Power Systems Transient Stability Indices: Hierarchical Clustering Based Detection of Coherent Groups Of Generators

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Abstract—In power system stability analysis, the identification of coherent groups of generators, i.e., machines with strongly correlated rotor angles, holds significant importance. This study presents a real-time methodology that employs hierarchical clustering techniques to assess the level of coherence among generators using the synchronization coefficient and the correlation coefficient of the generator’s rotor angle as indicators of coherency. Additionally, the study utilizes Power Transient Stability Indices (PTSI) to investigate the dynamic response of the power system. The method incorporates power system transient Stability indices, including the Power Connectivity Factor (CF) index, which highlights the generators exhibiting strong coherence within groups, the Power Separation Factor (SF) index, which reveals the extent to which generators in different groups tend to deviate from one another in the event of a disturbance, and the overall system separation index, demonstrating the system's overall separation status (CF/SF).

To validate the approach, extensive assessments were conducted using an IEEE-39 test system featuring a fully dynamic model. The simulation results presented in this paper underscore the effectiveness of the proposed methodology.

Keywords—Coherency Index; Correlation Coefficient, Synchronization Coefficient, Clustering, Coherency Detection, Power Transient Stability Indices

I. INTRODUCTION

The power grid frequently faces various disruptions that can rapidly lead to instability, potentially resulting in catastrophic blackouts due to cascading failures. Coherent groups of generators, specifically machines with highly correlated rotor angles, play a pivotal role in the analysis of power system stability [1]. Identifying these coherent regions is a crucial step in enhancing the grid’s resilience and mitigating the risk of cascading failures [2]. These attributes can be harmonized with additional corrective measures to determine practical islands within the power system, akin to solving a 0-1 knapsack problem.

Over the past decade, numerous methods have emerged for classifying coherent regions in operation and control studies. In [3], a wide-area coherency discovery approach based on Project Pursuit (PP) is proposed. Furthermore, a Projection Cumulative Contribution Rate (PCCR) index is introduced to determine central coherency status and to establish generator coherency groups under various disturbances. However, the selection of an appropriate PCCR remains a subject requiring further investigation. In [4], coherent generator groups are identified using the degree of variation in generator bus voltage phase angles, assisted by a hierarchical clustering approach. [5] presents a coherency recognition technique that employs linearization of non-equilibrium points. This method assesses oscillation status between generators by utilizing eigenvalues from the coefficient matrix of linearized models. [6] employs wide-area generator speed measurements through Fast Fourier Transform (FFT)-based spectral methods. Nonetheless, this approach relies on the analysis of linear and stationary data, an assumption that may not always hold.

In [7], generator coherence groups are established using the Partitioning Around Medoids (PAM) approach, and it is compared with K-means in [8]. While the K-means clustering approach is straightforward and efficient [9], [10], it struggles with data clustering without predefined centroids or a priori knowledge of the number of clusters, often necessitating multiple iterations [11,12]. In [13] approach was introduced to partitioning the power network based on the system’s dynamic response. In [14] modularity clustering for distribution networks to partition the network into coherent islands was employed. In [16], a constrained spectral k-embedded clustering technique is developed to identify islanding solutions while minimizing active power flow disruptions. In [17] a two-step Spectral Clustering Controlled Islanding (SCCI) approach, which uses generator coherency as the sole constraint to determine an appropriate islanding solution with minimal active power flow disruption was presented. A significant advantage of this approach to detecting islanding conditions is the employment of an online strategy combined with the center of inertia technique to ascertain generator coherency. This method has demonstrated its effectiveness across a variety of applications.

This paper introduces a novel methodology centered on hierarchical clustering techniques to identify generator coherency, leveraging the correlation index of rotor angles at each generator to quantify their association strength. Additionally, transient stability indices are computed, assessing generator coherency strength, network integrity, and overall system separation status. This method boasts computational efficiency, ease of implementation, and does not necessitate a predefined number of groups. Simulation
results conclusively demonstrate the effectiveness of the proposed approach.

II. DYNAMIC COHERENCY DECTTION

A. Correlation Coefficient as Coherency Measure

The Pearson product-moment Correlation Coefficient (CC) stands out as the most frequently employed metric for assessing the extent of correlation between linearly related variables. Typically, this correlation coefficient (CC) spans the range from -1.0 to +1.0, providing insight into both the strength and direction of the linear relationship between the two variables. When applied to the context of the power network, these variables symbolize the coherency between two distinct generators, with a value of +1.0 signifying an ideal positive association between the pair of generators. To quantify the degree of coherency between two different generators, we derive the CC for generator i and j using the following formula:

\[
CC_{ij} = \frac{n \sum \delta_i \delta_j - \sum \delta_i \sum \delta_j}{\sqrt{n \sum \delta_i^2 - (\sum \delta_i)^2} \sqrt{n \sum \delta_j^2 - (\sum \delta_j)^2}}
\]

(1)

where \(\delta_i = [\delta_{i1}, \delta_{i2}, \ldots, \delta_{in}]\) is the dataset of the rotor angle of the \(i^{th}\) generator in the needed time interval including \(n\) values of the rotor angle \(\delta_i\). Hence, the coherency between a pair of generators can be unveiled by gauging the correlation in the variation of rotor angles across these generators.

B. Generators Synchronization Coefficients as Coherency Measure

The coherency among the generators, i.e. their tendency to swing together, changes following a disturbance, a characteristic that is used in this methodology to find the generator coherency. Znidi et.al [16] proposed an algebraic model for calculating the synchronization coefficient between \(M\) generators in an \(n\) bus system using a classical model for transient analysis. Eq. 2 illustrates the synchronization coefficient among generator \(i\) and \(j\), where \(|E'_i|\) is the magnitude of the voltage behind the reactance in the synchronous generator, \(B_{ij}\) is the susceptance between the element \(i\) and \(j\) in the reduced system, and \(\delta_{ij}\) is the difference between the rotor angle of machines \(i\) and \(j\) [17-20].

\[
KS_{ij} = \sum_{E' \in E_j} |E'_i| |E'_j| (-B_{ij} \cos \delta_{ij})
\]

(2)

There is an associated complete weighted graph \(KS_M\) to the power system consisting of \(M\) machine where \(G = \{g_1, \ldots, g_M\}\) is the set of generators and \(KS = \{KS_{ij} | i, j \in G, i \neq j\}\) is the set of synchronization coefficient among the generators. The associated adjacency matrix of the \(KS_M\) is called \(KS\) matrix which is a square \(M \times M\) matrix, that can be easily formed in the real-time fashion for a power network. Hierarchical clustering techniques are employed in the next section to split the generators into the coherent groups of generators [21, 22].

C. Hierarchical Clustering

Clustering is the process of organizing a set of objects in such a way that objects within a cluster exhibit a connection to each other and distinction from objects in other clusters. In the context of power networks, this clustering approach divides the extensive network into several smaller ones characterized by similar rotor angle swing patterns. To put it differently, generators within the same cluster will exhibit connections to one another while being distinct from generators in other clusters. The Hierarchical clustering technique relies on the computation of Euclidean distances between all data points within the multidimensional space, subsequently dividing the generators based on the distance vector. The number of these distances is indicative of the similarities between generators and is calculated using the following equation:

\[
N_s = \frac{N_g (N_g - 1)}{2}
\]

(3)

where \(N_g\) is the number of generators. Therefore, the fuzzy Hierarchical clustering similarity matrix with a size of \(N_g \times N_g\) is used to determine the coherent groups. The components of the similarity matrix are established based on the \(KS\) matrix. Fig. 1 shows the clustering procedure utilized in the suggested method.

![Fig. 1. The Clustering Method](image)

Further, applying the hierarchical clustering techniques, the \(KS\) matrix is partitioned to the \(N\) groups of coherent generators. This has an associated \(N \times N\) matrix called \(KS\) or CC. Fig. 2 shows a generic extraction of \(KS\) from \(KS_M\) for the 10-machine system consisting of three coherent groups of generators. The diagonal elements of matrix \(KS\) represent the strength of coherency in each group while the off-diagonal elements show how strong is the coherency among different groups. Moreover, the Laplacian matrix and its eigenvalues present valuable information about the power system in real-time. The PTSI based on matrix \(KS\) is explained in the next section.
Fig. 2. Formation of Coherent Groups and KsGM from $K_{S,MC}$ of 10-machine System

D. Power Systems Transient Stability Indices

The symmetric square $N \times N$ matrix $K_{sGM} = (K_{sGM}_{ij} | i,j \in N)$ is the adjacency matrix associated with the complete graph of $N$ coherent groups of generators which has interesting properties that can be extracted by applying a simple algebraic process. The diagonal and off-diagonal elements present the strength of coherency between the generators inside a group and between the groups, respectively. Acquiring matrix KsGM in real-time fashion paves the way for future analysis to observe how is the integrity of the power network. To this end, the next subsections define the PTSI based on matrix KsGM.

The power Connectivity Factor (CF) index, is called as the mean of diagonal of the KsGM matrix, which presents coherently strong generators within the groups. The power Separation Factor (SF) index is called the mean of KsGM matrix off-diagonal which unveils to the extent that the generators in different groups tend to swing against the other groups after a disturbance. The overall system separation status (CF/SF) is defined as CF divided by SF, which shows the total system splitting status. Eq. 4, Eq. 5, and Eq. 6 demonstrate CF, SF, and the CF/SF respectively, where $a_{ii}$ is the diagonal element of $K_{sGM}$.

$$CF_i = a_{ii}$$

$$SF_{ij} = \sum_{i=1}^{n-1} \sum_{j=2}^{n} \frac{a_{ii} + a_{ij}}{2 \times a_{ij}}$$

$$CF/SF = \frac{\sum_{i=1}^{n-1} a_{ii}}{\sum_{i=1}^{n-1} \sum_{j=2}^{n} a_{ij}}$$

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

III. SIMULATION TEST CASES

The methodology efficiency is assessed via the simulation study performed on the modified IEEE 39-bus system shown in Fig. 3. The approach has been executed in MATLAB and all time-domain simulations are attained in DiGSIILENT PowerFactory. Table 1 lists the events that occurred as a result. Using the proposed approach, the generator coherence groups will be identified for different fault locations.

Fig. 3. EEE 39 bus system. The crosses are the event in the sample case study in scenario 1

A. Scenario 1: Stable Case

Table 1 lists the events that occurred as a result of the duration of the simulation time of 100 s.

| Time (s) | Description                  |
|---------|------------------------------|
| 2.00    | Short circuit on lines 3-4   |
| 2.40    | Switch event on lines 3-4    |
| 20.00   | Short circuit on lines 14-15 |
| 20.40   | Switch event on lines 14-15  |

The outage of lines 3-4 and 14-15 at $t=2$ and $t=20$ s respectively are considered as the events. Fig. 4 and 5 show the generator rotor angle oscillation and the bus frequencies respectively. As can be seen, the rotor angle fluctuations are damped, and all the generators stay in synchronization while groups of generators develop into stronger after the events. Fig. 4 shows the stability of the power system following the occurrence of the disturbances.

Fig. 4. Generator rotor angles in scenario 1
Therefore, by using the similarity matrix and utilizing the hierarchical clustering technique, the coherent groups of generators of the power network can be recognized. As seen in Fig. 3, grid generators are grouped into three separate groups: $\{G_4, G_5, G_6, G_7\}; \{G_8, G_9, G_{10}\}; \{G_1, G_2, G_3\}$. After the second outage, the CC between generators is calculated from Eq. 1 and the CC matrix is formulated. Applying hierarchical clustering on the CC results in three separate coherent groups of generators shown in Fig. 3. The power transient stability indices CF, SF, and (CF/SF) as shown in Fig. 6, 7 and 8 respectively become steady at 90 s.

As can be seen, after the first event at t=2s the CF and SF are slightly increased because the events cause the generators to swing, however, this failure did not cause total separation. The CF and SF have small variations because the generators stabilize between t=2 s and t=20 s. After the second event at t=20 s, the CF and SF are increased and decreased respectively because the faults cause the group of coherent generators to be separated. Similarly, the Ks among generators is calculated from (2) and the Ks matrix is formulated. Applying hierarchical clustering on the Ks results in three separate coherent groups of generators shown in Fig. 4. The power transient stability indices CF, SF, and (CF/SF) are shown in Fig. 9, 10, and 11 respectively become steady at 40 s.

B. Scenario 2: Unstable Case

Three short circuits (SC) events occurred in lines 3-4 at t=3 s and lines 13-14 and 16-17 at t=10 s. Table 2 list the events that occur in the testbed system during the simulation time of 30 s.

| Time (s) | Description                      |
|---------|----------------------------------|
| 3.00    | Short circuit on lines 3-4        |
| 10.00   | Short circuit on lines 13-14 and 16-17 |
| 15.20   | Switch event                      |

As can be seen, after the first event at t=2s the CF and SF are slightly increased because the events cause the generators to swing, however, this failure did not cause total separation. The CF and SF have small variations because the generators stabilize between t=2 s and t=20 s. After the second event at t=20 s, the CF and SF are increased and decreased respectively because the faults cause the group of coherent generators to be separated. Similarly, the Ks among generators is calculated from (2) and the Ks matrix is formulated. Applying hierarchical clustering on the Ks results in three separate coherent groups of generators shown in Fig. 4. The power transient stability indices CF, SF, and (CF/SF) are shown in Fig. 9, 10, and 11 respectively become steady at 40 s.
Using the CC among the generator as coherency measure and applying the hierarchical clustering methodology results in the variation of the CF, SF and CF/SF as shown in Fig. 14, 15 and 16 respectively following the events. As can be seen, after the first event at \( t=3 \) s the CF and SF are slightly increased because the events cause the generators to swing, however, this failure causes total separation at 25.25 s. The CF and SF have small variations because the generators stabilize between \( t=3 \) s and \( t=25 \) s. After the second event at \( t=20.25 \) s, the CF and SF become unstable. The behavior of the overall system separation status (CF/SF) using CC is shown in Fig. 16.

Similarly, the \( K_s \) among generators are calculated from Eq. 2 and the \( K_s \) matrix is formulated. Applying hierarchical clustering on the \( K_s \) results in the variation of the CF, SF and CF/SF shown in Fig. 17, 18 and 19 respectively following the events. The power transient stability indices CF, SF, and (CF/SF) become steady at 40 s. The CF, SF and CF/SF have small variations because the generators stabilize between \( t=3 \) s and \( t=25 \) s. After the second event at \( t=20.25 \) s, the CF and SF become unstable. The behavior of the power Connectivity Factor (CF) index using \( K_s \) in scenario 2 is shown in Fig. 17.

The behavior of the power Separation Factor (SF) index using \( K_s \) in scenario 2 is shown in Fig. 18.

The behavior of the overall system separation status (CF/SF) using \( K_s \) in scenario 2 is shown in Fig. 19.
IV. CONCLUSION

This paper proposes a novel methodology for discovering the degree of coherency among generators. It uses the synchronization coefficient and the correlation coefficient to measure the strength of the association between each pair of generators. The hierarchical clustering techniques were used to find the generator's coherency. Further, the strength of the generators coherency was assessed, the power systems transient stability indices, the integrity indices, and the overall system status was examined. It was evident from the results that this approach can determine the degree of coherency among any pair of generators accurately using synchronization coefficient and the correlation coefficient among the generators.

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