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Generator Coherency and Area Detection in Large Power Systems

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Abstract— This paper provides a new general approach for defining coherent generators in power systems based on the coherency in low frequency inter-area modes. The disturbance is considered to be distributed in the network by applying random load changes which is the random walk representation of real loads instead of a single fault and coherent generators are obtained by spectrum analysis of the generators velocity variations. In order to find the coherent areas and their borders in the inter-connected networks, non-generating buses are assigned to each group of coherent generator using similar coherency detection techniques. The method is evaluated on two test systems and coherent generators and areas are obtained for different operating points to provide a more accurate grouping approach which is valid across a range of realistic operating points of the system.

1. Introduction

The energy demand is vastly growing and the network expansion is not following the pace of load growth in power systems. This has led the inter-connected power systems to operate very close to their operation limits, which makes them more vulnerable to any possible disturbance. Therefore, there is increasing value for enhancement methods to maintain the stability of power systems.

In the case of disturbance in multi-machine power systems, some of the machines exhibit similar responses to the disturbance which means the difference between their swing curves is so small that they can be considered to be oscillating together and coherent. In power system dynamic

performance, coherency between generators is an important factor which has several applications including dynamic reduction of power systems and emergency protection and control schemes.

As mentioned, generator coherency has a vast application in power system dynamic reduction by aggregating coherent generator units. Several methods have been introduced in literature for system reduction based on grouping similar generators. One of the most common methods in power system dynamic reduction is slow coherency based methods [1]. In these methods, if the system is subjected to a disturbance, the generators that are coherent in low frequency modes are called slow coherent generators and they are usually considered to be in one area and the multi-machine power system can be represented as a multi area system [2]. Beside slow coherency based methods for power system dynamic reduction, some other methods have also been introduced to aggregate the coherent group of generators such as relation factor [3] and Krylov subspace methods [4]. Synchrony based algorithms are also among widely used methods which define and aggregate the areas based on different methods of synchrony and can be applied on small and large systems [5], [6].

Defining coherent generators is an essential part in some emergency protection methods such as controlled islanding when the system is subjected to a severe disturbance and the conventional control systems are unable to keep the system stable [7]. The stability of islands created in the aftermath of the disturbance is dependent to the coherency of the generators inside the islands which shows the importance of correctly detecting coherent generators.

Due to the importance of coherency detection in transient stability and control studies, several methods have been introduced to define the coherent groups of generators and areas in inter-connected power systems. Some of these methods use time-domain analysis on the linear dynamic model of power systems [8] and also frequency response analysis have been implemented in some articles [9]. Direct stability analysis methods such as Unstable Equilibrium Point (UEP) have been also applied for solving the generator coherency detection problem [10]. In the methods using the linearized dynamic model such as slow coherency method, the coherency between generators is obtained for the specific operating point and the change in the operating conditions may change the

coherency indices between the generators which should be investigated. Therefore, methods such as continuation method [11] have been applied to trace the coherency characteristics in the network. In [12] a method is proposed to use the phase of the oscillations to determine coherency using Hilbert–Huang transform. Application of wide area angle and generator speed measurement is another helpful tool in tracking the generator coherency in inter-connected power systems [13].

In this paper, a new method is proposed to find a general grouping of generators based on coherency by providing a distributed disturbance on the network which is applied by low level randomly changing of the load in all of the load buses. In the frequency range of electromechanical oscillations the load changes can be considered as white noise. This process is called as random walk process and has been applied for estimation of modal parameters [14]. The spectrum analysis is then applied on the generator velocity swings to obtain the significant inter-area modes and generator coherency to form the areas in the network. There have been approaches which have used spectrum analysis in detecting coherent generators [15], [16] and in this paper, spectrum analysis along with other statistical signal processing tools are used to define the generators in each area. In many applications such as system dynamic reduction and islanding defining the non generator buses which belong to each area is important; this task is addressed in few research works [17]. Therefore in order to provide a general area detection scheme, load buses related to each area are defined, which leads to detection of boundary buses, lines and the whole system is thus divided into areas. Defining areas for multiple operating points as presented in this paper also provides more accurate schemes to facilitate online control of inter-area dynamics.

The paper is organized as follows. Section 2 describes the proposed method for identifying coherent generators and related buses; in Section 3 the approach is applied to two test systems and the results are discussed; and conclusion is provided in Section 4.

2. Generator Coherency and Area Detection

Defining the areas in large inter-connected power systems consists of two steps, including finding coherent generators which form a group and assigning the non-generation buses to these groups. The generators which have similar behaviour after the disturbances in the systems are called coherent generators and usually the term “coherency” refers to the coherency of generators in the slow inter-area modes. To study the generator coherency a classical machine model is usually considered to be sufficient [3], [9]:

$$J_i \frac{d^2\delta_i}{dt^2} + D_i\omega_i = P_{mi} - P_{ei} \quad (1)$$

$$\omega_i = \frac{d\delta_i}{dt} \quad , \quad i = 1, \dots, n \quad (2)$$

In the equations above J_i is the inertia ratio, D_i is damping ratio, P_{mi} and P_{ei} are the mechanical power and electrical power of the ith machine, ω_i is the generator velocity, δ_i is the generator angle, and n is the number of generators. Electrical power P_{ei} depends on the load modeling in the system and by modeling them as constant impedances the differential algebraic equations (DAEs) will be simplified.

In most of the power system transient stability simulations, a disturbance is considered as a fault on a line or bus and the analysis is performed based on the single perturbation of the power system. In this approach instead of single disturbance in the system, the disturbance is distributed within the system to guarantee the excitation of all modes. This has been implemented by low level randomly changing of the load at all load buses which resembles the real load changes in power systems. This load change has the effect of a distributed disturbance in the power system, and will cause the generators to swing in a range of different frequencies related to different oscillation modes.

By applying the mentioned load disturbance, the velocity changes of all the machines in the system can be studied and spectrum analysis is applied to the output velocity of the generators. The

Discrete Fourier Transform (DFT) is a common method for spectrum analysis of discrete time signals and is seen in equation (3).

$$X_f = \sum_{n=0}^{N-1} x_n H e^{-\frac{i2\pi}{N} fn} \qquad f = 0, \dots, N-1 \qquad (3)$$

X_f is DFT, x_n is the sampled velocity of each generator, N is the number of samples, and H is the window function. The inter-area modes are usually between 0.1 and 1 Hz and depending on the sampling frequency the number of samples should be chosen big enough to ensure all low frequency modes are extracted.

The kinetic energy of machines plays a significant role in the importance of each mode in power systems. By having the kinetic energy of each machine and also the total kinetic energy of the system over the spectrum, the important modes with the higher kinetic energy and low frequency can be considered as the possible inter-area modes. The kinetic energy of machines and total kinetic energy of the system over the spectrum is calculated as (4-5), where $E_i(f)$ is the kinetic energy of each machine and $E_T(f)$ is the total kinetic energy of the system across the spectrum.

$$E_i(f) = {}^1\!/_2 J_i \omega_i(f)^2 \qquad (4)$$

$$E_T(f) = \sum_{i=i}^{n} E_i(f) \qquad (5)$$

To obtain the kinetic energy of each machine and total kinetic energy of system respectively over the spectrum, the DFT of generator velocities ω_i is calculated by (3) and obtained $\omega_i(f)$s are squared and multiplied by inertia ratio J_i according to (4) to define the spectral distribution of kinetic energy of each machine. Then referring to (5) the total kinetic energy across the spectrum can be easily calculated by adding the obtained kinetic energy of each generator. Then the obtained total kinetic energy is checked for low frequency to find the important inter-area modes.

As it is seen in the test results, the inter-area modes usually have the low oscillation frequency of 0.1 – 1 Hz while the kinetic energy analysis will also assist in defining inter-area oscillation frequencies. By studying the coherency of generators in the range of inter-area modes, the coherent generators are found and generator grouping is achieved. For the chosen disturbance, the velocity of generators can be considered as the random process and these signals are analysed in the inter-area frequency band. Therefore, the generators velocity signals are low pass filtered using a low pass digital signal filter such as Chebyshev filter to exclude the higher frequency oscillations. In this case for the filtered velocities, signal correlation coefficient is calculated as below:

$$r_{ij} = \frac{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})(f\omega_{jk} - \overline{f\omega_j})}{\sqrt{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})^2 \sum_{k=1}^{N}(f\omega_{jk} - f\overline{\omega_j})^2}} \qquad (6)$$

Where $f\omega_{ik}$ and $f\omega_{jk}$ are the kth element of filtered velocity signal of machine i and j, $\overline{f\omega_i}$ and $\overline{f\omega_j}$ are the sample means of these signals, and r_{ij} is the correlation coefficient between mentioned velocity signals. The resulting r_{ij} is a real number such that $-1 < r_{ij} < 1$ and its sign shows if the pairs are positively or negatively correlated.

Coherent groups of generators are identified by calculating the correlation coefficients for the low pass filtered velocities of generators as described above. Based on the results for each pair of generators, highly positive correlated generators will define the coherent groups of generators. This method is very efficient in large power systems as highly correlated generators in the inter-area frequencies are considered to form groups. In some cases, some generators may not only correlate with one group but also have higher correlations with other groups. In such cases and also for more accurate grouping and characterizing inter-area oscillations between areas, further analysis is performed on velocity of generators. To achieve this, the coherence and cross spectral density functions will be applied on the velocity changes of machines. The coherence (magnitude-squared coherence) [18] between two velocity signals related to machine i and j is calculated as:

$$C_{ij}(f) = \frac{|P_{ij}(f)|^2}{P_{ii}(f)P_{jj}(f)} \qquad (7)$$

Where $P_{ij}(f)$ is the cross spectral density of velocity of generators i and j, $P_{ii}(f)$ and $P_{jj}(f)$ are the power spectral density (PSD) of ω_i and ω_j calculated as (8-9). It can be inferred that cross spectral density and PSD functions are Discrete Fourier Transforms of cross-correlation $R_{ij}(n)$ and auto-correlation $R_{ii}(n)$ functions which can be obtained by (10-11) where $E\{\}$ is the expected value operator.

$$P_{ij}(f) = \sum_{n=0}^{N-1} R_{ij}(n) e^{-\frac{i2\pi}{N}fn} \qquad f = 0, \dots, N-1 \qquad (8)$$

$$P_{ii}(f) = \sum_{n=0}^{N-1} R_{ii}(n) e^{-\frac{i2\pi}{N}fn} \qquad f = 0, \dots, N-1 \qquad (9)$$

$$R_{ij}(n) = E\{\omega_i(m+n)\omega_j(m+n)^*\} \qquad (10)$$

$$R_{ii}(n) = E\{\omega_i(m+n)\omega_i(m+n)^*\} \qquad (11)$$

The coherence function (7) defines the coherency of the velocity output of machines across the frequency range and defines how the machines are correlated. This coherence function is not sufficient to define the coherent group of generators as it does not indicate if the generators are positively or negatively coherent in each frequency. To overcome this issue, the angle of cross spectral density function $P_{ij}(f)$ can show the angle that generators are correlated in each frequency at the range of inter-area modes. So if the angle is close to zero the machines are positively coherent and belong to a group and if it is close to 180 degrees, means the machines are negatively coherent for that frequency so they cannot be grouped and belong to different machine groups.

Comparing the coherence functions and cross spectral density angle between pairs of generators, the inter-area oscillation frequency band of every group of generators can be defined. In this approach, the generators in one group are highly and positively coherent with each other in that frequency band, while they are highly but negatively coherent to generators belonging to the other group. Therefore, generators in each area along with the inter-area oscillation frequency between different areas will be defined. This method is also applicable for the generators located in the area boundaries which can have high correlations with both of the neighbouring areas. These generators are checked for the specific inter-area frequency band of two areas to see their relation to each of the generator groups. In this case if the disputed generators are positively coherent at the inter-area oscillation frequency band with all of the generators in a group, these generators can be considered as a part of that group.

To define the concept of general coherency, the load and generation have to be randomly changed for several cases to check the coherency of generators over different loading scenarios. The purpose is to check if the grouping of generators is robust against the load changes in the system or grouping will change by changing the load in network. It is proven that load changes can affect the coherency characteristics of the power systems. In this case, some generators specially the generators in the boundaries may be swapped between the neighbouring areas.

Defining the coherent generator groups is the essential part of area detection in power systems. The second part will be to identify the non-generator buses located in each area. To determine which load and switching bus should be considered in an area, the angle swing of all load buses are obtained. For this reason, the loads can be considered as constant impedances and by having the generators angle swings the angle swings in load buses are obtained.

$$\boldsymbol{I} = \boldsymbol{YV} \tag{12}$$

$$\begin{bmatrix} \boldsymbol{I_G} \\ \boldsymbol{I_L} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y_{11}} & \boldsymbol{Y_{12}} \\ \boldsymbol{Y_{21}} & \boldsymbol{Y_{22}} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_G} \\ \boldsymbol{V_L} \end{bmatrix} \tag{13}$$

$$\boldsymbol{V_L} = \boldsymbol{Y_{22}^{-1} Y_{21} V_G} \tag{14}$$

$$\boldsymbol{\delta_L} = angle(\boldsymbol{V_L}) \tag{15}$$

$\boldsymbol{V_G}$ and $\boldsymbol{I_G}$ refer to the voltage and current injection at generators while $\boldsymbol{V_L}$ and $\boldsymbol{I_L}$ are the voltage and current at non-generation buses and $\boldsymbol{Y}$ is admittance matrix of the system.

As the inter-area oscillation frequency bands of neighbouring areas are known, the load buses located in each of the areas can be defined. Similar to the generators, the angle swing in non-generation buses are low pass filtered using a low pass digital signal filter to include only the low frequency inter-area modes and, signal correlation coefficient is calculated for the filtered angle swings.

$$rl_{ij} = \frac{\sum_{k=1}^{N_l}(f\delta_{ik} - \overline{f\delta_i})(f\delta_{jk} - \overline{f\delta_j})}{\sqrt{\sum_{k=1}^{N_l}(f\delta_{ik} - \overline{f\delta_i})^2 \sum_{k=1}^{N_l}(f\delta_{jk} - \overline{f\delta_j})^2}} \qquad (16)$$

Similar to (6) $f\delta_{ik}$ and $f\delta_{jk}$ are the kth element of filtered angle swing signal of non-generation buses i and j, $\overline{f\delta_i}$ and $\overline{f\delta_j}$ are the sample means of these signals, N_l is the number of non-generation buses, and rl_{ij} is the correlation coefficient between these signals. Calculating the correlation coefficient for the filtered angle swing of non-generation buses, highly positive correlated buses are considered to be in the same area. This method is applicable to large systems to assign highly correlated buses to each area. To exactly define the border lines (lines connecting the areas) and border buses (buses at each end of border lines) coherence function is calculated for each pair of the non-generation buses using (8-11) and replacing the generator velocity ω by angle swing δ_L in the mentioned equations. Each of the neighbour border buses connected through a border line belong to different areas. Therefore, the target is to find the neighbour non-generator buses which are negatively coherent in the inter-area oscillation frequencies and the border lines are obtained consequently.

In some cases same as the generators, it might be difficult to assign some of the non-generation buses to any area. These buses will usually swap between the areas depending on the load and generation changes in the system. Therefore, the border lines and buses may change due to the changes of the load and generation in the system.

3. Simulation on Test Systems

To verify the proposed method, it is evaluated on two test systems, a simple 4 machine system and modified 68 bus, 16 machine NPCC system [19].

3.1. Test Case 1

The first case is a simple 4 machine test system as illustrated in Fig. 1 with classical model of generators, and the transmission lines are modelled as constant impedances with zero resistance with the line reactance of 0.1 pu of all lines except for line connecting buses 6 and 7 which has the reactance of 0.5 pu.

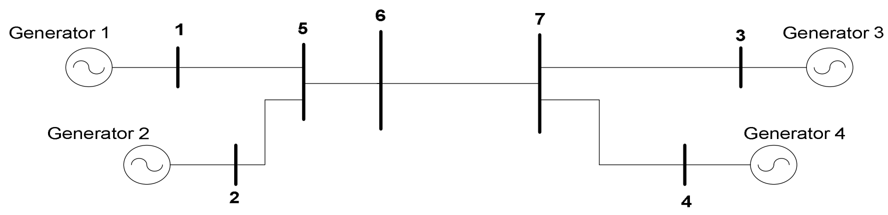

Fig. 1. Simple 4 machine test system.

The system is considered to be operating in its nominal operating point and the disturbance is applied on the system by randomly changing the loads in load buses. In this case the load change is considered to be a random change with 1% variance at each bus and applied at each time step which is 0.01 sec. As mentioned in previous section, the load change has the effect of continuous distributed disturbance on the system and causes the generators to swing as illustrated in Fig. 2 by velocity swings of the generators over a 10 sec period.

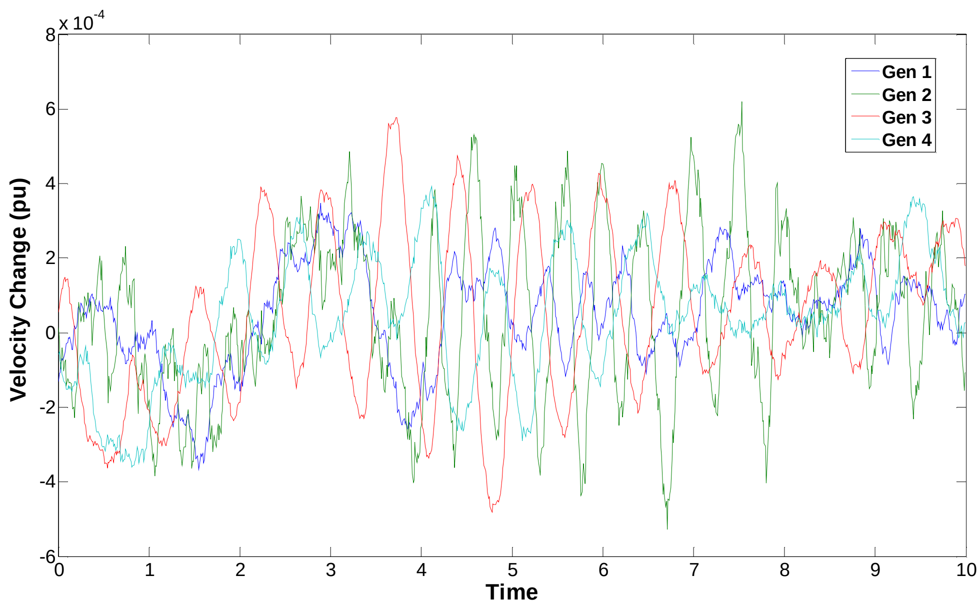

Fig. 2. Velocity changes in generators due to the disturbance.

To obtain the oscillation frequencies of the generators, spectrum analysis is applied on the velocity output of the generators. The simulation is performed on the system with a long simulation time and repeated to increase the accuracy of the obtained spectrum. For a more accurate result, DFT is calculated in several time frames and the average results are obtained as the spectrum output of the velocity swings shown in Fig. 3 along with the spectrum distribution of kinetic energy of whole system.

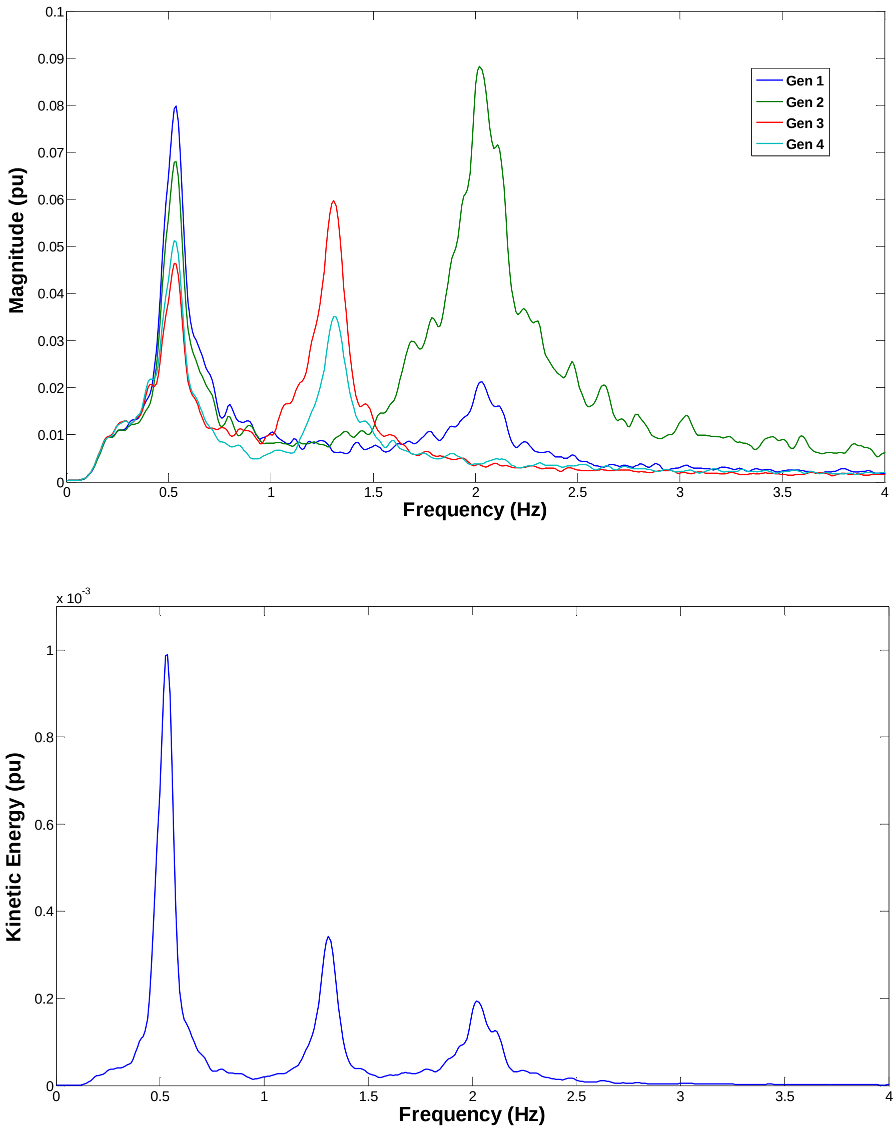

Fig. 3. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum.

The kinetic energy spectrum can define the important system oscillation frequencies and for this system three major oscillations can be observed. Inter-area modes usually have the frequency below 1 Hz and this example system has only 1 inter-area mode with the frequency of around 0.53 Hz. By checking the spectrum results of the generators velocity it can be observed that only in the inter-area oscillation frequency all the machines are oscillating while in all other major oscillation frequencies not all of the machines are participating in the oscillations which shows that the mentioned inter-area oscillation frequency is the sole inter-area mode of the system.

The system has only one inter-area mode which means it can be considered as two areas so the next step is to find the generators in each of the areas. Referring to the spectrum analysis, higher frequencies can be filtered from the velocity signals to preserve only the inter-area mode and correlation coefficient r_{ij} for the low pass filtered signals will define the generator grouping in the system which is shown in Table I.

TABLE I
Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals

$\boldsymbol{i,j}$	$\boldsymbol{r_{ij}}$	$\boldsymbol{i,j}$	$\boldsymbol{r_{ij}}$
1,2	0.987	2,3	-0.769
1,3	-0.788	2,4	-0.705
1,4	-0.725	3,4	0.959

It can be inferred from Table I that generators 1 and 2 are highly and positively correlated while being negatively correlated to generators 3 and 4 which means they belong to a same group. Similar result is observable for generators 3 and 4 which means these two generators are also forming a group. To clarify the grouping as mentioned in section 2, the coherence function and the angle of cross spectral density between pairs of generators are calculated as the generator in same groups are highly and positively coherent in the inter-area frequency band. The results are illustrated in Fig.4.

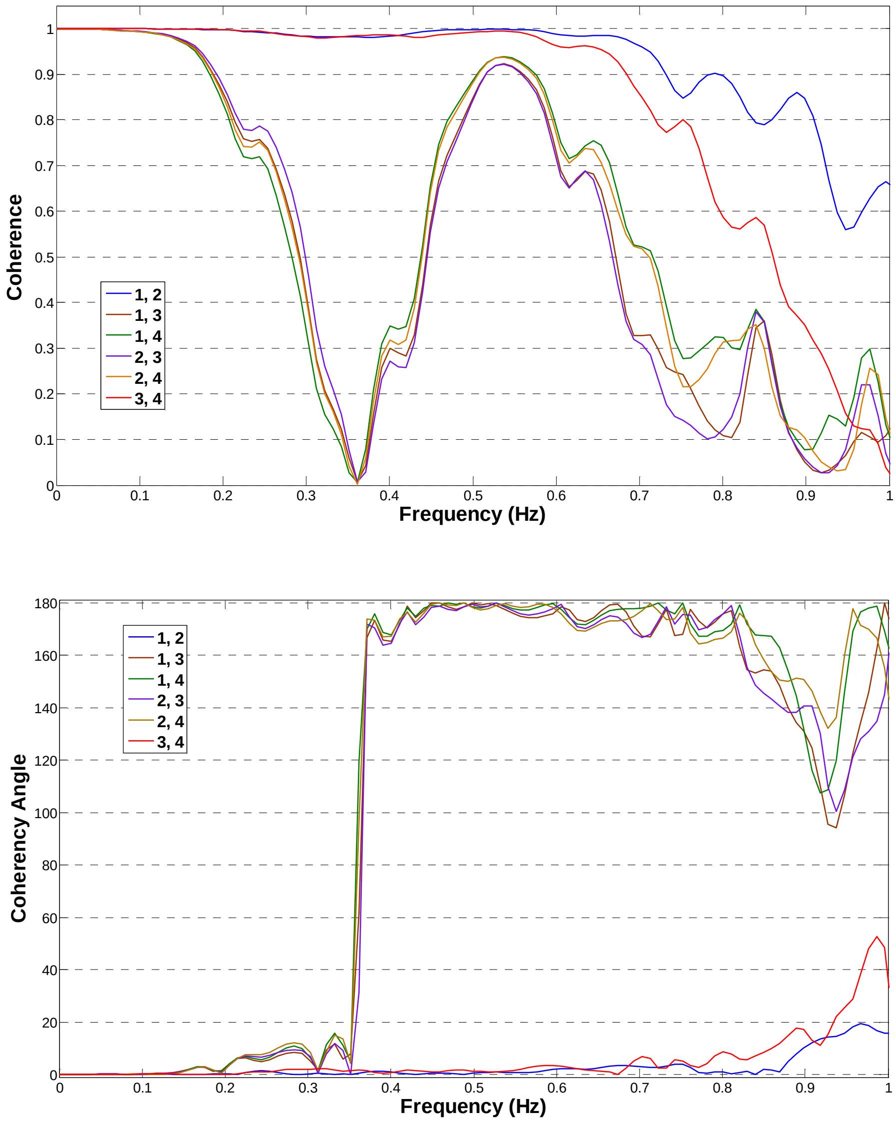

Fig. 4. Magnitude-squared coherence and angle of coherency between pairs of generators in test system 1.

The coherency results also validates the grouping obtained previously as it can be observed from Fig.4 only the generator groups 1, 2 and 3, 4 are highly and positively coherent in the inter-area frequency band which is around 0.53 Hz. These results also show that at the inter-area frequency, machines belong to other groups are highly but negatively coherent which validated the defined inter-area frequency to be the inter-area mode of system. Both of the proposed methods resulted in the same solution and defined the coherent group of generators. The next step is to define the load buses in each area and boundary buses between areas which will lead into finding the boundary lines connecting the areas.

This system consists of two neighbouring areas with one inter-area mode with the frequency of approximately 0.53 Hz. The angle swings in all of the non-generation buses are calculated using (12-15) and filtered to preserve only the inter-area frequency band. The correlation coefficient (16) is then calculated for these filtered signals and highly correlated non-generation buses are defined to be included in each area as shown in Table II.

TABLE II
Correlation Coefficient of Low-Pass Filtered Angle Swings of Load Buses

i, j	rl_{ij}
5,6	0.999
5,7	-0.969
6,7	-0.960

It can be inferred from the results in Table II that load buses no. 5 and 6 are highly and positively correlated in the inter-area frequency band which means they belong to the same group while they are highly and negatively correlated with bus no. 7. The buses 6 and 7 are neighbour buses and as they are negatively correlated they can be called border buses and the line connecting these two buses as border line. In this case calculating the coherency function for the angle swings might not be necessary as the correlation results defined the load bus grouping with a high accuracy.

3.2. Test Case 2

In the second case, the proposed method is simulated and tested on a more complex system containing 68 bus and 16 machines In order to apply this method and run the simulations, the system loads and line impedances are modified to accelerate the simulation process but general system properties remained unchanged.

The system is operating at a stable operating point and in this case the simulation is performed using random load deviation of 2% of the load amount at load buses at each time step which is considered to be the same as previous case. This random load change disturbs the system as the distributed disturbance and the generators will swing similar to the case 1 illustrated in Fig. 3. Running the simulation for a long simulation time, the oscillation frequencies of the generators can be obtained by applying the spectrum analysis on the obtained generator velocity changes. The average

DFT is calculated for several simulation time frames similar to the previous case to obtain the spectrum analysis of the generator velocities which is illustrated in Fig. 5 along with the distribution of total kinetic energy of system across the spectrum.

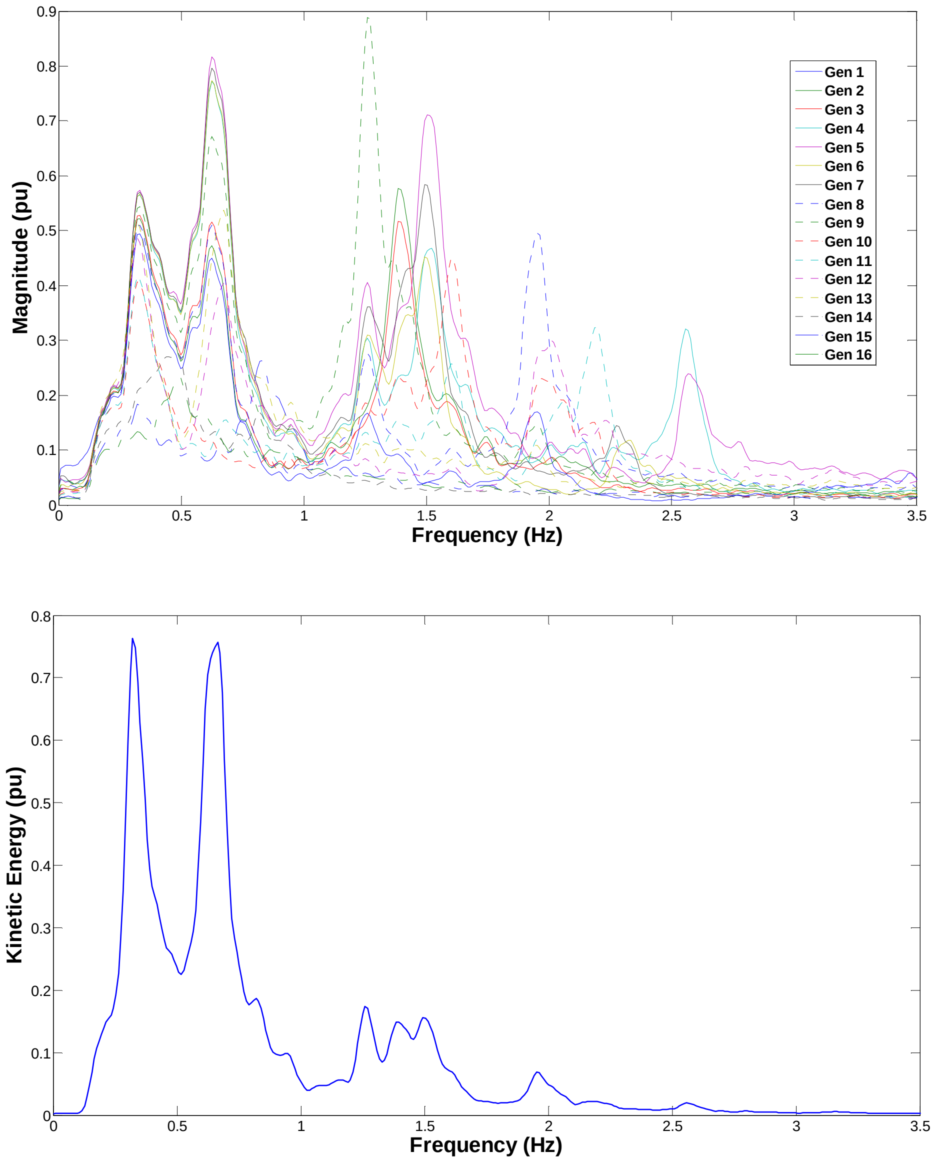

Fig. 5. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum in 16 machine system.

The kinetic Energy spectrum shows the important and high energy low frequency inter-area oscillations which are mostly below 1 Hz. Unlike the previous case, it is not easy to find the inter-area frequencies based on the kinetic energy spectrum. The velocity spectrums of most generators show higher frequency oscillations in the range of 1- 1.5 Hz and regardless of frequency and lower energy, these oscillations might be considered as inter-area modes. Therefore for more accurate assumption about the range of inter-area frequencies more analysis is required on the velocity signals.

Considering the inter-area modes to be in the range of below 1 Hz, the velocity signals are low pass filtered to exclude all the higher frequencies. The correlation coefficient is then calculated for every pair of these filtered signals to find the highly correlated signal which is given in Table III.

TABLE III

Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals for 16 Machine Test System

r_{ij}																
j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X	1.00	1.00	0.96	0.95	0.97	0.96	1.00	0.98	0.83	0.67	0.33	0.21	0.13	0.00	-0.06
2	1.00	X	1.00	0.96	0.95	0.96	0.96	0.99	0.97	0.84	0.68	0.34	0.22	0.11	-0.01	-0.07
3	1.00	1.00	X	0.97	0.96	0.98	0.97	1.00	0.98	0.81	0.64	0.30	0.17	0.11	-0.01	-0.07
4	0.96	0.96	0.97	X	1.00	1.00	1.00	0.97	0.98	0.67	0.47	0.10	-0.03	0.08	-0.02	-0.08
5	0.95	0.95	0.96	1.00	X	0.99	0.99	0.96	0.97	0.65	0.45	0.07	-0.05	0.08	-0.02	-0.08
6	0.97	0.96	0.98	1.00	0.99	X	1.00	0.98	0.98	0.67	0.48	0.10	-0.03	0.08	-0.02	-0.08
7	0.96	0.96	0.97	1.00	0.99	1.00	X	0.98	0.98	0.67	0.46	0.09	-0.04	0.08	-0.02	-0.08
8	1.00	0.99	1.00	0.97	0.96	0.98	0.98	X	0.99	0.80	0.63	0.28	0.16	0.12	-0.01	-0.06
9	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.99	X	0.71	0.53	0.16	0.03	0.09	-0.02	-0.07
10	0.83	0.84	0.81	0.67	0.65	0.67	0.67	0.80	0.71	X	0.97	0.79	0.70	0.19	0.04	0.04
11	0.67	0.68	0.64	0.47	0.45	0.48	0.46	0.63	0.53	0.97	X	0.91	0.86	0.16	0.04	0.05
12	0.33	0.34	0.30	0.10	0.07	0.10	0.09	0.28	0.16	0.79	0.91	X	0.99	0.09	0.03	0.00
13	0.21	0.22	0.17	-0.03	-0.05	-0.03	-0.04	0.16	0.03	0.70	0.86	0.99	X	0.07	0.02	-0.02
14	0.13	0.11	0.11	0.08	0.08	0.08	0.08	0.12	0.09	0.19	0.16	0.09	0.07	X	0.34	0.03
15	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	0.04	0.04	0.03	0.02	0.34	X	0.22
16	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.08	-0.06	-0.07	0.04	0.05	0.00	-0.02	0.03	0.22	X

Based on the calculated value of r_{ij} in the table above, it can be inferred that generators 1 to 9 are highly and positively correlated in the mentioned frequency range which means they can be considered as a group. Generators 11to13 also have a high correlation and can be considered as another group of generators. The correlation coefficients related to machines 14 to16 are not significantly high and these generators can not be grouped with any of other machines. The only remaining machine is generator 10 which has a high correlation with both of the defined generator groups but as it has a higher correlation with its neighbouring machine 11 we can consider it as a part of second group. This classification is based on the low pass filtered signals for the frequencies below

1 Hz while by changing the frequency cut off band for several cases from 1 to 1.5 Hz the general grouping did not change.

For a more accurate grouping especially for the generators that have high correlation with generators in two groups, the coherence function and the angle of cross spectral density between pairs of generators are calculated. The generators belong to the same area are highly and positively coherent in the range of inter-area frequency band. Therefore, the disputed generators can be checked for the inter-area oscillation frequency of the two groups so these generators will be assigned to the group of generators which are highly and positively coherent with them for that frequency. The results of coherence function and the angle of cross spectral density between selected pairs of generators are illustrated in Fig. 6.

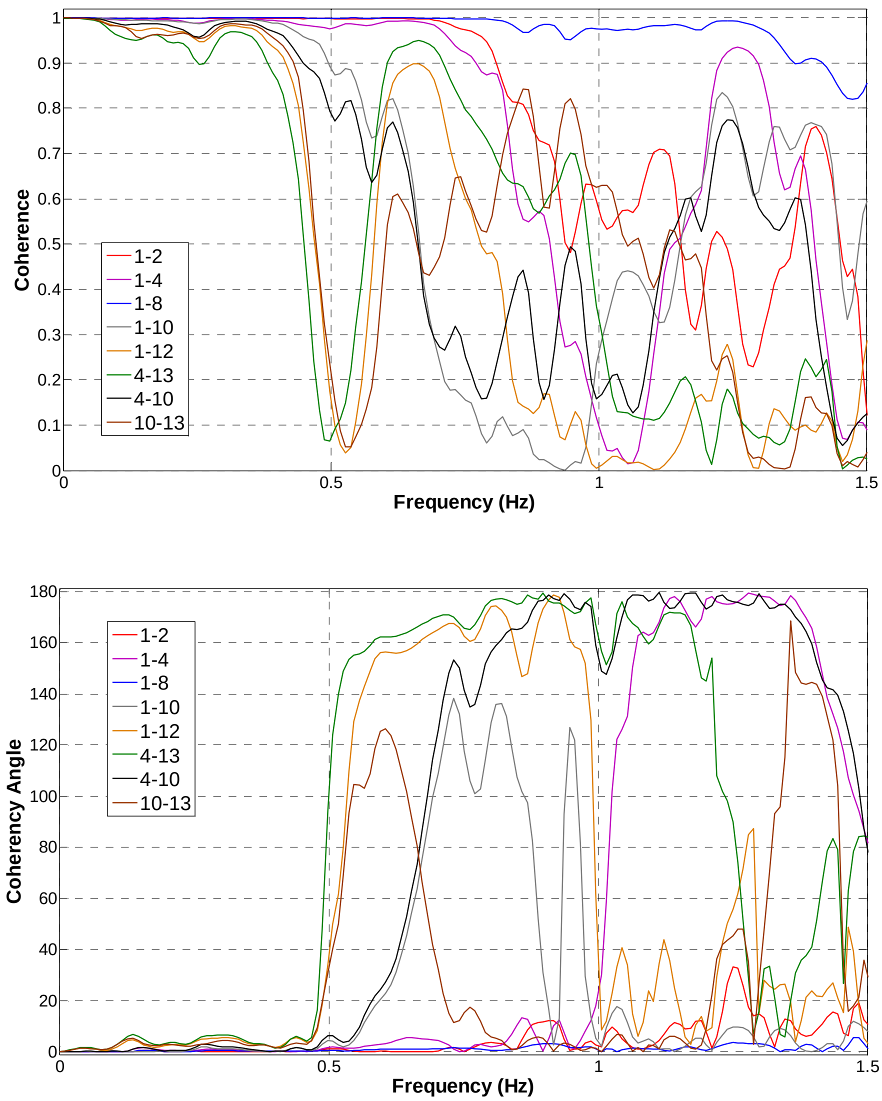

Fig. 6. Coherence and angle of coherency between selected pairs of generators in test system 2.

The result of the coherency analysis provides useful information about the system grouping and inter-area oscillation frequency range. It can be inferred that generators which are assumed to be in the same group based on the previous results, are not highly and positively coherent for the frequencies more than 1 Hz. Therefore, no big group of generators can be found to be coherent in the frequencies over 1 Hz which means those frequencies are not in the range of inter-area modes. Furthermore, the results provide more accurate results for the boundary generators which were difficult to be assigned to a group such as generator number 10 in this case. Based on the results shown in Fig. 6, machines 1 to 9 and 11 to 13 are oscillating against each other with the frequency around 0.62 Hz and in that frequency generator 10 has higher coherency with the first group while having higher coherency in other frequencies in the range of inter-area modes with the second group. Therefore, machine 10 is highly coherent with both of the groups and depending on the oscillation mode it can be assigned to one of the two groups.

By defining the coherent group of generators the next step is to find the load buses in each area and boundary buses and lines between the areas by analysis the angle swing of non-generator buses as described in previous section and case 1. Low pass filtering the angle swing signals for the inter-area frequency band, the correlation coefficient is calculated so highly and positively correlated buses can be assigned to the same group. The results provide a general grouping for load buses while for the buses located in the boundaries the coherency analysis should also be applied to provide the accurate grouping and defining boundary buses and lines.

Based on the machine grouping and the results of correlation between filtered angle swings of load buses, the buses with high and positive correlation coefficient are assigned to be in the same group. The coherency results help to find the boundary buses based on the inter-area oscillation frequency between neighbouring areas. In this case, the pair of neighbour non-generator buses with highly and negative coherence in the range of inter-area frequency of the two areas are considered as boundary buses and the line connecting them as the boundary line. Similar to defining the generators in each group, finding the neighbour load buses with negative coherency might not be easy and some buses might be disputed to be in either of the areas. In such cases instead of considering the neighbour buses the penetration is increased to search for the buses with one or two buses between them to find the boundary buses. Therefore by finding these kinds of boundary buses, the load buses between them are not assigned to any group where we call them mid-area buses. This usually happens for the load buses located next to or very close to the disputed machines such as machine 10 in this case. In Fig. 7 the result of system grouping for generators and load buses is illustrated.

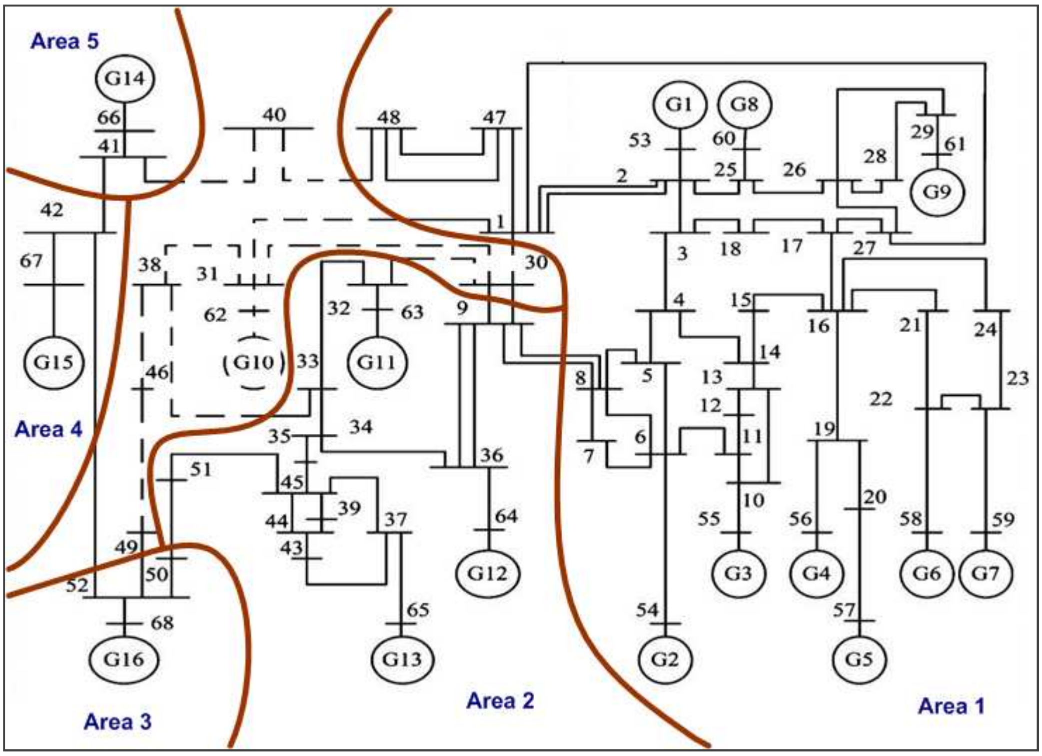

Fig. 7. Generator grouping and defined areas for 16 machine test system.

3.2.1. Operating Point Change

The proposed area detection process, similar to other methods, finds the generator grouping and area borders for a specified load and generation level. To provide a more general approach, the system steady state load and generation is examined for several cases with values selected over a range of up to 30% change to the original operating point and in each case the area definition process described above is followed. The results show that, generators and buses which had very high correlation still remain together regardless of which steady state load and generation case is selected, but the generators and buses which are not highly correlated to any area such as generator 10 may swap from one area to another area depending on the load change. The result of generator coherency and area

detection for a different operating point of test case 2 is illustrated in Fig. 8 showing few changes comparing to the previous results. For real systems, some sets of load and generation levels can be defined and the area definition process can be applied for each of these levels to have a clear and more accurate vision of system behaviour which is applicable in system reduction and online control schemes of inter-area modes.

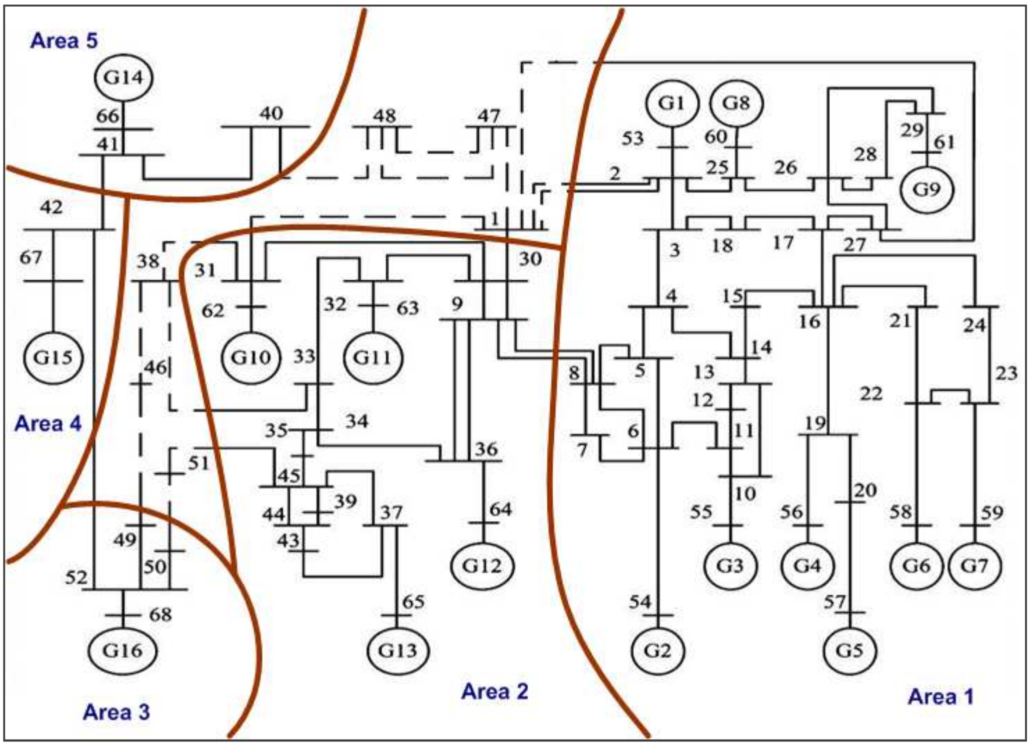

Fig. 8. Area detection for a different operating point in case 2

4. Conclusion

In this paper a new approach is proposed for detecting coherent generators and defining their related non-generator buses to form areas in inter-connected power systems. The method applies random load changes as a distributed disturbance on the system and spectrum analysis on velocity changes of generators is performed to obtain coherent generators in low frequency inter-area modes. Similar spectrum analysis is applied on the angle swing of load buses to obtain the related load buses to each group of generators and form the areas in the network. This method is applied on two test systems to prove the feasibility and applicability of the approach in various simple and complex networks. The results shows that in complex networks it might not be possible to fully divide the system into coherent group of areas and some generators and load buses may swap between neighbor areas by changing the operating point of the system. Applying the method on several realistic operating points of a system the results shows very similar grouping of generators. By changing the operating point the general grouping does not change but the boundary generators and buses (those not assigned to any area) may be grouped with the neighbour areas. The multiple operating point approach provides more accurate representation of generator grouping and area detection in large power systems. Therefore, as a general approach the generators and buses which do not stay coherent in most of the realistic loading conditions should be modelled separately or as separate areas which is an important issue in the aspect of control of inter-area modes.

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Generator Coherency and Area Detection in Large Power Systems

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Abstract— This paper provides a new general approach for defining coherent generators in power systems based on the coherency in low frequency inter-area modes. The disturbance is considered to be distributed in the network by applying random load changes which is the random walk representation of real loads instead of a single fault and coherent generators are obtained by spectrum analysis of the generators velocity variations. In order to find the coherent areas and their borders in the inter-connected networks, non-generating buses are assigned to each group of coherent generator using similar coherency detection techniques. The method is evaluated on two test systems and coherent generators and areas are obtained for different operating points to provide a more accurate grouping approach which is valid across a range of realistic operating points of the system.

1. Introduction

The energy demand is vastly growing and the network expansion is not following the pace of load growth in power systems. This has led the inter-connected power systems to operate very close to their operation limits, which makes them more vulnerable to any possible disturbance. Therefore, there is increasing value for enhancement methods to maintain the stability of power systems.

In the case of disturbance in multi-machine power systems, some of the machines exhibit similar responses to the disturbance which means the difference between their swing curves is so small that they can be considered to be oscillating together and coherent. In power system dynamic

performance, coherency between generators is an important factor which has several applications including dynamic reduction of power systems and emergency protection and control schemes.

As mentioned, generator coherency has a vast application in power system dynamic reduction by aggregating coherent generator units. Several methods have been introduced in literature for system reduction based on grouping similar generators. One of the most common methods in power system dynamic reduction is slow coherency based methods [1]. In these methods, if the system is subjected to a disturbance, the generators that are coherent in low frequency modes are called slow coherent generators and they are usually considered to be in one area and the multi-machine power system can be represented as a multi area system [2]. Beside slow coherency based methods for power system dynamic reduction, some other methods have also been introduced to aggregate the coherent group of generators such as relation factor [3] and Krylov subspace methods [4]. Synchrony based algorithms are also among widely used methods which define and aggregate the areas based on different methods of synchrony and can be applied on small and large systems [5], [6].

Defining coherent generators is an essential part in some emergency protection methods such as controlled islanding when the system is subjected to a severe disturbance and the conventional control systems are unable to keep the system stable [7]. The stability of islands created in the aftermath of the disturbance is dependent to the coherency of the generators inside the islands which shows the importance of correctly detecting coherent generators.

Due to the importance of coherency detection in transient stability and control studies, several methods have been introduced to define the coherent groups of generators and areas in inter-connected power systems. Some of these methods use time-domain analysis on the linear dynamic model of power systems [8] and also frequency response analysis have been implemented in some articles [9]. Direct stability analysis methods such as Unstable Equilibrium Point (UEP) have been also applied for solving the generator coherency detection problem [10]. In the methods using the linearized dynamic model such as slow coherency method, the coherency between generators is obtained for the specific operating point and the change in the operating conditions may change the

coherency indices between the generators which should be investigated. Therefore, methods such as continuation method [11] have been applied to trace the coherency characteristics in the network. In [12] a method is proposed to use the phase of the oscillations to determine coherency using Hilbert–Huang transform. Application of wide area angle and generator speed measurement is another helpful tool in tracking the generator coherency in inter-connected power systems [13].

In this paper, a new method is proposed to find a general grouping of generators based on coherency by providing a distributed disturbance on the network which is applied by low level randomly changing of the load in all of the load buses. In the frequency range of electromechanical oscillations the load changes can be considered as white noise. This process is called as random walk process and has been applied for estimation of modal parameters [14]. The spectrum analysis is then applied on the generator velocity swings to obtain the significant inter-area modes and generator coherency to form the areas in the network. There have been approaches which have used spectrum analysis in detecting coherent generators [15], [16] and in this paper, spectrum analysis along with other statistical signal processing tools are used to define the generators in each area. In many applications such as system dynamic reduction and islanding defining the non generator buses which belong to each area is important; this task is addressed in few research works [17]. Therefore in order to provide a general area detection scheme, load buses related to each area are defined, which leads to detection of boundary buses, lines and the whole system is thus divided into areas. Defining areas for multiple operating points as presented in this paper also provides more accurate schemes to facilitate online control of inter-area dynamics.

The paper is organized as follows. Section 2 describes the proposed method for identifying coherent generators and related buses; in Section 3 the approach is applied to two test systems and the results are discussed; and conclusion is provided in Section 4.

2. Generator Coherency and Area Detection

Defining the areas in large inter-connected power systems consists of two steps, including finding coherent generators which form a group and assigning the non-generation buses to these groups. The generators which have similar behaviour after the disturbances in the systems are called coherent generators and usually the term "coherency" refers to the coherency of generators in the slow inter-area modes. To study the generator coherency a classical machine model is usually considered to be sufficient [3], [9]:

$$J_i \frac{d^2\delta_i}{dt^2} + D_i\omega_i = P_{mi} - P_{ei} \quad (1)$$

$$\omega_i = \frac{d\delta_i}{dt} \quad , \quad i = 1, \ldots, n \quad (2)$$

In the equations above J_i is the inertia ratio, D_i is damping ratio, P_{mi} and P_{ei} are the mechanical power and electrical power of the i th machine, ω_i is the generator velocity, δ_i is the generator angle, and n is the number of generators. Electrical power P_{ei} depends on the load modeling in the system and by modeling them as constant impedances the differential algebraic equations (DAEs) will be simplified.

In most of the power system transient stability simulations, a disturbance is considered as a fault on a line or bus and the analysis is performed based on the single perturbation of the power system. In this approach instead of single disturbance in the system, the disturbance is distributed within the system to guarantee the excitation of all modes. This has been implemented by low level randomly changing of the load at all load buses which resembles the real load changes in power systems. This load change has the effect of a distributed disturbance in the power system, and will cause the generators to swing in a range of different frequencies related to different oscillation modes.

By applying the mentioned load disturbance, the velocity changes of all the machines in the system can be studied and spectrum analysis is applied to the output velocity of the generators. The

Discrete Fourier Transform (DFT) is a common method for spectrum analysis of discrete time signals and is seen in equation (3).

$$X_f = \sum_{n=0}^{N-1} x_n H e^{-\frac{i2\pi}{N} fn} \quad , \quad f = 0, \ldots, N-1 \qquad (3)$$

X_f is DFT, x_n is the sampled velocity of each generator, N is the number of samples, and H is the window function. The inter-area modes are usually between 0.1 and 1 Hz and depending on the sampling frequency the number of samples should be chosen big enough to ensure all low frequency modes are extracted.

The kinetic energy of machines plays a significant role in the importance of each mode in power systems. By having the kinetic energy of each machine and also the total kinetic energy of the system over the spectrum, the important modes with the higher kinetic energy and low frequency can be considered as the possible inter-area modes. The kinetic energy of machines and total kinetic energy of the system over the spectrum is calculated as (4-5), where $E_i(f)$ is the kinetic energy of each machine and $E_T(f)$ is the total kinetic energy of the system across the spectrum.

$$E_i(f) = \tfrac{1}{2} J_i \omega_i(f)^2 \qquad (4)$$

$$E_T(f) = \sum_{i=0}^{n} E_i(f) \qquad (5)$$

To obtain the kinetic energy of each machine and total kinetic energy of system respectively over the spectrum, the DFT of generator velocities ω_i is calculated by (3) and obtained $\omega_i(f)$ s are squared and multiplied by inertia ratio J_i according to (4) to define the spectral distribution of kinetic energy of each machine. Then referring to (5) the total kinetic energy across the spectrum can be easily calculated by adding the obtained kinetic energy of each generator. Then the obtained total kinetic energy is checked for low frequency to find the important inter-area modes.

As it is seen in the test results, the inter-area modes usually have the low oscillation frequency of 0.1 – 1 Hz while the kinetic energy analysis will also assist in defining inter-area oscillation frequencies. By studying the coherency of generators in the range of inter-area modes, the coherent generators are found and generator grouping is achieved. For the chosen disturbance, the velocity of generators can be considered as the random process and these signals are analysed in the inter-area frequency band. Therefore, the generators velocity signals are low pass filtered using a low pass digital signal filter such as Chebyshev filter to exclude the higher frequency oscillations. In this case for the filtered velocities, signal correlation coefficient is calculated as below:

$$r_{ij} = \frac{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})(f\omega_{jk} - \overline{f\omega_j})}{\sqrt{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})^2 \sum_{k=1}^{N}(f\omega_{jk} - \overline{f\omega_j})^2}} \qquad (6)$$

Where $f\omega_{ik}$ and $f\omega_{jk}$ are the k th element of filtered velocity signal of machine i and j, $\overline{f\omega_i}$ and $\overline{f\omega_j}$ are the sample means of these signals, and r_{ij} is the correlation coefficient between mentioned velocity signals. The resulting r_{ij} is a real number such that $-1 < r_{ij} < 1$ and its sign shows if the pairs are positively or negatively correlated.

Coherent groups of generators are identified by calculating the correlation coefficients for the low pass filtered velocities of generators as described above. Based on the results for each pair of generators, highly positive correlated generators will define the coherent groups of generators. This method is very efficient in large power systems as highly correlated generators in the inter-area frequencies are considered to form groups. In some cases, some generators may not only correlate with one group but also have higher correlations with other groups. In such cases and also for more accurate grouping and characterizing inter-area oscillations between areas, further analysis is performed on velocity of generators. To achieve this, the coherence and cross spectral density functions will be applied on the velocity changes of machines. The coherence (magnitude-squared coherence) [18] between two velocity signals related to machine i and j is calculated as:

$$C_{ij}(f) = \frac{\left|P_{ij}(f)\right|^2}{\left|P_{ii}(f)P_{jj}(f)\right|} \qquad (7)$$

Where $P_{ij}(f)$ is the cross spectral density of velocity of generators i and j, $P_{ii}(f)$ and $P_{jj}(f)$ are the power spectral density (PSD) of ω_i and ω_j calculated as (8-9). It can be inferred that cross spectral density and PSD functions are Discrete Fourier Transforms of cross-correlation $R_{ij}(n)$ and auto-correlation $R_{ii}(n)$ functions which can be obtained by (10-11) where $E\{\}$ is the expected value operator.

$$P_{ij}(f) = \sum_{n=0}^{N-1} R_{ij}(n) e^{-\frac{i2\pi}{N}fn} \quad , \quad f = 0,\ldots,N-1 \qquad (8)$$

$$P_{ii}(f) = \sum_{n=0}^{N-1} R_{ii}(n) e^{-\frac{i2\pi}{N}fn} \quad , \quad f = 0,\ldots,N-1 \qquad (9)$$

$$R_{ij}(n) = E\left\{\omega_i(m+n)\omega_j(m+n)^*\right\} \qquad (10)$$

$$R_{ii}(n) = E\left\{\omega_i(m+n)\omega_i(m+n)^*\right\} \qquad (11)$$

The coherence function (7) defines the coherency of the velocity output of machines across the frequency range and defines how the machines are correlated. This coherence function is not sufficient to define the coherent group of generators as it does not indicate if the generators are positively or negatively coherent in each frequency. To overcome this issue, the angle of cross spectral density function $P_{ij}(f)$ can show the angle that generators are correlated in each frequency at the range of inter-area modes. So if the angle is close to zero the machines are positively coherent and belong to a group and if it is close to 180 degrees, means the machines are negatively coherent for that frequency so they cannot be grouped and belong to different machine groups.

Comparing the coherence functions and cross spectral density angle between pairs of generators, the inter-area oscillation frequency band of every group of generators can be defined. In this approach, the generators in one group are highly and positively coherent with each other in that frequency band, while they are highly but negatively coherent to generators belonging to the other group. Therefore, generators in each area along with the inter-area oscillation frequency between different areas will be defined. This method is also applicable for the generators located in the area boundaries which can have high correlations with both of the neighbouring areas. These generators are checked for the specific inter-area frequency band of two areas to see their relation to each of the generator groups. In this case if the disputed generators are positively coherent at the inter-area oscillation frequency band with all of the generators in a group, these generators can be considered as a part of that group.

To define the concept of general coherency, the load and generation have to be randomly changed for several cases to check the coherency of generators over different loading scenarios. The purpose is to check if the grouping of generators is robust against the load changes in the system or grouping will change by changing the load in network. It is proven that load changes can affect the coherency characteristics of the power systems. In this case, some generators specially the generators in the boundaries may be swapped between the neighbouring areas.

Defining the coherent generator groups is the essential part of area detection in power systems. The second part will be to identify the non-generator buses located in each area. To determine which load and switching bus should be considered in an area, the angle swing of all load buses are obtained. For this reason, the loads can be considered as constant impedances and by having the generators angle swings the angle swings in load buses are obtained.

$$I = YV \tag{12}$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{13}$$

$$V_L = Y_{22}^{-1} Y_{21} V_G \tag{14}$$

$$\delta_L = angle(V_L) \tag{15}$$

V_G and I_G refer to the voltage and current injection at generators while V_L and I_L are the voltage and current at non-generation buses and Y is admittance matrix of the system.

As the inter-area oscillation frequency bands of neighbouring areas are known, the load buses located in each of the areas can be defined. Similar to the generators, the angle swing in non-generation buses are low pass filtered using a low pass digital signal filter to include only the low frequency inter-area modes and, signal correlation coefficient is calculated for the filtered angle swings.

$$rl_{ij} = \frac{\sum_{k=1}^{N_l}(f\delta_{ik} - \overline{f\delta_i})(f\delta_{jk} - \overline{f\delta_j})}{\sqrt{\sum_{k=1}^{N_l}(f\delta_{ik} - \overline{f\delta_i})^2 \sum_{k=1}^{N_l}(f\delta_{jk} - \overline{f\delta_j})^2}} \quad (16)$$

Similar to (6) $f\delta_{ik}$ and $f\delta_{jk}$ are the k th element of filtered angle swing signal of non-generation buses i and j, $\overline{f\delta_i}$ and $\overline{f\delta_j}$ are the sample means of these signals, N_l is the number of non-generation buses, and rl_{ij} is the correlation coefficient between these signals. Calculating the correlation coefficient for the filtered angle swing of non-generation buses, highly positive correlated buses are considered to be in the same area. This method is applicable to large systems to assign highly correlated buses to each area. To exactly define the border lines (lines connecting the areas) and border buses (buses at each end of border lines) coherence function is calculated for each pair of the non-generation buses using (8-11) and replacing the generator velocity ω by angle swing δ_L in the mentioned equations. Each of the neighbour border buses connected through a border line belong to different areas. Therefore, the target is to find the neighbour non-generator buses which are negatively coherent in the inter-area oscillation frequencies and the border lines are obtained consequently.

In some cases same as the generators, it might be difficult to assign some of the non-generation buses to any area. These buses will usually swap between the areas depending on the load and generation changes in the system. Therefore, the border lines and buses may change due to the changes of the load and generation in the system.

3. Simulation on Test Systems

To verify the proposed method, it is evaluated on two test systems, a simple 4 machine system and modified 68 bus, 16 machine NPCC system [19].

3.1. Test Case 1

The first case is a simple 4 machine test system as illustrated in Fig. 1 with classical model of generators, and the transmission lines are modelled as constant impedances with zero resistance with the line reactance of $0.1\ pu$ of all lines except for line connecting buses 6 and 7 which has the reactance of $0.5\ pu$.

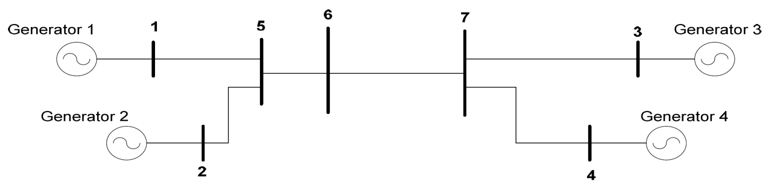

Fig. 1. Simple 4 machine test system.

The system is considered to be operating in its nominal operating point and the disturbance is applied on the system by randomly changing the loads in load buses. In this case the load change is considered to be a random change with 1% variance at each bus and applied at each time step which is 0.01 sec. As mentioned in previous section, the load change has the effect of continuous distributed disturbance on the system and causes the generators to swing as illustrated in Fig. 2 by velocity swings of the generators over a 10 sec period.

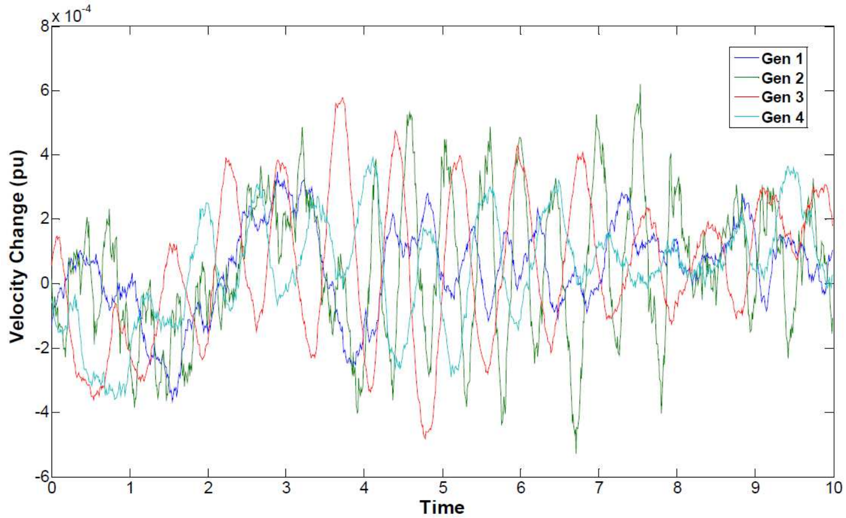

Fig. 2. Velocity changes in generators due to the disturbance.

To obtain the oscillation frequencies of the generators, spectrum analysis is applied on the velocity output of the generators. The simulation is performed on the system with a long simulation time and repeated to increase the accuracy of the obtained spectrum. For a more accurate result, DFT is calculated in several time frames and the average results are obtained as the spectrum output of the velocity swings shown in Fig. 3 along with the spectrum distribution of kinetic energy of whole system.

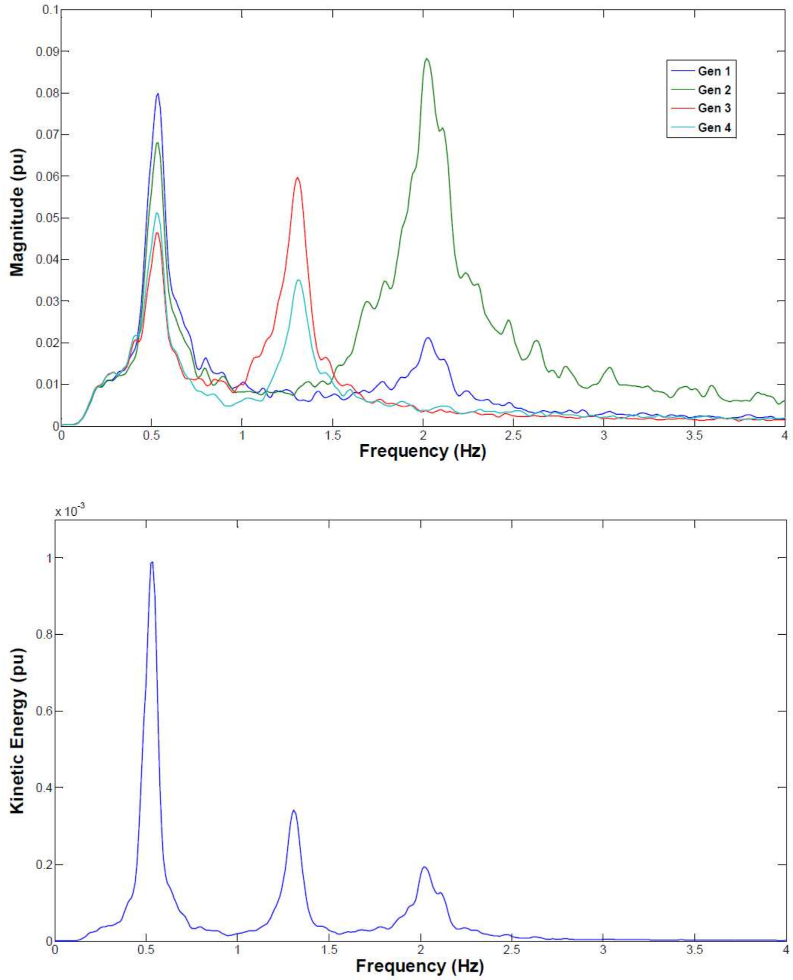

Fig. 3. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum.

The kinetic energy spectrum can define the important system oscillation frequencies and for this system three major oscillations can be observed. Inter-area modes usually have the frequency below 1 Hz and this example system has only 1 inter-area mode with the frequency of around 0.53 Hz. By checking the spectrum results of the generators velocity it can be observed that only in the inter-area oscillation frequency all the machines are oscillating while in all other major oscillation frequencies not all of the machines are participating in the oscillations which shows that the mentioned inter-area oscillation frequency is the sole inter-area mode of the system.

The system has only one inter-area mode which means it can be considered as two areas so the next step is to find the generators in each of the areas. Referring to the spectrum analysis, higher frequencies can be filtered from the velocity signals to preserve only the inter-area mode and correlation coefficient r_{ij} for the low pass filtered signals will define the generator grouping in the system which is shown in Table I.

TABLE I
Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals

i , j	r_{ij}	i , j	r_{ij}
1,2	0.987	2,3	-0.769
1,3	-0.788	2,4	-0.705
1,4	-0.725	3,4	0.959

It can be inferred from Table I that generators 1 and 2 are highly and positively correlated while being negatively correlated to generators 3 and 4 which means they belong to a same group. Similar result is observable for generators 3 and 4 which means these two generators are also forming a group. To clarify the grouping as mentioned in section 2, the coherence function and the angle of cross spectral density between pairs of generators are calculated as the generator in same groups are highly and positively coherent in the inter-area frequency band. The results are illustrated in Fig. 4.

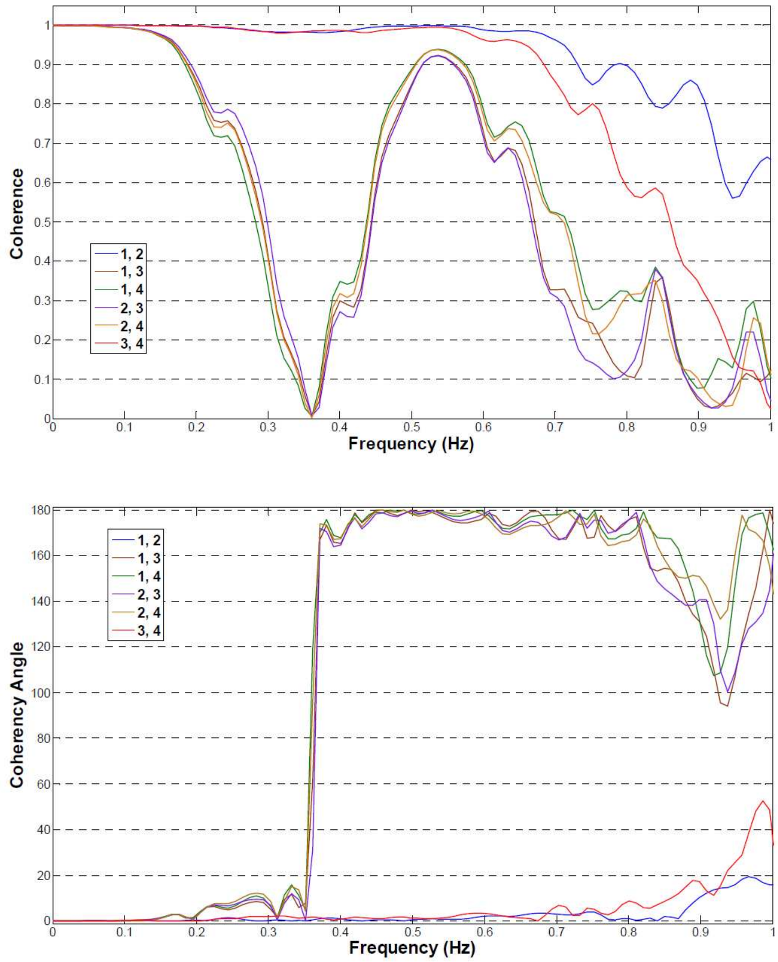

Fig. 4. Magnitude-squared coherence and angle of coherency between pairs of generators in test system 1.

The coherency results also validates the grouping obtained previously as it can be observed from Fig. 4 only the generator groups 1, 2 and 3, 4 are highly and positively coherent in the inter-area frequency band which is around 0.53 Hz. These results also show that at the inter-area frequency, machines belong to other groups are highly but negatively coherent which validated the defined inter-area frequency to be the inter-area mode of system. Both of the proposed methods resulted in the same solution and defined the coherent group of generators. The next step is to define the load buses in each area and boundary buses between areas which will lead into finding the boundary lines connecting the areas.

This system consists of two neighbouring areas with one inter-area mode with the frequency of approximately 0.53 Hz. The angle swings in all of the non-generation buses are calculated using (12-

15) and filtered to preserve only the inter-area frequency band. The correlation coefficient (16) is then calculated for these filtered signals and highly correlated non-generation buses are defined to be included in each area as shown in Table II.

TABLE II

Correlation Coefficient of Low-Pass Filtered Angle Swings of Load Buses

i , j	rl_{ij}
5,6	0.999
5,7	-0.969
6,7	-0.960

It can be inferred from the results in Table II that load buses no. 5 and 6 are highly and positively correlated in the inter-area frequency band which means they belong to the same group while they are highly and negatively correlated with bus no. 7. The buses 6 and 7 are neighbour buses and as they are negatively correlated they can be called border buses and the line connecting these two buses as border line. In this case calculating the coherency function for the angle swings might not be necessary as the correlation results defined the load bus grouping with a high accuracy.

3.2. Test Case 2

In the second case, the proposed method is simulated and tested on a more complex system containing 68 bus and 16 machines In order to apply this method and run the simulations, the system loads and line impedances are modified to accelerate the simulation process but general system properties remained unchanged.

The system is operating at a stable operating point and in this case the simulation is performed using random load deviation of 2% of the load amount at load buses at each time step which is considered to be the same as previous case. This random load change disturbs the system as the distributed disturbance and the generators will swing similar to the case 1 illustrated in Fig. 3. Running the simulation for a long simulation time, the oscillation frequencies of the generators can be obtained by applying the spectrum analysis on the obtained generator velocity changes. The average DFT is calculated for several simulation time frames similar to the previous case to obtain the spectrum analysis of the generator velocities which is illustrated in Fig. 5 along with the distribution of total kinetic energy of system across the spectrum.

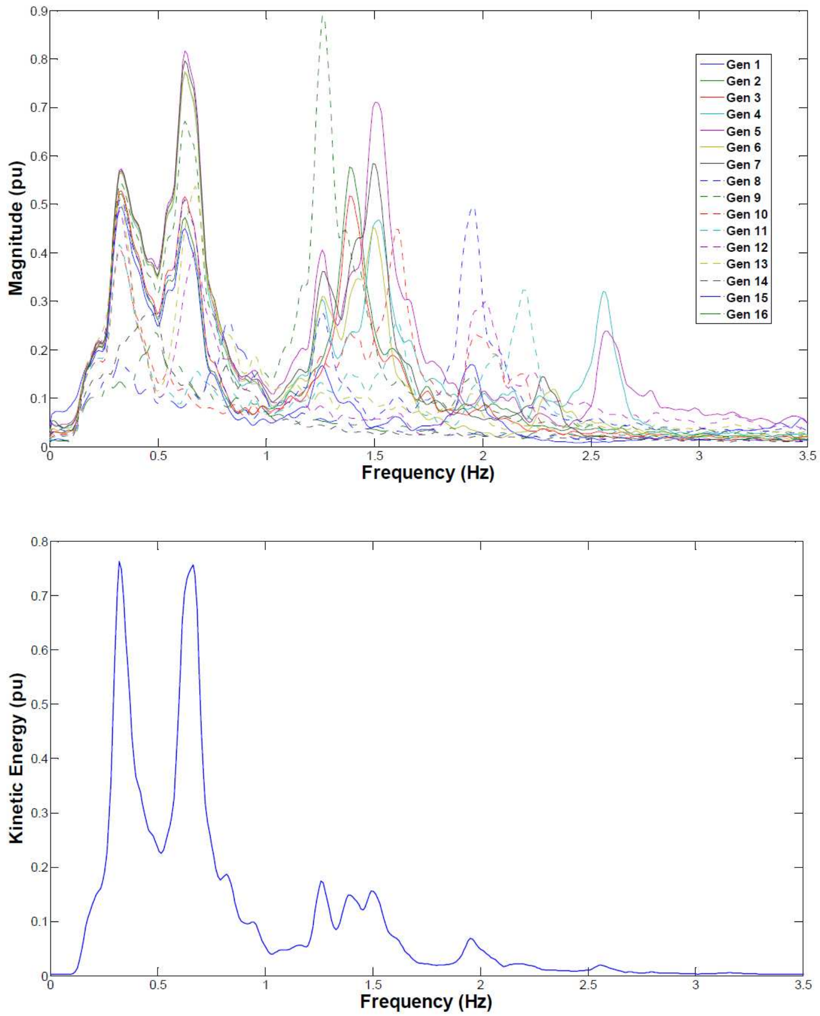

Fig. 5. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum in 16 machine system.

The kinetic Energy spectrum shows the important and high energy low frequency inter-area oscillations which are mostly below 1 Hz. Unlike the previous case, it is not easy to find the inter-area frequencies based on the kinetic energy spectrum. The velocity spectrums of most generators show higher frequency oscillations in the range of 1- 1.5 Hz and regardless of frequency and lower energy, these oscillations might be considered as inter-area modes. Therefore for more accurate assumption about the range of inter-area frequencies more analysis is required on the velocity signals.

Considering the inter-area modes to be in the range of below 1 Hz, the velocity signals are low pass filtered to exclude all the higher frequencies. The correlation coefficient is then calculated for every pair of these filtered signals to find the highly correlated signal which is given in Table III.

TABLE III

Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals for 16 Machine Test System

r_{ij}																
j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X	1.00	1.00	0.96	0.95	0.97	0.96	1.00	0.98	0.83	0.67	0.33	0.21	0.13	0.00	-0.06
2	1.00	X	1.00	0.96	0.95	0.96	0.96	0.99	0.97	0.84	0.68	0.34	0.22	0.11	-0.01	-0.07
3	1.00	1.00	X	0.97	0.96	0.98	0.97	1.00	0.98	0.81	0.64	0.30	0.17	0.11	-0.01	-0.07
4	0.96	0.96	0.97	X	1.00	1.00	1.00	0.97	0.98	0.67	0.47	0.10	-0.03	0.08	-0.02	-0.08
5	0.95	0.95	0.96	1.00	X	0.99	0.99	0.96	0.97	0.65	0.45	0.07	-0.05	0.08	-0.02	-0.08
6	0.97	0.96	0.98	1.00	0.99	X	1.00	0.98	0.98	0.67	0.48	0.10	-0.03	0.08	-0.02	-0.08
7	0.96	0.96	0.97	1.00	0.99	1.00	X	0.98	0.98	0.67	0.46	0.09	-0.04	0.08	-0.02	-0.08
8	1.00	0.99	1.00	0.97	0.96	0.98	0.98	X	0.99	0.80	0.63	0.28	0.16	0.12	-0.01	-0.06
9	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.99	X	0.71	0.53	0.16	0.03	0.09	-0.02	-0.07
10	0.83	0.84	0.81	0.67	0.65	0.67	0.67	0.80	0.71	X	0.97	0.79	0.70	0.19	0.04	0.04
11	0.67	0.68	0.64	0.47	0.45	0.48	0.46	0.63	0.53	0.97	X	0.91	0.86	0.16	0.04	0.05
12	0.33	0.34	0.30	0.10	0.07	0.10	0.09	0.28	0.16	0.79	0.91	X	0.99	0.09	0.03	0.00
13	0.21	0.22	0.17	-0.03	-0.05	-0.03	-0.04	0.16	0.03	0.70	0.86	0.99	X	0.07	0.02	-0.02
14	0.13	0.11	0.11	0.08	0.08	0.08	0.08	0.12	0.09	0.19	0.16	0.09	0.07	X	0.34	0.03
15	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	0.04	0.04	0.03	0.02	0.34	X	0.22
16	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.08	-0.06	-0.07	0.04	0.05	0.00	-0.02	0.03	0.22	X

Based on the calculated value of r_{ij} in the table above, it can be inferred that generators 1 to 9 are highly and positively correlated in the mentioned frequency range which means they can be considered as a group. Generators 11 to 13 also have a high correlation and can be considered as another group of generators. The correlation coefficients related to machines 14 to 16 are not significantly high and these generators can not be grouped with any of other machines. The only remaining machine is generator 10 which has a high correlation with both of the defined generator groups but as it has a higher correlation with its neighbouring machine 11 we can consider it as a part of second group. This classification is based on the low pass filtered signals for the frequencies below

1 Hz while by changing the frequency cut off band for several cases from 1 to 1.5 Hz the general grouping did not change.

For a more accurate grouping especially for the generators that have high correlation with generators in two groups, the coherence function and the angle of cross spectral density between pairs of generators are calculated. The generators belong to the same area are highly and positively coherent in the range of inter-area frequency band. Therefore, the disputed generators can be checked for the inter-area oscillation frequency of the two groups so these generators will be assigned to the group of generators which are highly and positively coherent with them for that frequency. The results of coherence function and the angle of cross spectral density between selected pairs of generators are illustrated in Fig. 6.

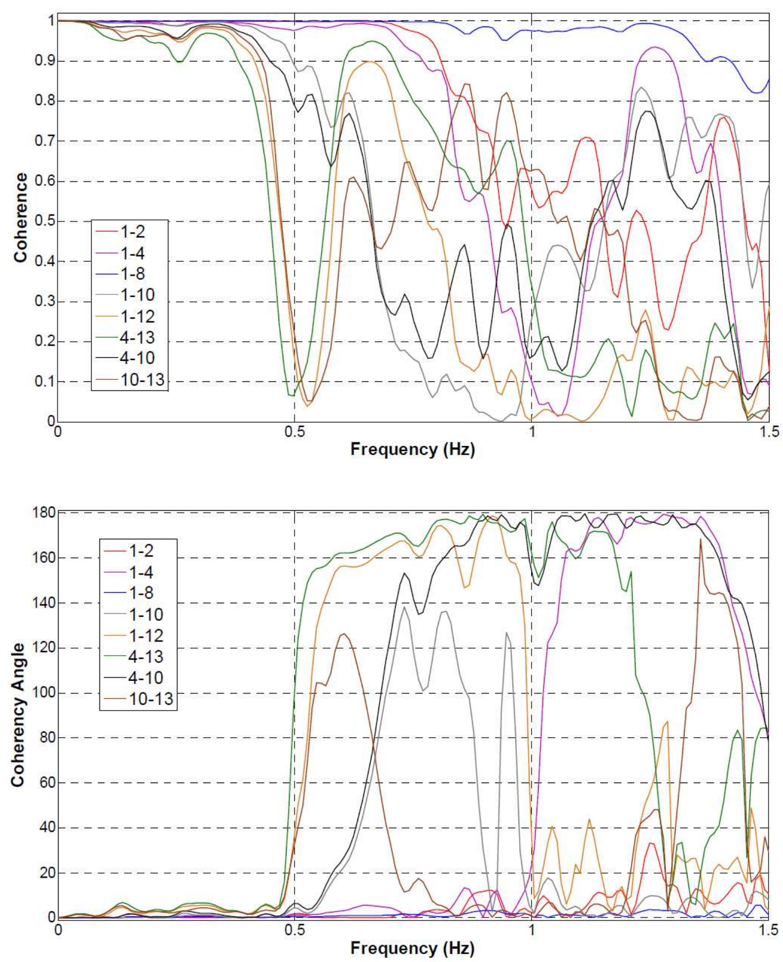

Fig. 6. Coherence and angle of coherency between selected pairs of generators in test system 2.

The result of the coherency analysis provides useful information about the system grouping and inter-area oscillation frequency range. It can be inferred that generators which are assumed to be in the same group based on the previous results, are not highly and positively coherent for the frequencies more than 1 Hz. Therefore, no big group of generators can be found to be coherent in the frequencies over 1 Hz which means those frequencies are not in the range of inter-area modes. Furthermore, the results provide more accurate results for the boundary generators which were difficult to be assigned to a group such as generator number 10 in this case. Based on the results shown in Fig. 6, machines 1 to 9 and 11 to 13 are oscillating against each other with the frequency around 0.62 Hz and in that frequency generator 10 has higher coherency with the first group while having higher coherency in other frequencies in the range of inter-area modes with the second group. Therefore, machine 10 is highly coherent with both of the groups and depending on the oscillation mode it can be assigned to one of the two groups.

By defining the coherent group of generators the next step is to find the load buses in each area and boundary buses and lines between the areas by analysis the angle swing of non-generator buses as described in previous section and case 1. Low pass filtering the angle swing signals for the inter-area frequency band, the correlation coefficient is calculated so highly and positively correlated buses can be assigned to the same group. The results provide a general grouping for load buses while for the buses located in the boundaries the coherency analysis should also be applied to provide the accurate grouping and defining boundary buses and lines.

Based on the machine grouping and the results of correlation between filtered angle swings of load buses, the buses with high and positive correlation coefficient are assigned to be in the same group. The coherency results help to find the boundary buses based on the inter-area oscillation frequency between neighbouring areas. In this case, the pair of neighbour non-generator buses with highly and negative coherence in the range of inter-area frequency of the two areas are considered as boundary buses and the line connecting them as the boundary line. Similar to defining the generators in each group, finding the neighbour load buses with negative coherency might not be easy and some buses might be disputed to be in either of the areas. In such cases instead of considering the neighbour buses the penetration is increased to search for the buses with one or two buses between them to find the boundary buses. Therefore by finding these kinds of boundary buses, the load buses between them are not assigned to any group where we call them mid-area buses. This usually happens for the load buses located next to or very close to the disputed machines such as machine 10 in this case. In Fig. 7 the result of system grouping for generators and load buses is illustrated.

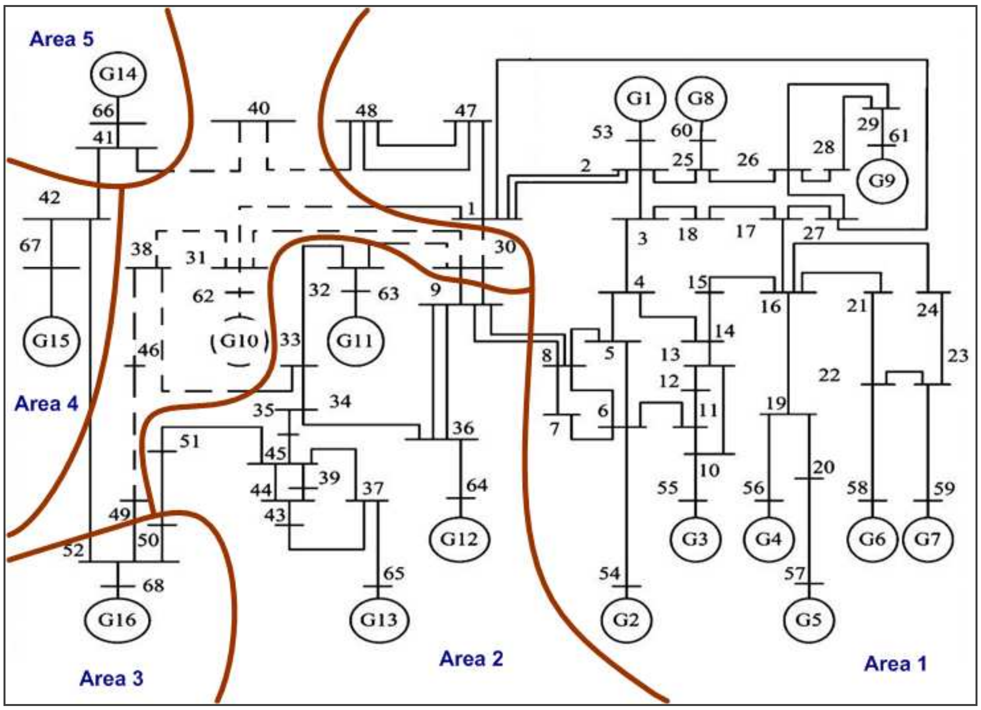

Fig. 7. Generator grouping and defined areas for 16 machine test system.

3.2.1. Operating Point Change

The proposed area detection process, similar to other methods, finds the generator grouping and area borders for a specified load and generation level. To provide a more general approach, the system steady state load and generation is examined for several cases with values selected over a range of up to 30% change to the original operating point and in each case the area definition process described above is followed. The results show that, generators and buses which had very high correlation still remain together regardless of which steady state load and generation case is selected, but the generators and buses which are not highly correlated to any area such as generator 10 may swap from one area to another area depending on the load change. The result of generator coherency and area

detection for a different operating point of test case 2 is illustrated in Fig. 8 showing few changes comparing to the previous results. For real systems, some sets of load and generation levels can be defined and the area definition process can be applied for each of these levels to have a clear and more accurate vision of system behaviour which is applicable in system reduction and online control schemes of inter-area modes.

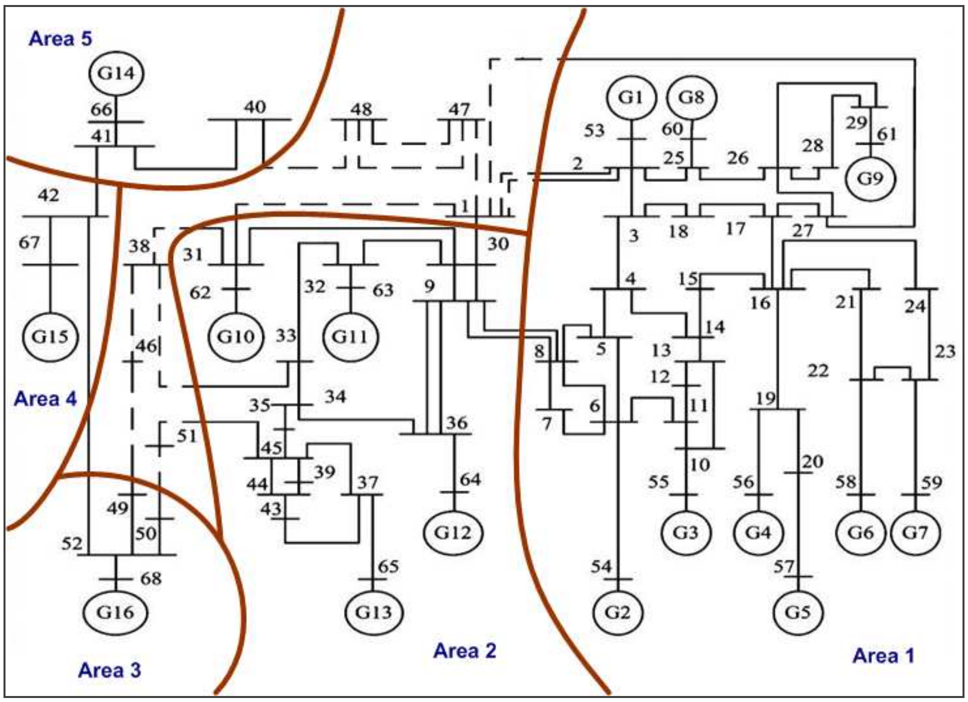

Fig. 8. Area detection for a different operating point in case 2

4. Conclusion

In this paper a new approach is proposed for detecting coherent generators and defining their related non-generator buses to form areas in inter-connected power systems. The method applies random load changes as a distributed disturbance on the system and spectrum analysis on velocity changes of generators is performed to obtain coherent generators in low frequency inter-area modes. Similar spectrum analysis is applied on the angle swing of load buses to obtain the related load buses to each group of generators and form the areas in the network. This method is applied on two test systems to prove the feasibility and applicability of the approach in various simple and complex networks. The results shows that in complex networks it might not be possible to fully divide the system into coherent group of areas and some generators and load buses may swap between neighbor areas by changing the operating point of the system. Applying the method on several realistic operating points of a system the results shows very similar grouping of generators. By changing the operating point the general grouping does not change but the boundary generators and buses (those not assigned to any area) may be grouped with the neighbour areas. The multiple operating point approach provides more accurate representation of generator grouping and area detection in large power systems. Therefore, as a general approach the generators and buses which do not stay coherent in most of the realistic loading conditions should be modelled separately or as separate areas which is an important issue in the aspect of control of inter-area modes.

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Generator Coherency and Area Detection in Large Power Systems

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Abstract**—** This paper provides a new general approach for defining coherent generators in power systems based on the coherency in low frequency inter-area modes. The disturbance is considered to be distributed in the network by applying random load changes which is the random walk representation of real loads instead of a single fault and coherent generators are obtained by spectrum analysis of the generators velocity variations. In order to find the coherent areas and their borders in the inter-connected networks, non-generating buses are assigned to each group of coherent generator using similar coherency detection techniques. The method is evaluated on two test systems and coherent generators and areas are obtained for different operating points to provide a more accurate grouping approach which is valid across a range of realistic operating points of the system.

1. Introduction

The energy demand is vastly growing and the network expansion is not following the pace of load growth in power systems. This has led the inter-connected power systems to operate very close to their operation limits, which makes them more vulnerable to any possible disturbance. Therefore, there is increasing value for enhancement methods to maintain the stability of power systems.

In the case of disturbance in multi-machine power systems, some of the machines exhibit similar responses to the disturbance which means the difference between their swing curves is so small that they can be considered to be oscillating together and coherent. In power system dynamic

performance, coherency between generators is an important factor which has several applications including dynamic reduction of power systems and emergency protection and control schemes.

As mentioned, generator coherency has a vast application in power system dynamic reduction by aggregating coherent generator units. Several methods have been introduced in literature for system reduction based on grouping similar generators. One of the most common methods in power system dynamic reduction is slow coherency based methods [1]. In these methods, if the system is subjected to a disturbance, the generators that are coherent in low frequency modes are called slow coherent generators and they are usually considered to be in one area and the multi-machine power system can be represented as a multi area system [2]. Beside slow coherency based methods for power system dynamic reduction, some other methods have also been introduced to aggregate the coherent group of generators such as relation factor [3] and Krylov subspace methods [4]. Synchrony based algorithms are also among widely used methods which define and aggregate the areas based on different methods of synchrony and can be applied on small and large systems [5], [6].

Defining coherent generators is an essential part in some emergency protection methods such as controlled islanding when the system is subjected to a severe disturbance and the conventional control systems are unable to keep the system stable [7]. The stability of islands created in the aftermath of the disturbance is dependent to the coherency of the generators inside the islands which shows the importance of correctly detecting coherent generators.

Due to the importance of coherency detection in transient stability and control studies, several methods have been introduced to define the coherent groups of generators and areas in inter-connected power systems. Some of these methods use time-domain analysis on the linear dynamic model of power systems [8] and also frequency response analysis have been implemented in some articles [9]. Direct stability analysis methods such as Unstable Equilibrium Point (UEP) have been also applied for solving the generator coherency detection problem [10]. In the methods using the linearized dynamic model such as slow coherency method, the coherency between generators is obtained for the specific operating point and the change in the operating conditions may change the

coherency indices between the generators which should be investigated. Therefore, methods such as continuation method [11] have been applied to trace the coherency characteristics in the network. In [12] a method is proposed to use the phase of the oscillations to determine coherency using Hilbert–Huang transform. Application of wide area angle and generator speed measurement is another helpful tool in tracking the generator coherency in inter-connected power systems [13].

In this paper, a new method is proposed to find a general grouping of generators based on coherency by providing a distributed disturbance on the network which is applied by low level randomly changing of the load in all of the load buses. In the frequency range of electromechanical oscillations the load changes can be considered as white noise. This process is called as random walk process and has been applied for estimation of modal parameters [14]. The spectrum analysis is then applied on the generator velocity swings to obtain the significant inter-area modes and generator coherency to form the areas in the network. There have been approaches which have used spectrum analysis in detecting coherent generators [15], [16] and in this paper, spectrum analysis along with other statistical signal processing tools are used to define the generators in each area. In many applications such as system dynamic reduction and islanding defining the non generator buses which belong to each area is important; this task is addressed in few research works [17]. Therefore in order to provide a general area detection scheme, load buses related to each area are defined, which leads to detection of boundary buses, lines and the whole system is thus divided into areas. Defining areas for multiple operating points as presented in this paper also provides more accurate schemes to facilitate online control of inter-area dynamics.

The paper is organized as follows. Section 2 describes the proposed method for identifying coherent generators and related buses; in Section 3 the approach is applied to two test systems and the results are discussed; and conclusion is provided in Section 4.

2. Generator Coherency and Area Detection

Defining the areas in large inter-connected power systems consists of two steps, including finding coherent generators which form a group and assigning the non-generation buses to these groups. The generators which have similar behaviour after the disturbances in the systems are called coherent generators and usually the term "coherency" refers to the coherency of generators in the slow inter-area modes. To study the generator coherency a classical machine model is usually considered to be sufficient [3], [9]:

$$J_i \frac{d^2\delta_i}{dt^2} + D_i\omega_i = P_{mi} - P_{ei} \quad (1)$$

$$\omega_i = \frac{d\delta_i}{dt} \quad , \quad i = 1,\ldots,n \quad (2)$$

In the equations above J_i is the inertia ratio, D_i is damping ratio, P_{mi} and P_{ei} are the mechanical power and electrical power of the i th machine, ω_i is the generator velocity, δ_i is the generator angle, and n is the number of generators. Electrical power P_{ei} depends on the load modeling in the system and by modeling them as constant impedances the differential algebraic equations (DAEs) will be simplified.

In most of the power system transient stability simulations, a disturbance is considered as a fault on a line or bus and the analysis is performed based on the single perturbation of the power system. In this approach instead of single disturbance in the system, the disturbance is distributed within the system to guarantee the excitation of all modes. This has been implemented by low level randomly changing of the load at all load buses which resembles the real load changes in power systems. This load change has the effect of a distributed disturbance in the power system, and will cause the generators to swing in a range of different frequencies related to different oscillation modes.

By applying the mentioned load disturbance, the velocity changes of all the machines in the system can be studied and spectrum analysis is applied to the output velocity of the generators. The

Discrete Fourier Transform (DFT) is a common method for spectrum analysis of discrete time signals and is seen in equation (3).

$$X_f = \sum_{n=0}^{N-1} x_n H e^{-\frac{i2\pi}{N} fn} \quad , \quad f = 0,\ldots,N-1 \qquad (3)$$

X_f is DFT, x_n is the sampled velocity of each generator, N is the number of samples, and H is the window function. The inter-area modes are usually between 0.1 and 1 Hz and depending on the sampling frequency the number of samples should be chosen big enough to ensure all low frequency modes are extracted.

The kinetic energy of machines plays a significant role in the importance of each mode in power systems. By having the kinetic energy of each machine and also the total kinetic energy of the system over the spectrum, the important modes with the higher kinetic energy and low frequency can be considered as the possible inter-area modes. The kinetic energy of machines and total kinetic energy of the system over the spectrum is calculated as (4-5), where $E_i(f)$ is the kinetic energy of each machine and $E_T(f)$ is the total kinetic energy of the system across the spectrum.

$$E_i(f) = \frac{1}{2} J_i \omega_i(f)^2 \qquad (4)$$

$$E_T(f) = \sum_{i=0}^{n} E_i(f) \qquad (5)$$

To obtain the kinetic energy of each machine and total kinetic energy of system respectively over the spectrum, the DFT of generator velocities ω_i is calculated by (3) and obtained $\omega_i(f)$s are squared and multiplied by inertia ratio J_i according to (4) to define the spectral distribution of kinetic energy of each machine. Then referring to (5) the total kinetic energy across the spectrum can be easily calculated by adding the obtained kinetic energy of each generator. Then the obtained total kinetic energy is checked for low frequency to find the important inter-area modes.

As it is seen in the test results, the inter-area modes usually have the low oscillation frequency of 0.1 – 1 Hz while the kinetic energy analysis will also assist in defining inter-area oscillation frequencies. By studying the coherency of generators in the range of inter-area modes, the coherent generators are found and generator grouping is achieved. For the chosen disturbance, the velocity of generators can be considered as the random process and these signals are analysed in the inter-area frequency band. Therefore, the generators velocity signals are low pass filtered using a low pass digital signal filter such as Chebyshev filter to exclude the higher frequency oscillations. In this case for the filtered velocities, signal correlation coefficient is calculated as below:

$$r_{ij} = \frac{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})(f\omega_{jk} - \overline{f\omega_j})}{\sqrt{\sum_{k=1}^{N}(f\omega_{ik} - \overline{f\omega_i})^2 \sum_{k=1}^{N}(f\omega_{jk} - \overline{f\omega_j})^2}} \qquad (6)$$

Where $f\omega_{ik}$ and $f\omega_{jk}$ are the k th element of filtered velocity signal of machine i and j, $\overline{f\omega_i}$ and $\overline{f\omega_j}$ are the sample means of these signals, and r_{ij} is the correlation coefficient between mentioned velocity signals. The resulting r_{ij} is a real number such that $-1 < r_{ij} < 1$ and its sign shows if the pairs are positively or negatively correlated.

Coherent groups of generators are identified by calculating the correlation coefficients for the low pass filtered velocities of generators as described above. Based on the results for each pair of generators, highly positive correlated generators will define the coherent groups of generators. This method is very efficient in large power systems as highly correlated generators in the inter-area frequencies are considered to form groups. In some cases, some generators may not only correlate with one group but also have higher correlations with other groups. In such cases and also for more accurate grouping and characterizing inter-area oscillations between areas, further analysis is performed on velocity of generators. To achieve this, the coherence and cross spectral density functions will be applied on the velocity changes of machines. The coherence (magnitude-squared coherence) [18] between two velocity signals related to machine i and j is calculated as:

$$C_{ij}(f) = \frac{\left|P_{ij}(f)\right|^2}{\left|P_{ii}(f)P_{jj}(f)\right|} \qquad (7)$$

Where $P_{ij}(f)$ is the cross spectral density of velocity of generators i and j, $P_{ii}(f)$ and $P_{jj}(f)$ are the power spectral density (PSD) of ω_i and ω_j calculated as (8-9). It can be inferred that cross spectral density and PSD functions are Discrete Fourier Transforms of cross-correlation $R_{ij}(n)$ and auto-correlation $R_{ii}(n)$ functions which can be obtained by (10-11) where $E\{\}$ is the expected value operator.

$$P_{ij}(f) = \sum_{n=0}^{N-1} R_{ij}(n) e^{-\frac{i2\pi}{N}fn} \quad , \quad f = 0,\dots,N-1 \qquad (8)$$

$$P_{ii}(f) = \sum_{n=0}^{N-1} R_{ii}(n) e^{-\frac{i2\pi}{N}fn} \quad , \quad f = 0,\dots,N-1 \qquad (9)$$

$$R_{ij}(n) = E\left\{\omega_i(m+n)\omega_j(m+n)^*\right\} \qquad (10)$$

$$R_{ii}(n) = E\left\{\omega_i(m+n)\omega_i(m+n)^*\right\} \qquad (11)$$

The coherence function (7) defines the coherency of the velocity output of machines across the frequency range and defines how the machines are correlated. This coherence function is not sufficient to define the coherent group of generators as it does not indicate if the generators are positively or negatively coherent in each frequency. To overcome this issue, the angle of cross spectral density function $P_{ij}(f)$ can show the angle that generators are correlated in each frequency at the range of inter-area modes. So if the angle is close to zero the machines are positively coherent and belong to a group and if it is close to 180 degrees, means the machines are negatively coherent for that frequency so they cannot be grouped and belong to different machine groups.

Comparing the coherence functions and cross spectral density angle between pairs of generators, the inter-area oscillation frequency band of every group of generators can be defined. In this approach, the generators in one group are highly and positively coherent with each other in that frequency band, while they are highly but negatively coherent to generators belonging to the other group. Therefore, generators in each area along with the inter-area oscillation frequency between different areas will be defined. This method is also applicable for the generators located in the area boundaries which can have high correlations with both of the neighbouring areas. These generators are checked for the specific inter-area frequency band of two areas to see their relation to each of the generator groups. In this case if the disputed generators are positively coherent at the inter-area oscillation frequency band with all of the generators in a group, these generators can be considered as a part of that group.

To define the concept of general coherency, the load and generation have to be randomly changed for several cases to check the coherency of generators over different loading scenarios. The purpose is to check if the grouping of generators is robust against the load changes in the system or grouping will change by changing the load in network. It is proven that load changes can affect the coherency characteristics of the power systems. In this case, some generators specially the generators in the boundaries may be swapped between the neighbouring areas.

Defining the coherent generator groups is the essential part of area detection in power systems. The second part will be to identify the non-generator buses located in each area. To determine which load and switching bus should be considered in an area, the angle swing of all load buses are obtained. For this reason, the loads can be considered as constant impedances and by having the generators angle swings the angle swings in load buses are obtained.

$$I = YV \tag{12}$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{13}$$

$$V_L = Y_{22}^{-1} Y_{21} V_G \tag{14}$$

$$\delta_L = angle(V_L) \tag{15}$$

V_G and I_G refer to the voltage and current injection at generators while V_L and I_L are the voltage and current at non-generation buses and Y is admittance matrix of the system.

As the inter-area oscillation frequency bands of neighbouring areas are known, the load buses located in each of the areas can be defined. Similar to the generators, the angle swing in non-generation buses are low pass filtered using a low pass digital signal filter to include only the low frequency inter-area modes and, signal correlation coefficient is calculated for the filtered angle swings.

$$rl_{ij} = \frac{\sum_{k=1}^{N_l} (f\delta_{ik} - \overline{f\delta_i})(f\delta_{jk} - \overline{f\delta_j})}{\sqrt{\sum_{k=1}^{N_l} (f\delta_{ik} - \overline{f\delta_i})^2 \sum_{k=1}^{N_l} (f\delta_{jk} - \overline{f\delta_j})^2}} \qquad (16)$$

Similar to (6) $f\delta_{ik}$ and $f\delta_{jk}$ are the k th element of filtered angle swing signal of non-generation buses i and j, $\overline{f\delta_i}$ and $\overline{f\delta_j}$ are the sample means of these signals, N_l is the number of non-generation buses, and rl_{ij} is the correlation coefficient between these signals. Calculating the correlation coefficient for the filtered angle swing of non-generation buses, highly positive correlated buses are considered to be in the same area. This method is applicable to large systems to assign highly correlated buses to each area. To exactly define the border lines (lines connecting the areas) and border buses (buses at each end of border lines) coherence function is calculated for each pair of the non-generation buses using (8-11) and replacing the generator velocity ω by angle swing δ_L in the mentioned equations. Each of the neighbour border buses connected through a border line belong to different areas. Therefore, the target is to find the neighbour non-generator buses which are negatively coherent in the inter-area oscillation frequencies and the border lines are obtained consequently.

In some cases same as the generators, it might be difficult to assign some of the non-generation buses to any area. These buses will usually swap between the areas depending on the load and generation changes in the system. Therefore, the border lines and buses may change due to the changes of the load and generation in the system.

3. Simulation on Test Systems

To verify the proposed method, it is evaluated on two test systems, a simple 4 machine system and modified 68 bus, 16 machine NPCC system [19].

3.1. Test Case 1

The first case is a simple 4 machine test system as illustrated in Fig. 1 with classical model of generators, and the transmission lines are modelled as constant impedances with zero resistance with the line reactance of $0.1\ pu$ of all lines except for line connecting buses 6 and 7 which has the reactance of $0.5\ pu$.

Fig. 1. Simple 4 machine test system.

The system is considered to be operating in its nominal operating point and the disturbance is applied on the system by randomly changing the loads in load buses. In this case the load change is considered to be a random change with 1% variance at each bus and applied at each time step which is 0.01 sec. As mentioned in previous section, the load change has the effect of continuous distributed disturbance on the system and causes the generators to swing as illustrated in Fig. 2 by velocity swings of the generators over a 10 sec period.

Fig. 2. Velocity changes in generators due to the disturbance.

To obtain the oscillation frequencies of the generators, spectrum analysis is applied on the velocity output of the generators. The simulation is performed on the system with a long simulation time and repeated to increase the accuracy of the obtained spectrum. For a more accurate result, DFT is calculated in several time frames and the average results are obtained as the spectrum output of the velocity swings shown in Fig. 3 along with the spectrum distribution of kinetic energy of whole system.

Fig. 3. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum.

The kinetic energy spectrum can define the important system oscillation frequencies and for this system three major oscillations can be observed. Inter-area modes usually have the frequency below 1 Hz and this example system has only 1 inter-area mode with the frequency of around 0.53 Hz. By checking the spectrum results of the generators velocity it can be observed that only in the inter-area oscillation frequency all the machines are oscillating while in all other major oscillation frequencies not all of the machines are participating in the oscillations which shows that the mentioned inter-area oscillation frequency is the sole inter-area mode of the system.

The system has only one inter-area mode which means it can be considered as two areas so the next step is to find the generators in each of the areas. Referring to the spectrum analysis, higher frequencies can be filtered from the velocity signals to preserve only the inter-area mode and correlation coefficient r_{ij} for the low pass filtered signals will define the generator grouping in the system which is shown in Table I.

TABLE I
Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals

i , j	r_{ij}	i , j	r_{ij}
1,2	0.987	2,3	-0.769
1,3	-0.788	2,4	-0.705
1,4	-0.725	3,4	0.959

It can be inferred from Table I that generators 1 and 2 are highly and positively correlated while being negatively correlated to generators 3 and 4 which means they belong to a same group. Similar result is observable for generators 3 and 4 which means these two generators are also forming a group. To clarify the grouping as mentioned in section 2, the coherence function and the angle of cross spectral density between pairs of generators are calculated as the generator in same groups are highly and positively coherent in the inter-area frequency band. The results are illustrated in Fig. 4.

Fig. 4. Magnitude-squared coherence and angle of coherency between pairs of generators in test system 1.

The coherency results also validates the grouping obtained previously as it can be observed from Fig. 4 only the generator groups 1, 2 and 3, 4 are highly and positively coherent in the inter-area frequency band which is around 0.53 Hz. These results also show that at the inter-area frequency, machines belong to other groups are highly but negatively coherent which validated the defined inter-area frequency to be the inter-area mode of system. Both of the proposed methods resulted in the same solution and defined the coherent group of generators. The next step is to define the load buses in each area and boundary buses between areas which will lead into finding the boundary lines connecting the areas.

This system consists of two neighbouring areas with one inter-area mode with the frequency of approximately 0.53 Hz. The angle swings in all of the non-generation buses are calculated using (12-15) and filtered to preserve only the inter-area frequency band. The correlation coefficient (16) is then calculated for these filtered signals and highly correlated non-generation buses are defined to be included in each area as shown in Table II.

TABLE II
Correlation Coefficient of Low-Pass Filtered Angle Swings of Load Buses

$i\ ,\ j$	rl_{ij}
5,6	0.999
5,7	-0.969
6,7	-0.960

It can be inferred from the results in Table II that load buses no. 5 and 6 are highly and positively correlated in the inter-area frequency band which means they belong to the same group while they are highly and negatively correlated with bus no. 7. The buses 6 and 7 are neighbour buses and as they are negatively correlated they can be called border buses and the line connecting these two buses as border line. In this case calculating the coherency function for the angle swings might not be necessary as the correlation results defined the load bus grouping with a high accuracy.

3.2. Test Case 2

In the second case, the proposed method is simulated and tested on a more complex system containing 68 bus and 16 machines In order to apply this method and run the simulations, the system loads and line impedances are modified to accelerate the simulation process but general system properties remained unchanged.

The system is operating at a stable operating point and in this case the simulation is performed using random load deviation of 2% of the load amount at load buses at each time step which is considered to be the same as previous case. This random load change disturbs the system as the distributed disturbance and the generators will swing similar to the case 1 illustrated in Fig. 3. Running the simulation for a long simulation time, the oscillation frequencies of the generators can be obtained by applying the spectrum analysis on the obtained generator velocity changes. The average DFT is calculated for several simulation time frames similar to the previous case to obtain the spectrum analysis of the generator velocities which is illustrated in Fig. 5 along with the distribution of total kinetic energy of system across the spectrum.

Fig. 5. Spectrum analysis of the generator velocity changes; and distribution of kinetic energy of whole system across the spectrum in 16 machine system.

The kinetic Energy spectrum shows the important and high energy low frequency inter-area oscillations which are mostly below 1 Hz. Unlike the previous case, it is not easy to find the inter-area frequencies based on the kinetic energy spectrum. The velocity spectrums of most generators show higher frequency oscillations in the range of 1- 1.5 Hz and regardless of frequency and lower energy, these oscillations might be considered as inter-area modes. Therefore for more accurate assumption about the range of inter-area frequencies more analysis is required on the velocity signals.

Considering the inter-area modes to be in the range of below 1 Hz, the velocity signals are low pass filtered to exclude all the higher frequencies. The correlation coefficient is then calculated for every pair of these filtered signals to find the highly correlated signal which is given in Table III.

TABLE III
Correlation Coefficient of Low-Pass Filtered Generator Velocity Signals for 16 Machine Test System

	r_{ij}															
j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X	1.00	1.00	0.96	0.95	0.97	0.96	1.00	0.98	0.83	0.67	0.33	0.21	0.13	0.00	-0.06
2	1.00	X	1.00	0.96	0.95	0.96	0.96	0.99	0.97	0.84	0.68	0.34	0.22	0.11	-0.01	-0.07
3	1.00	1.00	X	0.97	0.96	0.98	0.97	1.00	0.98	0.81	0.64	0.30	0.17	0.11	-0.01	-0.07
4	0.96	0.96	0.97	X	1.00	1.00	1.00	0.97	0.98	0.67	0.47	0.10	-0.03	0.08	-0.02	-0.08
5	0.95	0.95	0.96	1.00	X	0.99	0.99	0.96	0.97	0.65	0.45	0.07	-0.05	0.08	-0.02	-0.08
6	0.97	0.96	0.98	1.00	0.99	X	1.00	0.98	0.98	0.67	0.48	0.10	-0.03	0.08	-0.02	-0.08
7	0.96	0.96	0.97	1.00	0.99	1.00	X	0.98	0.98	0.67	0.46	0.09	-0.04	0.08	-0.02	-0.08
8	1.00	0.99	1.00	0.97	0.96	0.98	0.98	X	0.99	0.80	0.63	0.28	0.16	0.12	-0.01	-0.06
9	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.99	X	0.71	0.53	0.16	0.03	0.09	-0.02	-0.07
10	0.83	0.84	0.81	0.67	0.65	0.67	0.67	0.80	0.71	X	0.97	0.79	0.70	0.19	0.04	0.04
11	0.67	0.68	0.64	0.47	0.45	0.48	0.46	0.63	0.53	0.97	X	0.91	0.86	0.16	0.04	0.05
12	0.33	0.34	0.30	0.10	0.07	0.10	0.09	0.28	0.16	0.79	0.91	X	0.99	0.09	0.03	0.00
13	0.21	0.22	0.17	-0.03	-0.05	-0.03	-0.04	0.16	0.03	0.70	0.86	0.99	X	0.07	0.02	-0.02
14	0.13	0.11	0.11	0.08	0.08	0.08	0.08	0.12	0.09	0.19	0.16	0.09	0.07	X	0.34	0.03
15	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	0.04	0.04	0.03	0.02	0.34	X	0.22
16	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.08	-0.06	-0.07	0.04	0.05	0.00	-0.02	0.03	0.22	X

Based on the calculated value of r_{ij} in the table above, it can be inferred that generators 1 to 9 are highly and positively correlated in the mentioned frequency range which means they can be considered as a group. Generators 11 to 13 also have a high correlation and can be considered as another group of generators. The correlation coefficients related to machines 14 to 16 are not significantly high and these generators can not be grouped with any of other machines. The only remaining machine is generator 10 which has a high correlation with both of the defined generator groups but as it has a higher correlation with its neighbouring machine 11 we can consider it as a part of second group. This classification is based on the low pass filtered signals for the frequencies below 1 Hz while by changing the frequency cut off band for several cases from 1 to 1.5 Hz the general grouping did not change.

For a more accurate grouping especially for the generators that have high correlation with generators in two groups, the coherence function and the angle of cross spectral density between pairs of generators are calculated. The generators belong to the same area are highly and positively coherent in the range of inter-area frequency band. Therefore, the disputed generators can be checked for the inter-area oscillation frequency of the two groups so these generators will be assigned to the group of generators which are highly and positively coherent with them for that frequency. The results of coherence function and the angle of cross spectral density between selected pairs of generators are illustrated in Fig. 6.

Fig. 6. Coherence and angle of coherency between selected pairs of generators in test system 2.

The result of the coherency analysis provides useful information about the system grouping and inter-area oscillation frequency range. It can be inferred that generators which are assumed to be in the same group based on the previous results, are not highly and positively coherent for the frequencies more than 1 Hz. Therefore, no big group of generators can be found to be coherent in the frequencies over 1 Hz which means those frequencies are not in the range of inter-area modes. Furthermore, the results provide more accurate results for the boundary generators which were difficult to be assigned to a group such as generator number 10 in this case. Based on the results shown in Fig. 6, machines 1 to 9 and 11 to 13 are oscillating against each other with the frequency around 0.62 Hz and in that frequency generator 10 has higher coherency with the first group while having higher coherency in other frequencies in the range of inter-area modes with the second group. Therefore, machine 10 is highly coherent with both of the groups and depending on the oscillation mode it can be assigned to one of the two groups.

By defining the coherent group of generators the next step is to find the load buses in each area and boundary buses and lines between the areas by analysis the angle swing of non-generator buses as described in previous section and case 1. Low pass filtering the angle swing signals for the inter-area frequency band, the correlation coefficient is calculated so highly and positively correlated buses can be assigned to the same group. The results provide a general grouping for load buses while for the buses located in the boundaries the coherency analysis should also be applied to provide the accurate grouping and defining boundary buses and lines.

Based on the machine grouping and the results of correlation between filtered angle swings of load buses, the buses with high and positive correlation coefficient are assigned to be in the same group. The coherency results help to find the boundary buses based on the inter-area oscillation frequency between neighbouring areas. In this case, the pair of neighbour non-generator buses with highly and negative coherence in the range of inter-area frequency of the two areas are considered as boundary buses and the line connecting them as the boundary line. Similar to defining the generators in each group, finding the neighbour load buses with negative coherency might not be easy and some buses might be disputed to be in either of the areas. In such cases instead of considering the neighbour buses the penetration is increased to search for the buses with one or two buses between them to find the boundary buses. Therefore by finding these kinds of boundary buses, the load buses between them are not assigned to any group where we call them mid-area buses. This usually happens for the load buses located next to or very close to the disputed machines such as machine 10 in this case. In Fig. 7 the result of system grouping for generators and load buses is illustrated.

Fig. 7. Generator grouping and defined areas for 16 machine test system.

3.2.1. Operating Point Change

The proposed area detection process, similar to other methods, finds the generator grouping and area borders for a specified load and generation level. To provide a more general approach, the system steady state load and generation is examined for several cases with values selected over a range of up to 30% change to the original operating point and in each case the area definition process described above is followed. The results show that, generators and buses which had very high correlation still remain together regardless of which steady state load and generation case is selected, but the generators and buses which are not highly correlated to any area such as generator 10 may swap from one area to another area depending on the load change. The result of generator coherency and area

detection for a different operating point of test case 2 is illustrated in Fig. 8 showing few changes comparing to the previous results. For real systems, some sets of load and generation levels can be defined and the area definition process can be applied for each of these levels to have a clear and more accurate vision of system behaviour which is applicable in system reduction and online control schemes of inter-area modes.

Fig. 8. Area detection for a different operating point in case 2

4. Conclusion

In this paper a new approach is proposed for detecting coherent generators and defining their related non-generator buses to form areas in inter-connected power systems. The method applies random load changes as a distributed disturbance on the system and spectrum analysis on velocity changes of generators is performed to obtain coherent generators in low frequency inter-area modes. Similar spectrum analysis is applied on the angle swing of load buses to obtain the related load buses to each group of generators and form the areas in the network. This method is applied on two test systems to prove the feasibility and applicability of the approach in various simple and complex networks. The results shows that in complex networks it might not be possible to fully divide the system into coherent group of areas and some generators and load buses may swap between neighbor areas by changing the operating point of the system. Applying the method on several realistic operating points of a system the results shows very similar grouping of generators. By changing the operating point the general grouping does not change but the boundary generators and buses (those not assigned to any area) may be grouped with the neighbour areas. The multiple operating point approach provides more accurate representation of generator grouping and area detection in large power systems. Therefore, as a general approach the generators and buses which do not stay coherent in most of the realistic loading conditions should be modelled separately or as separate areas which is an important issue in the aspect of control of inter-area modes.

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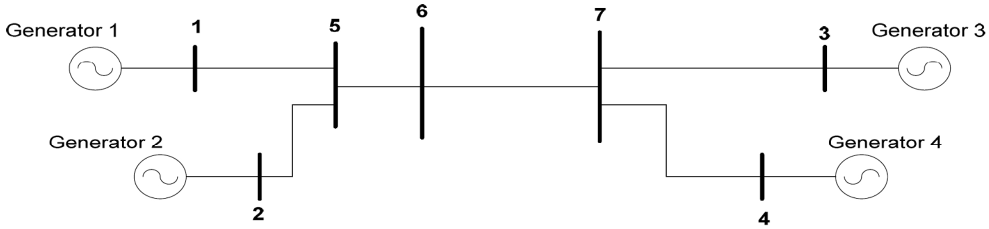

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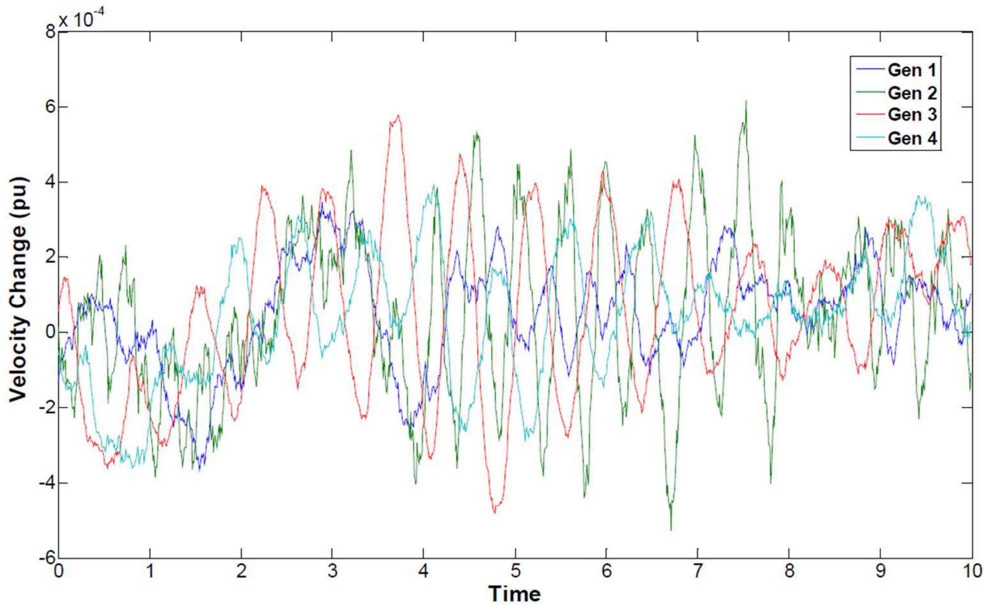

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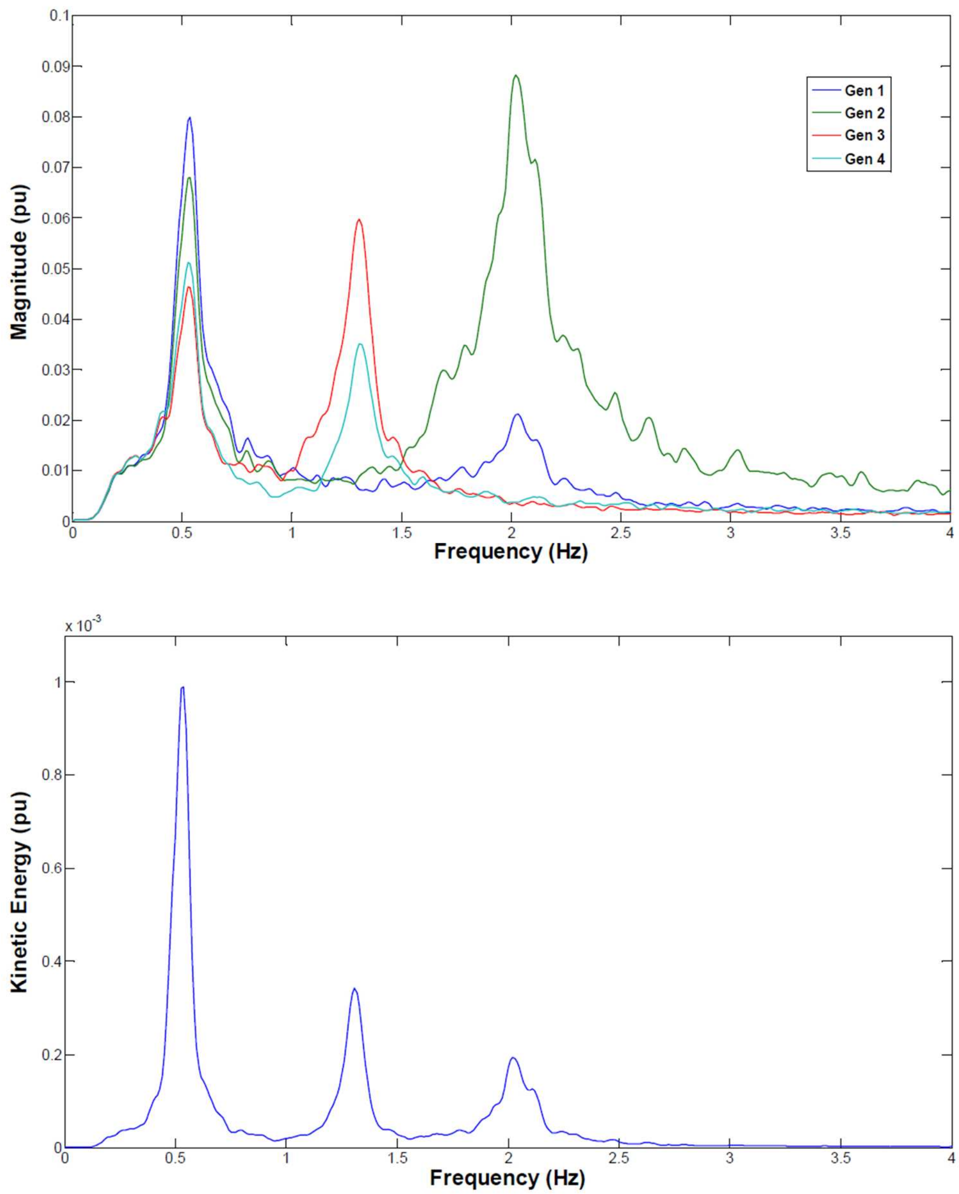

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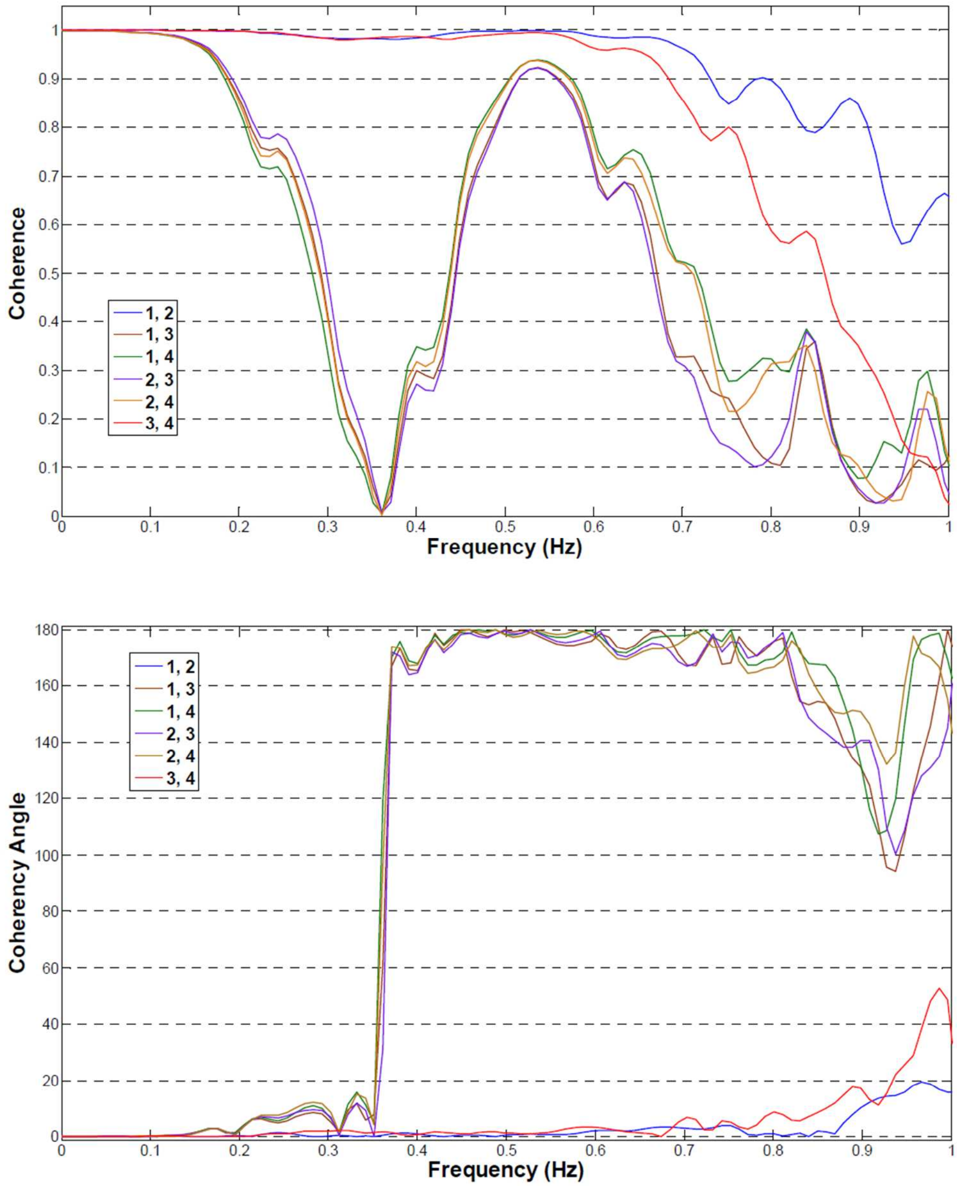

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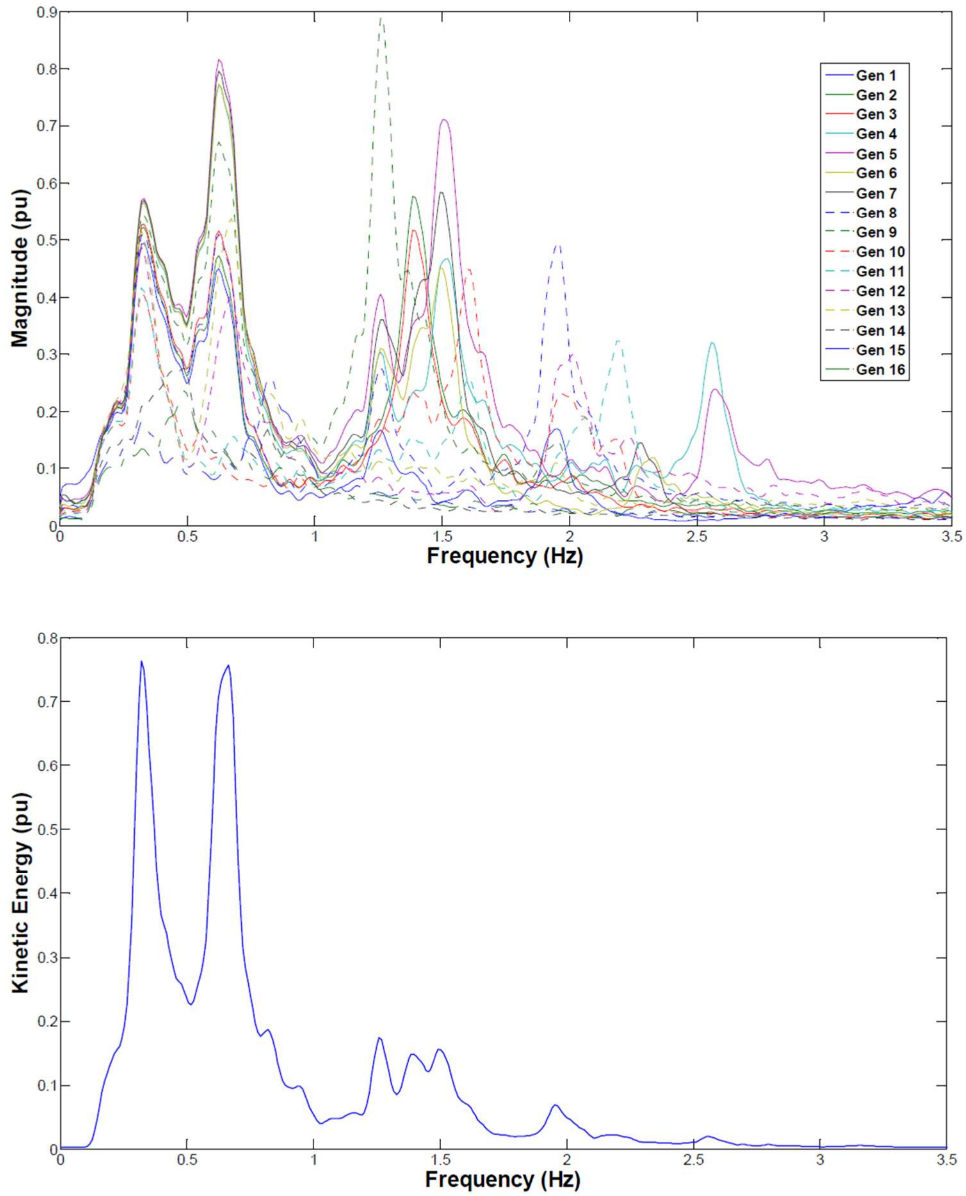

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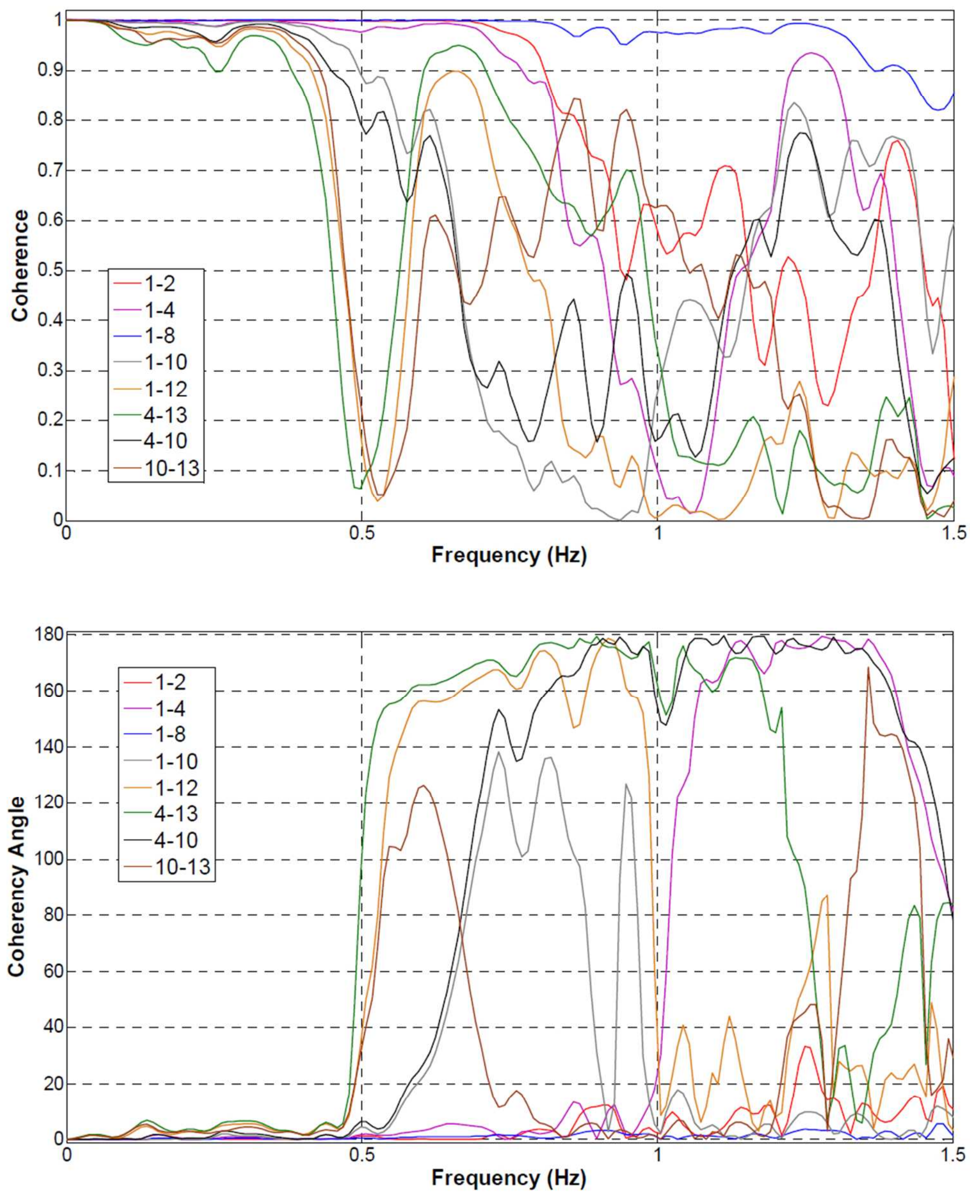

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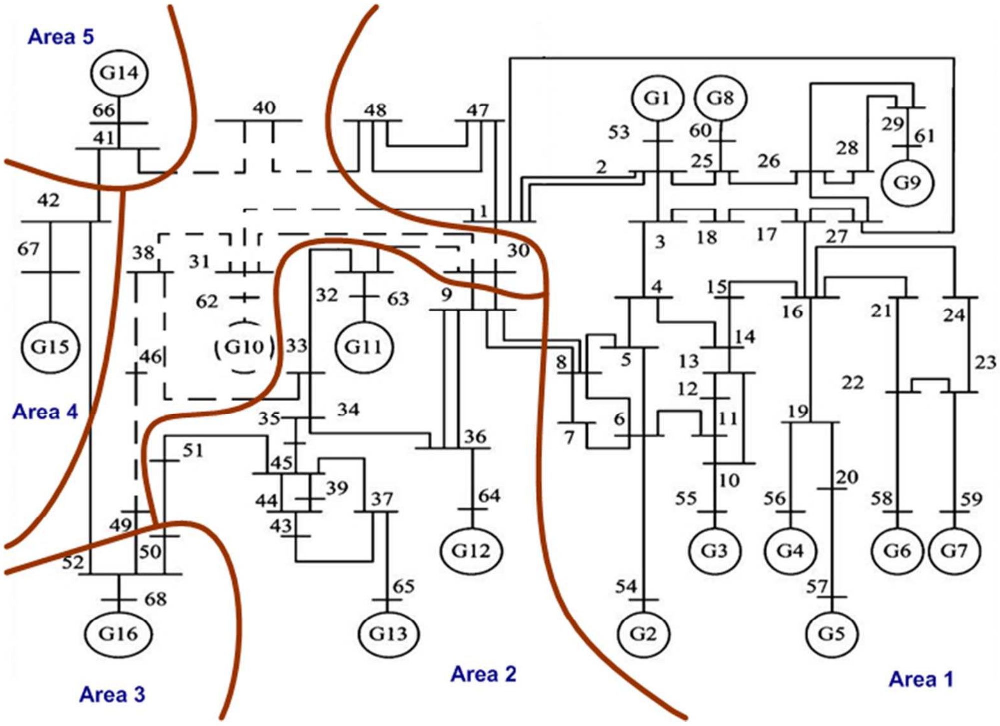

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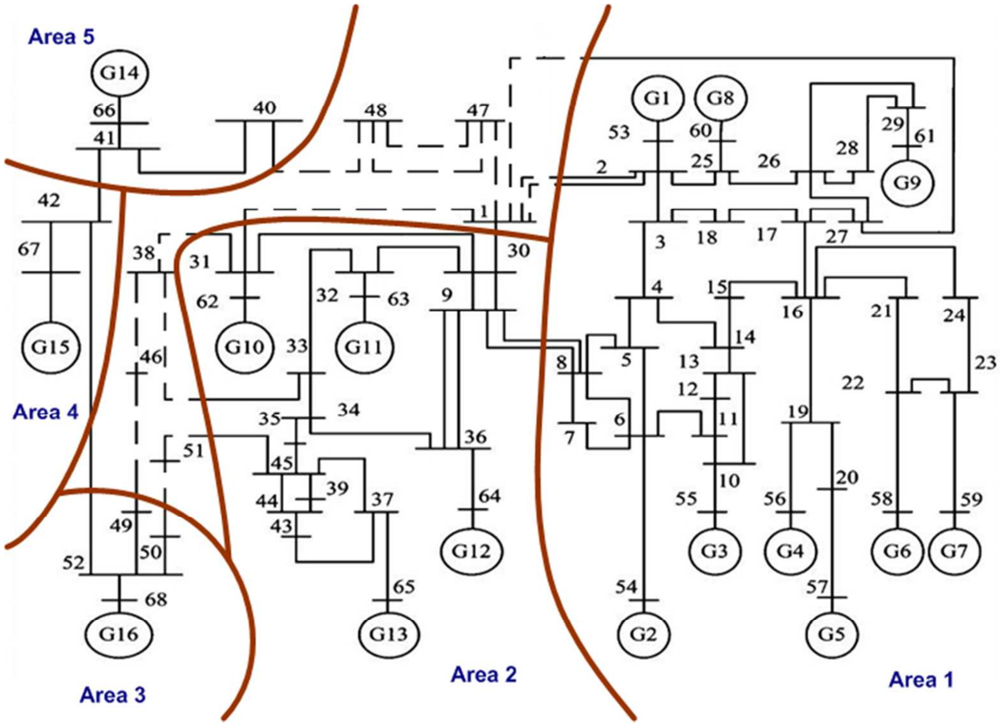

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