

and areas; 3) this scheme can identify the dynamic generator coherency according to the current system state so that it can cooperate with different start-up criterions. This paper is organized as follows. Section 2 gives the details of the phase-plane based dynamic coherency identification scheme and section 3 verifies its effectiveness. The conclusion is given in section 4.

2. Phase-plane based Dynamic Coherency Identification Scheme

The dynamic coherency identification scheme proposed in this paper consists of two parts: the identification of coherent generators and the determination of coherent electrical areas.

2.1 Identification of coherent generators For a multi-machine power system, the i -th, and j -th generators are coherent in the time period of $[t_1, t_2]$ if their angle satisfy (1).

$$\max_{t \in [t_1, t_2]} |\Delta\delta_i - \Delta\delta_j| \leq \varepsilon \quad (1)$$

where ε is a small constant; $\Delta\delta_i$ and $\Delta\delta_j$ are the angle increments of the i -th and j -th generators. From (1), it is necessary to observe the power angle of generators for a period of time to identify the coherent generators. However, long-time observation is not allowed in practice because the controlled islanding requires a fast identification of coherent generator groups with the least measurement data. Thus, deeper state information of generators, rather than only the power angle, should be used to fully evaluate the motion status of generators. To this end, the phase trajectory vectors (PTVs) are applied to identify the dynamic coherency of generators in this paper.

For the i -th generator of the power system, its dynamic status at moment t can be represented by the phase point $(\delta_i(t), \Delta\omega_i(t))$ on the phase plane where the x -axis is the angle δ and the y -axis is the speed deviation $\Delta\omega$. Thus, the vector starting from the point $(\delta_i(t - \Delta t), \Delta\omega_i(t - \Delta t))$ to the point $(\delta_i(t), \Delta\omega_i(t))$ describes the motion of the i -th generator at time t . These vectors are called the Phase Trajectory Vectors (PTVs), which were first proposed in [24] and applied to identify the critical machines for transient stability assessment. As Fig. 1 shows, one PTV stands for one generator, respectively, and we can obtain N PTVs on the phase plane for an N -machine power system at each moment.

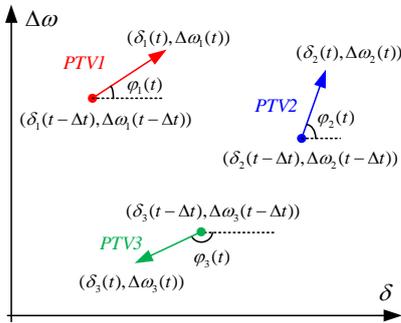


Fig. 1 The Phase Trajectory Vectors on the phase plane

Two features, the location and motion direction of the PTVs, are extracted to describe the dynamics of generators at time t . The standardized feature matrix is defined as (2).

$$\mathbf{A}_s(t) = \begin{bmatrix} \vec{V}_{1s} \\ \vec{V}_{2s} \\ \vdots \\ \vec{V}_{Ns} \end{bmatrix} = \begin{bmatrix} \delta_{1s}(t) & \Delta\omega_{1s}(t) & \varphi_{1s}(t) \\ \delta_{2s}(t) & \Delta\omega_{2s}(t) & \varphi_{2s}(t) \\ \vdots & \vdots & \vdots \\ \delta_{Ns}(t) & \Delta\omega_{Ns}(t) & \varphi_{Ns}(t) \end{bmatrix} \quad (2),$$

where $\vec{V}_{is}(t)$ is the standardized feature vector of i -th PTV at time t . In (2), the variables are defined as follows.

$$\delta_{is}(t) = \frac{\delta_i(t)}{\sum \delta_i(t)/N}, \Delta\omega_{is}(t) = \frac{\Delta\omega_i(t)}{\sum \Delta\omega_i(t)/N}, \varphi_{is}(t) = \frac{\varphi_i(t)}{\pi} \quad (3),$$

where $\delta_i(t)$ and $\Delta\omega_i(t)$ are the angle and speed deviation of the i -th generator at time t , indicating the location of the PTV. $\varphi_i(t)$ is the angle between the PTV and the positive x -axis at time t , representing the moving direction of the PTV. It is obtained by (4)

$$\varphi_i(t) = \arccos\left(\frac{\vec{p}_i \cdot \vec{e}}{\|\vec{p}_i\| \|\vec{e}\|}\right) \quad (4),$$

where $\vec{p}_i = (\delta_i(t) - \delta_i(t - \Delta t), \Delta\omega_i(t) - \Delta\omega_i(t - \Delta t))$, $\vec{e} = (1, 0)$.

The PTVs on the phase plane, in fact, show much more information about the generators dynamics beyond the power angle. The speed deviation, $\Delta\omega_i(t)$, is the derivative of the power angle with respect to time, indicating the changing trend of power angle. And $\varphi_i(t)$ predicts the motions of PTVs, indicating the changing trend of generators' angle and speed. Thus, from the PTVs on the phase plane at time t , we can obtain the current status of generators, and even predict the future dynamics of generators.

For coherent generators, the power angle increments should be similar over time. As a result, not only the angle but also the future motion of coherent generators should be similar during the given specific period. In another word, the PTVs should be similar at any time during this period if these generators are coherent. Thus, the PTVs at time t can be applied to identify coherent generators for the near period.

To identify the dynamic coherency with the aid of PTVs, we need to address two problems, that is, how to compare the similarity of PTVs correctly and how to determine the number of coherent groups. The hierarchical clustering method is adopted in this paper due to its high accuracy and no limits on cluster numbers. It consists of the following three steps:

Step 1: feature matrix formation. This step is to extract the dynamic features of generators at time t into a matrix. The standardized feature matrix $\mathbf{A}_s(t)$ is given in (2).

Step 2: hierarchical cluster tree formation. In this step, the Euclidean Distance is adopted to measure the distance from generator pair i to j , shown in (5).

$$\text{dist}(\vec{V}_{is}, \vec{V}_{js}) = \|\vec{V}_{is} - \vec{V}_{js}\|_2 \quad (5)$$

The cluster tree is formed step by step as follows.

- Each generator is an independent cluster.
- The clusters with the minimum distance are clustered into a new cluster. For example, if the distance from cluster p to q is the minimum, then clusters p and q form a new cluster r .
- The distances from other clusters to the new cluster is re-calculated by the nearest neighbor:

$$\text{dist}(r, s) = \min(\text{dist}(x_{ri}, x_{sj})), i \in (1, \dots, n_r), j \in (1, \dots, n_s) \quad (6)$$

In(6), n_r is the number of generators in the new cluster r and x_{ri} is the i -th generator in cluster r . n_s is the number of generators in

the other cluster s and x_{sj} is the j -th generator in cluster s .
 d) Return to b) and form a new cluster with the minimum distance until all generators belong to one cluster.
 e) Draw the dendrogram of the cluster tree.

Step 3: cluster number determination. This step is to determine the number of coherent generator groups based on the cluster tree. A threshold, d_s , is required to cut the cluster tree into groups. Coherent groups are formed when a node and all its sub-nodes have inconsistent values less than the threshold value.

2.2 Association of non-generator buses To determine the controlled islands, we need to assign the non-generator buses to corresponding coherent generators groups. A straight idea is to compute the electrical distances from non-generator buses to generator groups and assign them to the nearest generator groups. To compute the electrical distance, we need to put all buses in the same state space. The dynamics of generators are well expressed on the conventional phase plane; however, the non-generator buses cannot be represented as vectors on the PPG. To this end, we propose a special “phase plane” for all the buses where the x-axis is the voltage angle θ and the y-axis is the frequency f . These two state variables satisfy (7)[25].

$$f(t) = \frac{1}{2\pi f_0} \frac{\theta(t) - \theta(t - \Delta t)}{\Delta t} \quad (7),$$

where f_0 is the system nominal frequency and θ is the voltage phase angle of buses. From (7), f is the derivative of θ on the phase plane for the buses (PPB), which is similar to the relation between $\Delta\omega$ and δ on the phase plane for generators (PPG). In another word, the proposed PPB can also describe the dynamic behaviors of the power system, the same as PPG. Moreover, all buses can be drawn on the PPB, which can be used to determine the association of non-generator buses and coherent generator groups. To simplify the computation, we use the location information of buses on the PPB to determine the association of buses as follows.

step 1. Compute the centers of generator groups (CGGs). For example, the center phase point, $(\theta_{C,p}, f_{C,p})$, of coherent generator group p is computed by(8).

$$\theta_{C,p} = \frac{\sum_{i \in p} \theta_i}{N_p}, f_{C,p} = \frac{\sum_{i \in p} f_i}{N_p} \quad (8),$$

where θ_i, f_i are the voltage angle and frequency of generator buses that belong to coherent group p , and N_p is the number of generator buses in this group. If there are m groups of coherent generators, we can obtain m CGGs in this step.

step 2. Standardize the state variables. To balance the weight of variables on PPB, we apply a standardization to all non-generator buses and CGGs as (9) shows.

$$\theta^s = \frac{\theta}{\theta_{\max}}, f^s = \frac{f}{f_{\max}} \quad (9),$$

where $\theta_{\max} = \max\{\theta_{C,1}, \theta_{C,2}, \dots, \theta_{C,m}\}$, $f_{\max} = \max\{f_{C,1}, f_{C,2}, \dots, f_{C,m}\}$ and m is the number of CGGs.

step 3. Compute the distance from non-generator buses to each CGG. In this paper, the Euclidean distance is used to compare the electrical distance. For the non-generator bus i , the distance to CGG p is obtained by (10).

$$d_{i,p} = \sqrt{(\theta_i^s - \theta_{C,p}^s)^2 + (f_i^s - f_{C,p}^s)^2} \quad (10)$$

It is noted that the distance from bus i to different CGGs should be computed, respectively. If there are m CGGs, the distances should be computed as $d_{i,1}, d_{i,2}, \dots, d_{i,m}$.

step 4. Assign the non-generator buses to the nearest CGG. The non-generator bus i is assigned to the group q if it satisfies (11).

$$d_{i,q} = \min\{d_{i,1}, d_{i,2}, \dots, d_{i,m}\} \quad (11)$$

step 5. Repeat steps 3 and 4 until all non-generator buses have already been assigned to corresponding coherent generator groups.

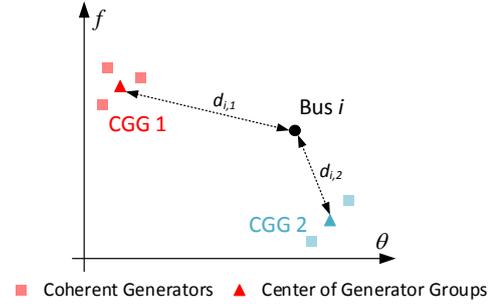


Fig. 2 The association of non-generator bus i and coherent generator groups on the phase plane for the buses (PPB)

Fig. 2 explains the association of non-generator buses and coherent generator groups. For the given case in the figure, two groups of coherent generators have been identified by the PTV method. Thus, two CGGs are firstly computed by (8). After the standardization by (9), the distances from non-generator bus i to two CGGs are computed by (10) as $d_{i,1}$ and $d_{i,2}$, respectively. The bus i is finally assigned to the group 2 because $d_{i,2} < d_{i,1}$. The assignment of non-generator buses is highly efficient because it only takes little computation, which facilitates the fast determination of controlled islanding strategy. Meanwhile, the principle of “minimum electrical distance” ensures that each island composed of coherent generators and associated non-generator buses is connected in topology, which is the guarantee of an effective controlled islanding strategy.

2.3 Flowchart of the proposed scheme

The flowchart of the proposed dynamic coherency identification scheme for controlled islanding is given in Fig. 3. There're 5 steps in this scheme.

step 1. Initiate the scheme by the grid operator's instructions or the preset start-up criterion.

step 2. Collect the data including the state variables for all generators and all buses from PMUs. The required data include the power angle and rotor speed of all generators and the voltage angle and frequency of all buses. If the start-up time is t , the data of t and $t + \Delta t$ are required.

step 3. Identify the coherent generator groups with the PTV methods proposed in section 2.1.

step 4. Assign the non-generator buses to the coherent generator groups with the method proposed in section 2.2.

step 5. Intentionally disconnect certain transmission lines to form the separated islands based on the identified electrical areas.

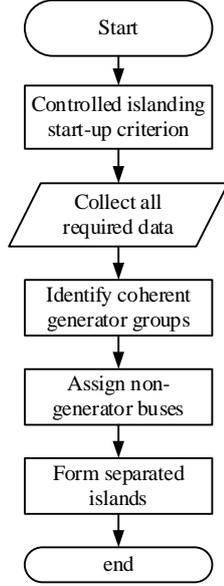


Fig. 3 Flowchart of the proposed scheme

3. Cases Study

The IEEE 39-bus 10-machine power system is selected to verify the effectiveness of the proposed scheme. The required data includes the power angle and rotor speed of all generators, and the frequency and voltage angle of all buses. These transient responses of the power system are simulated on the PSASP-a platform for power system transient simulation and analysis. In the simulation, the two-axis generator model is adopted, and each generator is equipped with the automatic voltage regulators (AVRs) and Power System Stabilizers (PSSs). The simulated data input the proposed scheme as the real-time measurement data from the PMUs. The sample time interval, Δt , is 0.01s and the value of d_c to cut off the cluster tree is 1.

As it is pointed out in section 2, the proposed scheme aims to determine the controlled islanding strategy after the controlled islanding is initiated. The controlled islanding is initiated by the grid operator's instruction or preset start-up scheme. In this paper, an angle-threshold based start-up scheme is adopted as follows:

step:1 Collect required generators information from PMUs, including the power angle and speed deviation of all generators at time t ;

step:2 Search for the maximum angle $\delta_{\max}(t)$ and the minimum angle $\delta_{\min}(t)$ at time t ;

step:3 Compute the maximum angle difference $\Delta\delta_{\max}(t)$ at time t by $\Delta\delta_{\max}(t) = \delta_{\max}(t) - \delta_{\min}(t)$;

step:4 Compare $\Delta\delta_{\max}(t)$ with the preset angle threshold $\Delta\delta_{set}$. If $\Delta\delta_{\max}(t) > \Delta\delta_{set}$, controlled islanding strategy is then started. Otherwise, return to step 1 and continuously detect the out-of-step of the power system according to the measurement information of the next moment.

To fully examine the effectiveness of the proposed scheme, we use two different angle thresholds to launch the controlled

islanding:

Start-up criterion 1: $\Delta\delta_{set} = \pi$.

Start-up criterion 2: $\Delta\delta_{set} = 2\pi$.

Two cases are simulated for the verification. In each case, the proposed scheme will be tested twice because the scheme is initiated by two different criteria respectively.

3.1 Case 1

In case 1, a three-phase short-circuit ground fault occurs on line 27-28 at 0s and then the fault line is cleared at 0.2s. Generator angle curves of case 1 are given in Fig. 4, which indicate G38 is out-of-step relative to other generators. The controlled islanding is initiated at t_{c1} (1.1s) by criterion 1 and at t_{c2} (1.4s) by criterion 2 respectively, which correspond to scenario 1 and 2.

In scenario 1, after the controlled islanding is initiated at 1.1s, the scheme immediately collects the data of generators and buses at time 1.1s and 1.11s. The power angle and speed deviation of generators are used to form the PTVs on the phase plane for generators (PPG). Then the PTV-based method is applied to identify the coherent generator groups. The feature matrix of scenario 1 is given in Table 1, on which generators are identified into two coherent groups: {G38} and {G30-G37, G39}. The coherent generator groups are shown vividly on the PPG in Fig. 5 (a). Afterward, the phase plane for buses (PPB) is built in Fig. 5 (b) using the state variables of all buses at time 1.1s, and all non-generator buses are assigned to the coherent generator groups following the minimum distance principle. The identified coherent generators and areas of scenario 1 are given in Table 2. According to the results, the line 25-26 is disconnected intentionally to form the separated islands, as shown in Fig. 7. Only requiring the data of two sampling moments after start-up, the proposed scheme correctly identifies the coherent generator groups and immediately determines the controlled islanding strategy after the start-up.

For scenario 2, Fig. 6 (a) gives the PTVs on the PPG and Table 2 gives the feature matrix, on which the coherent generators are identified based. Same coherent generator groups are obtained. Then the PPB is built in Fig. 6 (b) to assign the non-generator buses. The final coherent generators and areas of scenario 2 are the same as that of scenario 1. Despite started at different moments in two scenarios, the controlled islanding strategy is same in case 1.

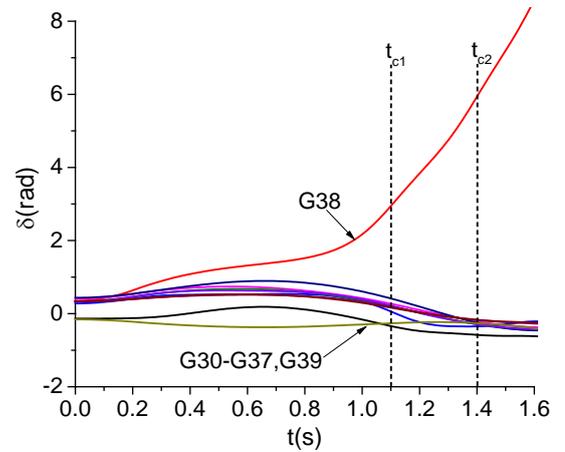


Fig. 4 Angle Curves of All Generators in Case 1

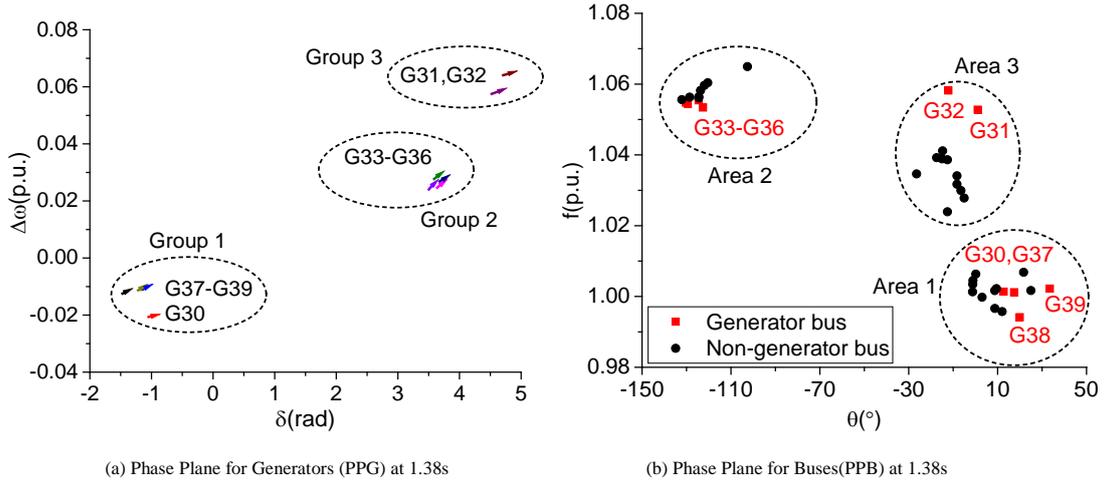


Fig. 10 PPG and PPB of Scenario 2 in case 2

Table 3 Coherent Generators and Areas of Scenario 1 in Case 2

Areas	Coherent Generators	Associated Non-generator buses
1	30 37 38 39	1 2 3 9 17 18 25 26 27 28 29
2	31 32 33 34 35 36	4 5 6 7 8 10 11 12 13 14 15 16 19 20 21 22 23 24

Table 4 Coherent Generators and Areas of Scenario 2 in Case 2

Areas	Coherent Generators	Associated Non-generator buses
1	30 37 38 39	1 2 3 9 17 18 25 26 27 28 29
2	33 34 35 36	15 16 19 20 21 22 23 24
3	31 32	4 5 6 7 8 10 11 12 13 14

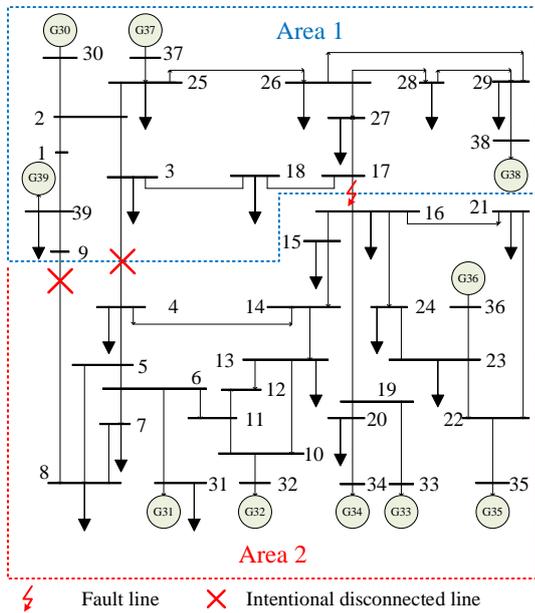


Fig. 11 Areas Corresponding to Scenario 1 in Case 2

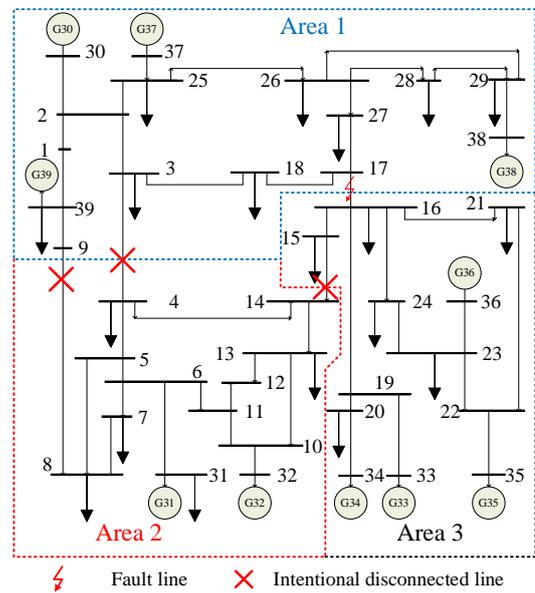


Fig. 12 Areas Corresponding to Scenario 2 in Case 2

4. Conclusion

In this paper, a dynamic coherency identification scheme is proposed for controlled islanding. Firstly, the generator coherency is identified by a PTV based method. The dynamics of generators are represented by the PTVs on the PPG and the hierarchical clustering method is applied to determine the coherent groups. Then a phase plane composed of bus voltage angle and frequency is built to assign the non-generator buses to the coherent groups.

According to the identified coherent generators and areas, certain transmission lines are disconnected intentionally to form the separated islands. The case studies in the test system show that the proposed scheme can identify the dynamic generator coherency and make proper islanding strategy according to current system states.

The proposed controlled islanding method requires the full-observability of the power system. In other words, the

real-time state information of all generators and buses should be accessed accurately and timely to ensure the reliability of the proposed method. This assumption, however, is difficult to implement in the present power system. Study on the application of the proposed method in scenarios that PMUs information is incomplete or with noises is required in the future.

Besides, how to maintain the stability of the islands after the separation is also a research focus. The proposed scheme ensures the coherency of generators in each island, which is the guarantee of angle stability. However, the problems such as the frequency regulation caused by power imbalance remain unsolved, which will be one of our future work priorities.

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