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Coherency Identification Using Hierarchical Clustering Method in Power Systems

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Abstract

In the study of large interconnected power systems, it is essential to aggregate, the power system into several parts, such that each part represents a number of generators. In the words, the coherent generators lie in one part. In this paper, the coherent generators are determined using a pattern recognition technique called hierarchical clustering method**.** In this method, firstly**,** rotor angles of the generators are obtained based on transient stability technique which are calculated by solving state space model of system during three phase short circuit fault Then, the coherency measure which is the similarity matrix is formed using the rotor angles. After that the coherent generators are determined using hierarchical clustering method. The proposed method is then applied to the 39-Bus New England test system. Results of the simulation show that this method is capable in finding the coherent generators in the power system.

Keywords: Coherency, Hierarchical clustering, Similarity matrix, Rotor angles

1 INTRODUCTION

In order to analyze the power system, increase reliability and reducing the computation time, the use of dynamic aggregation is necessary. To find the dynamic aggregation, the coherent synchronous generators should be identified. In the previous studies of identifying the coherent generators, the power system is divided based on the location and magnitude of the disturbance. In this method, the system is divided into two subsystems, called the “study system” and the “external system” [1-3].

Recently, clustering techniques are used for large network to determine coherent generator identification. This method is based on the similarity of the data. The data can be gathered from different location and can have different values. In the clustering methods such as hierarchical clustering, fuzzy C-means and neural clustering, the power system is divided into several groups and the coherent generators lie in one group. The generator grouping is performed based on the data similarity matrix.

The hierarchical tree clustering is also capable to put the coherent groups into coherent subgroup. The similarity matrix in the hierarchical clustering can be based on fuzzy logic. In this case, similarity matrix is named fuzzy clustering matrix [7]. In this method, the fuzzy similarity matrix is calculated based on rotor angles obtained from multi-machine transient stability analysis [6].

In this paper, the coherent generators are identified using unsupervised hierarchical clustering method. Then the Dendrogram plot is employed to show the clusters of the coherent generators. The paper is formed as flows: in Section II, the modeling of the power system is discussed. The coherency measure is explained in Section III, which describes the similarities among the generators. In Section IV, the hierarchical clustering which is a single linkage clustering is used in this paper. Finally, in Section V, the simulation of the proposed method on a test system is presented.

2 MODEL OF POWER SYSYTEM

In the most of coherency identification methods, the classic model of the synchronous generator is used. In this study the classical model is also employed to describe dynamic behavior of the synchronous generators.

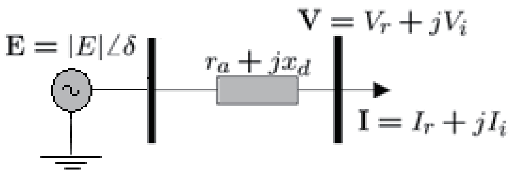


Figure 1. Classic model of the Synchronous generator

In this paper, as shown in Figure 1, the term x_d refers to the transient reactance.

The power system can be described by differential and algebraic equations [15].

$$X' = F(X, Y) \quad (1)$$

$$0 = G(X, Y) \quad (2)$$

Where the set of differential equations, X', refers to the dynamic of state variables X, associated with the rotor angle and the speed of the synchronous generators.

In (2), the set of algebraic equations expresses the relationship between the state variable, X, and the variables of the network Y.

Equation (1) can be expressed as:

$$\delta' = \omega \quad (3)$$

$$\omega' = \frac{1}{M}(T_{mech} - |E|(\cos(\delta)I_r + \sin(\delta)I_i) - D\omega) \quad (4)$$

Equation (2) also can be expanded as

$$G_1 = 0 = \frac{(|E|\cos(\delta) - V_r)r_a + (|E_a|\cos(\delta) - V_r)x_d}{{r_a}^2 + {x_d}^2} - I_i \quad (5)$$

$$G_2 = 0 = \omega - \varpi \quad (6)$$

The equations of network for buses are given by

$$P_i = \sum_{k=1}^{n} V_i V_r [G_{ir}\cos(\theta_i - \theta_r) + B_{ir}\sin(\theta_i - \theta_r)] \quad (7)$$

$$Q_i = \sum_{k=1}^{n} V_i V_r [G_{ir}\sin(\theta_i - \theta_r) + B_{ir}\cos(\theta_i - \theta_r)] \quad (8)$$

Where P_i and Q_i are the net injected active and reactive power into Bus i.

3 COHERENCY MEASURE

The coherency measure is derived from the swing curves obtained from a three phase short circuit at a specific location of the network. At first, an approximated of derivative of rotor angle response is obtained by:

$$\omega_i(t_k) = \frac{\delta_i(t_k) - \delta_i(t_{k-1})}{t_k - t_{k-1}} \quad (9)$$

Where t_k is the kth time sample.

Then, the total distance between the swing curves of generator *i* and generator *j* is expressed by the $Dist_{ij}$ index.

$$Dist_{ij} \cong \sum_{t_k \in [0,T]} |\omega_i(t_k) - \omega_i(t_{k-1})| \quad (10)$$

In (10), the summation $Dist_{ij}$ is computed for all of the time samples t_k during the interval period [0,T]. Every index $Dist_{ij}$ is normalized to become an index $Dnorm_{ij}$ as .

$$Dnorm_{ij} \equiv \frac{Dist_{ij}}{\max(Dist_{ij})} \quad (11)$$

The index $Dnorm_{ij}$ measures the degree of phase difference in the swing waveforms. Then, the coherency measure between generator *i* and generator *j* is obtained from

$$Coh_{ij} = 1 - Dnorm_{ij} \quad (12)$$

It is clear that, $0 \le Coh_{ij} < 1$, $Coh_{ii} = 1$ and $Coh_{ij} = Coh_{ji}$.

The generators can be grouped based on the coherency measure which is also called fuzzy similarity matrix. The similarity strength is represented by a number between zero and one, where number 1 means the maximum similarity. For example the number of similarity degree between a generator and itself is 1.

4 HIERARCHICAL CLUSTERING

Clustering is a kind of classification of a system components such that the components associated with one group are more similar to themselves rather than to the generators of other groups [8-10]. In power system clustering technique, large networks divides into several smaller ones with similar rotor angle swing curve. Generators in the same groups are more similar to each other than to other generators.

Hierarchical clustering is one of the unsupervised clustering method, which the groups the generators into certain clusters. In the hierarchical clustering, Euclidean distance is used to calculate the distance between the data. By using Euclidean distance, similar generator are grouped into coherent groups. Hierarchical clustering divides the generators by the distance vector. The method is based on the selection of data matrix. Hierarchical clustering calculates the distance between all of the samples in the multidimensional space.

The number of the distances associated with the similarities determined from

$$N_S = \frac{N_g(N_g - 1)}{2} \quad (13)$$

Where is N_g equal to the number of generators.

It should be noted that the distances are computed hierarchically. In the method of hierarchical clustering, the identification of coherent groups is performed using fuzzy similarity matrix with size of $N_g \times N_g$. The elements of the similarity matrix are determined based on (12).

The clustering process used in this paper is as follows:

1. Each generator is placed in one cluster. It means for N_g generator we consider N_g clusters.
2. From the total of the clusters, find pairs of the clusters which have the maximum closeness of the coherence measure compare to other clusters. The degree of closeness of the distance between the generator rotor angles specifies the pair coherent generators at this stage. Then, merge them into a single cluster. Therefore, the number of clusters is reduced by 1.
3. Compute the distance between the new formed clusters and each of the old clusters.
4. Repeat steps 2 and 3 till the all samples are grouped into single cluster with the size of N_g.

Hierarchical clustering is like a tree structure which is called Dendrogram plot. If the network is divided into k clusters, (k-1)th highest link is cut from the Dendrogram plot.]

To clarify the steps 1 to 4 in the proposed method, a typical Dendrogram plot for a typical four-generator network is shown in Figure 2. This figure shows that depends on the number of clusters (that are desired), which generators belong to each of clusters. For example if two clusters are desired, Generators 4 and 3 lie in one cluster and the rest of the generators are grouped in the other cluster. In general, if the number of the desired clusters are k, then the (k-1) highest horizontal lines in the Dendrogram plot should be removed. Figure 3. shows another pictorial explanation for Figure 2.

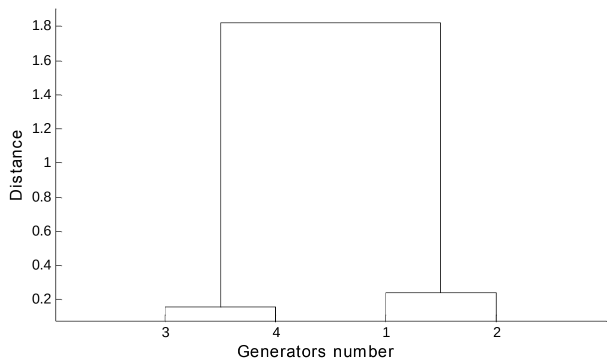


Figure 2. The Dendrogram plot of a 4- generator in network

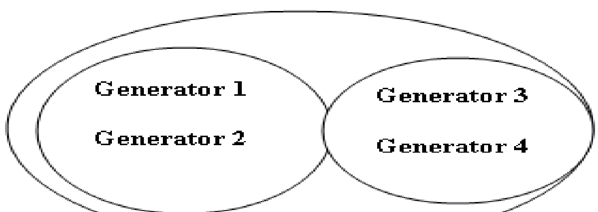


Figure 3. A typical classification of coherent generators using hierarchical clustering method

In this paper, the measure for determining the generators of one cluster is based on the data of the similarity matrix.

5 SIMULATION RESULTS

In this section, the proposed method is simulated on the 39-Bus New England test system.

The test system is shown in Figure 4. The coherent generators are identified for different fault location using the proposed method in this paper.

The simulation is performed by creating a two short circuit tests. In the first short circuit test, the fault occurs in line 3-4 near Bus 3 and the fault is cleared by opening the line between Bus 3 and Bus 4 at t= 0.25 s. The total simulation time is 3 seconds. In the simulation of the test system, the classical models of the generators are used and their excitation system is ignored in the modeling. Rotor angle swing curves for the three phase short circuit in Bus 3, are shown in Figure 5. For the test system, the fuzzy similarity matrix is illustrated in Table 1. Hierarchical clustering method identifies the coherent generators of network by fuzzy similarity matrix.

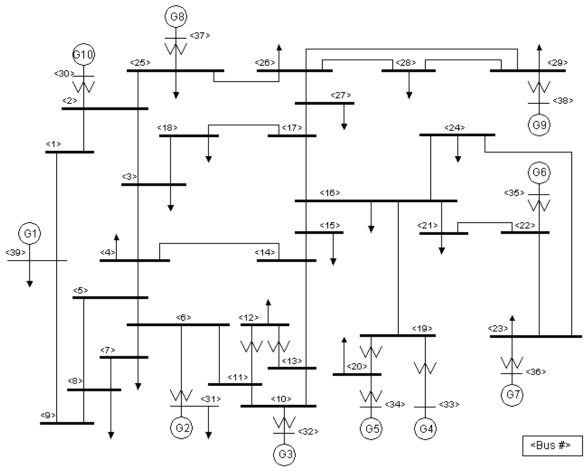


Figure 4. Single line diagram of New England test system [14]

In the simulation, the swing curves of four coherent groups with equivalent generator for each cluster for a 3 phase fault near Bus 3 in line 3-4 are illustrated in Figure 6. There Generators 2,3,4,6 and 7 are grouped in one cluster, using hierarchical clustering. Swing curves of these generators with their equivalent generator are shown in Figure 6.a. Generators 2 and 3 are located in another cluster. Swing curves of these generators with their equivalent generator rotor angle is shown in Figure 6.b. Swing curves of generator 5 and 10 which are in separate groups are shown in Figure 6.c and 6.d, respectively. In Figures 6.a and 6.b, the equivalent rotor angle is shown with thick line.

The Dendrogram plot for the 3 phase fault near Bus 3 in line 3-4 is depicted in Figure 7. In the Dendrogram plot each link in the kth level is equivalent to division of $N_g - K + 1$ clusters.

Table 1 Fuzzy similarity matrix for three phase short circuit near Bus 3 line 3-4

j \ i	1	2	3	4	5	6	7	8	9	10
1	1.0000	0.5286	0.4760	0.6151	0.4745	0.7253	0.6984	0.6308	0.6955	0.3999
2	0.5286	1.000	0.6846	0.4830	0.1533	0.5315	0.5396	0.5061	0.4848	0.2389
3	0.4760	0.6846	1.000	0.3924	0.1105	0.5097	0.5120	0.4478	0.4367	0.1550
4	0.6151	0.4830	0.3924	1.000	0.6156	0.7803	0.8259	0.7326	0.8440	0.1717
5	0.4745	0.1533	0.1105	0.6156	1.000	0.5923	0.5869	0.4543	0.6413	0
6	0.7253	0.5315	0.5097	0.7803	0.5923	1.000	0.9341	0.6549	0.8818	0.1723
7	0.6984	0.5396	0.5120	0.8259	0.5869	0.9341	1.000	0.7055	0.8892	0.1796
8	0.6308	0.5061	0.4478	0.7326	0.4543	0.6549	0.7055	1.000	0.6793	0.3582
9	0.6955	0.4848	0.4367	0.8440	0.6413	0.8818	0.8892	0.6793	1.000	0.1969
10	0.3999	0.2389	0.1550	0.1717	0	0.1723	0.1796	0.3582	0.1969	1.000

Cutting the Dendodiagram links is performed according to similarity degree in smaller the generator groups.

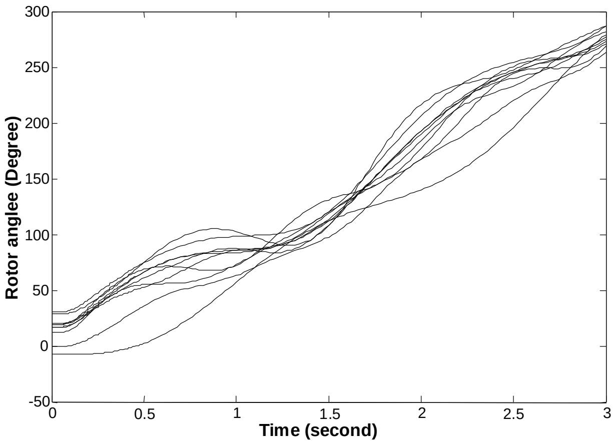
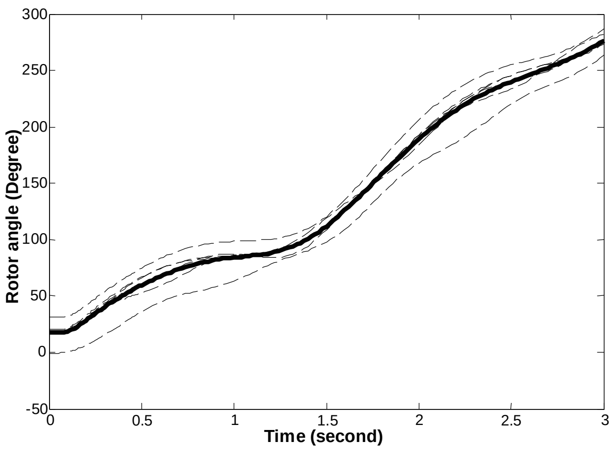
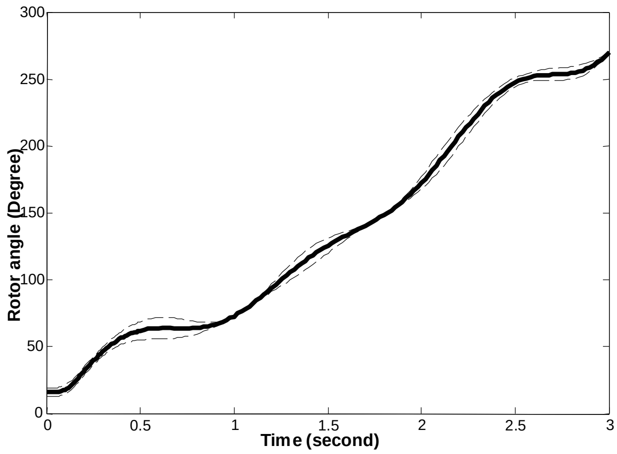


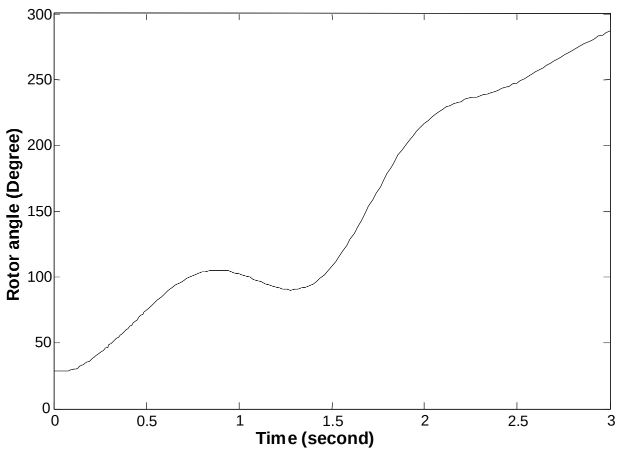
Figure 5. The swing curve of all generators for thee phase fault near Bus 3 line 3-4



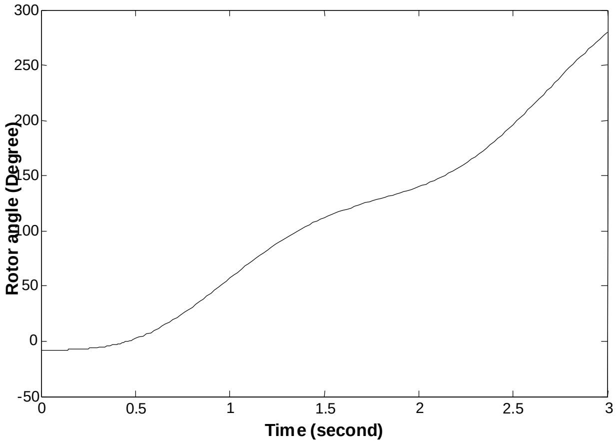
(a) Group one



(b) Group two



(c) Group three



(d) Group four

Figure 6. The swing curves of four groups (fault near Bus 3)

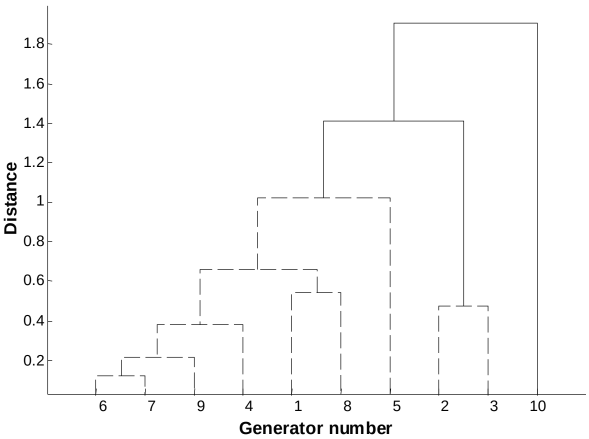


Figure 7. The Dendrogram plot of all generators for three phase fault near Bus 3 line 3-4

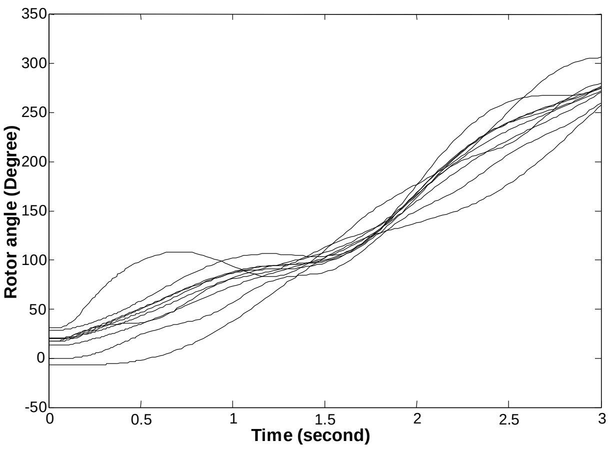


Figure 8. Swing curve of all generators for three phase fault near Bus 25 at Line 25-26

Dendodiagram of the generators in the network is determined using coherency measure in the transient stability simulation of power system.

The second three phase short circuit is assumed to be occurred near Bus 25 in Line 25-26 for the duration of 0.1 second. The rotor angle swing curve and the Dendrogram plot for this fault are depicted in Figures 8. and 9., respectively.

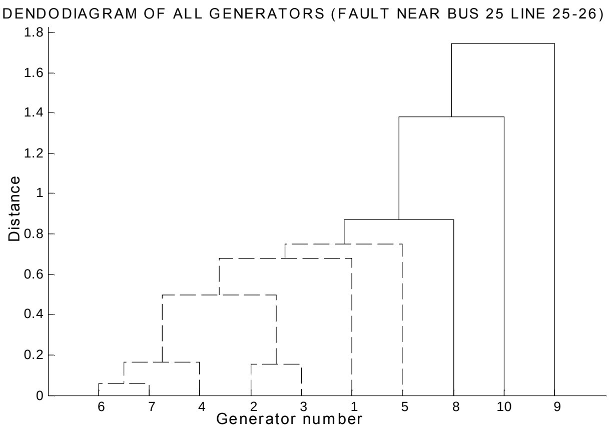


Figure 9. The Dendrogram plot of all generators for three fault near Bus 3 line 3-4

Changing the location and clearance time of the fault leads to different results in grouping the coherent generators. From the Dendrogram plot, the generators which are affected more by the fault in a special location of network are located in separate clusters.

The summary of the results of clustering for different groups and locations of two faults is depicted in Table 2.

These results can be seen for different groups in the Dendrogram plot. The performance of the six equivalent groups for short circuit three phase fault near Bus 25 in line 25-26 is illustrated in Figure 10.

The equivalent generators performances are very similar to the generators of the network.

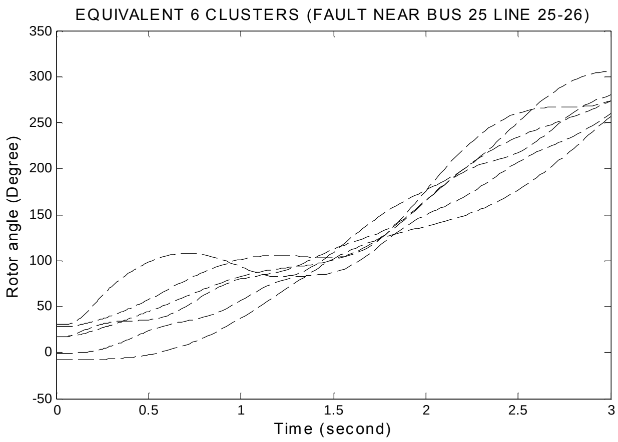


Figure 10. Swing curve of equivalent six groups for three phase fault near Bus 25 at Lines 25-26

Table 2. Result of clustering for different grouping of generators in different fault location

Fault location	Number of clusters	Generator groups
Near Bus 3 at Line 3-4	4	(1,4,6,7,8,9),(2,3),(5),(10)
Near Bus 3 at Line 3-4	5	(1),(2,3),(4,6,7,8,9),(5),(10)
Near Bus 3 at Line 3-4	6	(1),(2,3),(4,6,7,9),(5),(8),(10)
Near Bus 25 at Line 25-26	4	(1,10),(2,3,4,5,6,7),(8),(9)
Near Bus 25 at Line 25-26	5	(1),(2,3,4,5,6,7),(8),(9),(10)
Near Bus 25 at Line 25-26	6	(1),(2,3,4,6,7),(5),(8),(9),(10)

6 CONCLUSIONS

In this paper, a new method is proposed for identification of coherent generators. This method is based on the hierarchical clustering method. This method uses a coherency measure which is determined by rotor angle swing curves in the transient stability simulation of power system. Firstly, the swing rotor angle of the generators due to a short circuit is determined. In the next step, the Dendrogram plot of network generators is obtained. Finally, the rotor angle swing curves of equivalent groups are identified using the Dendrogram plot. The simulation results are dependent on the location of fault. This is a great advantage of the proposed method in on-line identification of the coherent. The results show the validity of the proposed method in on-line clustering coherent generator identification.

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