ , G ₁₁ , G ₁₈ , G ₃₆ , G ₄₅ , G ₁₅₉ , G ₁₆₂ }	L _{76–82} , L _{86–180} , L _{153–175} , L _{153–177} , L _{153–179} , L _{14–29}	41.441
WAMS-based method proposed	{G ₁₃ , G ₁₅ , G ₃₀ , G ₃₅ , G ₄₀ , G ₄₃ , G ₄₇ , G ₆₅ , G ₇₀ , G ₇₇ , G ₇₉ , G ₁₀₃ , G ₁₁₂ , G ₁₁₆ , G ₁₁₈ , G ₁₃₈ , G ₁₄₀ , G ₁₄₄ , G ₁₄₈ , G ₁₄₉ }, {G ₄ , G ₆ , G ₉ , G ₁₁ , G ₁₈ }, {G ₃₆ , G ₄₅ , G ₁₅₉ , G ₁₆₂ }	L _{86–180} , L _{8–163} , L _{5–160} , L _{14–29}	22.132

5 Conclusion

A coherency identification algorithm is first presented to determine the coherent generation groups based on the hierarchical clustering and WAMS. The clustering dendrograms are obtained for identifying the coherent groups of generators. Then, the optimization model of controlled islanding schemes for interconnected power systems is proposed with coherent generation groups considered. Finally, the case studies are performed on the 16-generator 68-bus test power system and the reduced WECC 29-unit 179-bus power system for checking the effectiveness of the proposed WAMS-based islanding schemes. The results show that the proposed WAMS-based islanding scheme could divide the power system into less islands according to different operating characteristic of different cases when comparing to the traditional slow coherency based islanding scheme, and power flow disruptions could be reduced by the proposed WAMS-based islanding scheme which would decrease the disturbance level on the split islands and then would be helpful for maintaining the stability of split islands.

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