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Identification of coherent-generator groups using the Huang's empirical mode decompositions and correlations between IMFs

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Abstract. Modern power systems are a very complex dynamical system spreading over a large geographical area. They indicate very complex phenomena in some parts as well as in the whole interconnected power system. In large and complex systems, there are coherent groups of generators. A group of generators in one area swings against a group of generators in another area. In this paper, using the Huang's Empirical Mode Decomposition (EMD) signals of the rotor-angle oscillations are separated into several Intrinsic Mode Functions (IMFs) and, thereafter, the correlations between IMFs are applied as a coherency measure and criterion for identification of coherent- generator groups in a power system. The applied approach is analysed for the Kundur two area-four machines test system and New England (NE) bus 39 test system. A comparison between the results of NE bus 39 test system with those of other researches shows a high degree of similarity.

Keywords: Power Systems, Coherent Generator Groups, Empirical Mode Decompositions, Correlations

Identifikacija povezanih skupin generatorjev z uporabo Huangove empirične razstavitve in korelacije med lastnimi funkcijami

Sodobni energetski sistemi so kompleksni in razpredeni prek širših geografskih območij. Pri velikih energetskih sistemih lahko obstaja skupina povezanih generatorjev, ki ne deluje sinhrono z drugimi generatorji, posledica tega pa so oscilacije v omrežju. V članku je predstavljena razstavitev rotorskih oscilacij v lastne funkcije. S korelacijo lastnih funkcij nato določimo kriterij za povezanost generatorjev v energetskem sistemu in stopnjo povezanosti. Predlagani pristop smo analizirali na testnem sistemu Kundur in NE 39.

1 INTRODUCTION

Coherent groups of generators are the result of connecting small (national) power systems in large interconnections via interconnection lines, and after a disturbance, the generators of the same group tend to swing together [1], [2], [3]. An identification of the change in the coherent groups can indicate a modification of the network topology following a disturbance [3]. The oscillation frequency of a generator group in one area swinging against a generator group in another area is usually in the range of up to 1 Hz, where the low-frequency mode involves all generators in the system, while a higher frequency involves generator subgroups swinging against each other [1]. In literature, there are several approaches to identify coherent-generator groups. The electrical distance between two generators and inertial time constants as a coherency measure are used in [4]. The linear correlation coefficient is a measure of the degree of the 'coupling' or 'coherency' in multi-machine power systems and depending on the value of the coefficient it determines which generators swing together upon a remote disturbance [4]. In [5] the observed low-frequency inter-area includes Power System Stabilization (PSS) and proposes a method for PSS at damping inter-area power oscillations using coherency in the generators dynamics based on eigenvalue analysis. Several researches to identify coherent-generator groups in power systems based on artificial intelligence methods can be found in Refs. [6], [7], [8]. In a large power system, the Fuzzy C-Means Clustering Algorithm, dynamic equivalents and time response of a linearised power-system model are used for identification of coherent generators [9]. In [10], the authors conclude that most of the generators in a large power system have some similar transient power-angle characteristics according to which they can be grouped. For the power-system stability analysis they present a very useful GPS technique using the power-angle measurement based on the coherent-group theory [10]. An approach to detect coherent generators in inter-connected power systems is applied on two test systems by changing in the load of load buses. The Discrete Fourier Transform (DFT) is one of the methods used for the spectrum analysis of the generator velocity with statistical signal processing tools to obtain the significant inter-area modes and generator coherency [11]. A very interesting approach based on the Nonlinear Koopman Modes, Hierarchical Clustering Method, Graph Theory, Principal Component Analysis

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(PCA), Independent Component Analysis (ICA), etc., can be found in Refs. [11]-[23]. Two techniques for non-linear and non-stationary signal processing applied to identify coherent-generator groups based on the Hilbert Huang Transform (HHT) and Empirical Mode Decompositions (EMD) and Wavelet Phase Difference (WPD) approach are presented in [2] and [3], respectively. The EMD algorithm is applied to identify the dominant oscillatory mode in signals (as a ratio of the IMF norm to the norm of the original signal [2]) and coherency between generators is tracked by examining the instantaneous phase differences among inter-area oscillations [2]. The WPD approach allows for observation of the movement of the inter-area components that move or do not move together in the time-frequency plane and provides an excellent visualization of the observed phenomena [3].

In this paper, using the Huang's EMD approach at signals of the rotor-angle oscillations (with a sampling rate of up to a 10 Hz-range of the low-frequency electromechanical oscillations) several IMFs are obtained and thereafter correlations between them are used as a coherency measure and criterion for identification of the coherent-generator groups. Applying this approach avoids determination of the dominant low-frequency electromechanical (inter-area) modes and monitoring co-movement between them or dominant IMFs in relation to the basic signals.

The rest of the paper is organized as follows.. The background of the applied approach is briefly described in Section II. In Section III, an analysis with a discussion of the results is made for the Kundur two area-four machines test system and New England (NE) bus 39 test system. Conclusions are given in Section IV.

2 Applied Approach

Based on Refs. [16] and [1], [2], [3], the applied approach can be shortly presented as follows:

- ✓ Set the sampling rate of the rotor-angle oscillation signals from all generators in the range of up to 10 Hz. According to the Nyquist criterion, the subject of analysis are the signals in the range of up to 5 Hz, i.e. the low-frequency electromechanical oscillatory modes.
- ✓ At the signals of a rotors-angle oscillation, apply the EMD algorithm and separate the signals into several IMFs and residual.

Shortly, the EMD algorithm can be can be described as:

1. Find the local maxima and minima of signal $\delta(t)$,
2. Perform a cubic spline interpolation between the maxima and the minima to obtain envelopes $u(t)$ and $d(t)$.
3. Determinate the mean value of the envelopes:

$$m_1(t) = \big(u(t) + d(t)\big)/2 \tag{1}$$

4. Extract:

$$h_1(t) = \delta(t) - m_1(t) \tag{2}$$

5. $h_1(t) = c_1(t)$ is IMF (conditions for the IMF existance: the number of local extreme $h_1(t)$ is equal to or differs from the number of the zero crossings by one, and the average of $h_1(t)$ is zero). If $h_1(t)$ is not IMF, repeat steps 1-4 replacing $\delta(t)$ by $h_1(t)$, until new $h_1(t)$ satisfies the conditions for IMF.
6. Compute the residue, $r(t) = \delta(t) - c_1(t)$

The algorithm will in several steps find all the components (the final residue should be a constant or monotonic function), or until a pre-defined condition is fulfilled. Finally, the original signal has the following form:

$$\delta(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{3}$$

where $c_i(t)$ is the ith IMF, n is the number of the intrinsic modes and $r_n(t)$ is the residual.

- ✓ After obtaining IMFs neglect all residuals which represent the trend of the analyzed signals. Then between all the obtained IMFs calculate the correlations.
- ✓ Between the generators find the most significant (positive) correlation from IMFs and assign them as the same group. Affiliation to the same group means that all generators in the group have a significant (positive) correlation between themselves (and thus the IMF components oscillate together).

3 Applications to the Test Systems

As discussed above, the performance of the proposed approach is tested on two test systems. The first test system, i.e. the Kundur two area four generator test system, is shown in Fig. 1. All details about this system can be found in [1]. After simulation of a Three-Phase Short Circuit (TPSC) in 0.1 sec in bus 8, oscillations occur in the system.

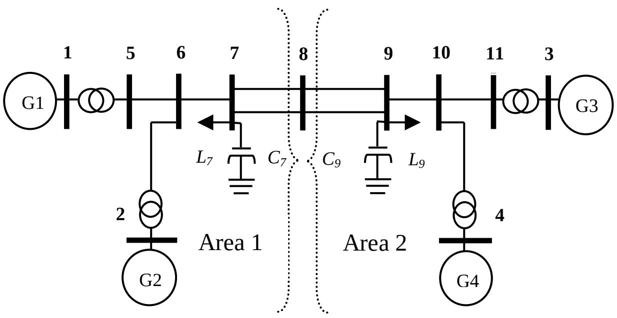

Figure 1. Kundur two area-four machines test system [1]

The generator rotor-angle oscillations resulting from a simulated disturbance over a 10 sec period are plotted in Fig. 2. As seen, these are two areas in this system. It is simple to identify (G1, G2) and (G3, G4) as coherent-generator groups. This can also be concluded from Fig. 2, observing the movement or co-movement of the two generators rotor-angles. After applying the EMD algorithm, two IMFs and residuals from the signals in Fig. 2 are obtained (Fig. 3).

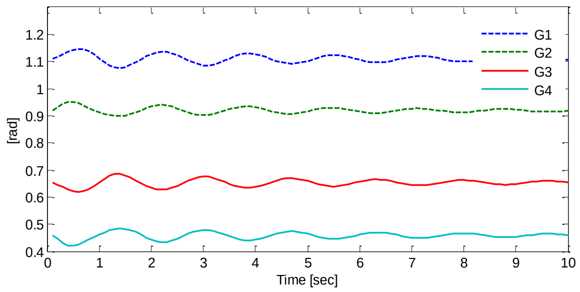

Figure 2. Generator rotor-angle oscillations due to the disturbance over a 10 sec period

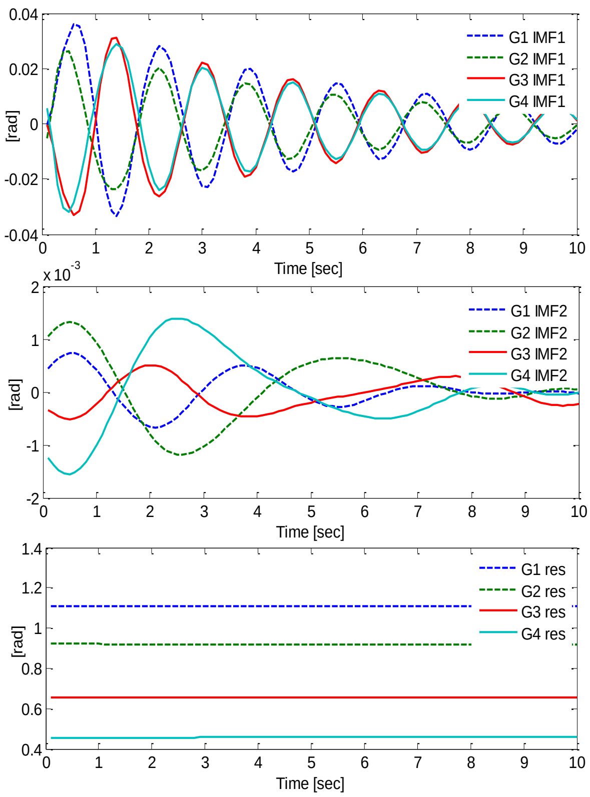

Figure 3. IMFs after EMD of the signals in Fig. 2

From Fig. 3 it is clear that the IMFs 1 amplitudes are greater than the IMFs 2 amplitudes. Also, it is clear that the IMFs 1 frequency is about 0.5 Hz, and for this test system it represents inter-area oscillatory modes [1]. Further, using the proposed approach described in Section II, correlations between IMFs from Fig. 3 are calculated, and the results are presented in Table 1. The most significant positive correlation between IMFs are identified between IMFs 1 which come from the signals of generators G1 and G2, and between IMFs 1 which come from the signals of generators G3 and G4. This result is expected based on the characteristics of IMFs 1 presented in Fig. 3. In other words, it is clear that IMFs 1 of generators G1 and G2 co-move together with a similar amplitude, which can also be concluded for IMFs 1 of generators G3 and G4.

Table 1.Correlations between IMFs.

G1 \ G2	IMF1	IMF2	G3 \ G4	IMF1	IMF2
IMF1	0.940578	0.128439	**IMF1**	0.976093	0.134673
IMF2	0.130279	0.479522	**IMF2**	0.145409	0.34228
G1 \ G3	**IMF1**	**IMF2**	**G2 \ G3**	**IMF1**	**IMF2**
IMF1	-0.99478	-0.14269	**IMF1**	-0.95892	-0.12395
IMF2	-0.11449	-0.76217	**IMF2**	-0.11441	-0.40988
G1 \ G4	**IMF1**	**IMF2**	**G2 \ G4**	**IMF1**	**IMF2**
IMF1	-0.97199	-0.15999	**IMF1**	-0.98908	-0.12857
IMF2	-0.15297	-0.5291	**IMF2**	-0.10875	-0.96938

It should be noted that the values of a strong correlation imply the values in the rang from ±0,7 to ±1. The sign of the correlations determinates the directions of connections between two variables: + (plus) presents a positive direction of the linear relationship between two variables and the increase in one variable is associated with the increase in other variables, while the sign – (minus) presents a negative direction of the linear relationship between two variables and the increase in one variable is associated with the decrease in other variables. Finally, based on the proposed approach, the most significant correlations between individual IMFs are separated in Table 2.

Table 2. The most important (significant) correlations between IMFs.

	G1	G2	G3	G4
G1	x	0.940578	-0.99478	-0.97199
G2		x	-0.95892	-0.98908
G3			x	0.976093
G4				x

These results show that generators G1 and G2 are in the same coherent group, while generators G3 and G4 are in another coherent group. As stated above, a positive correlation coefficient indicates that the components move together; an increase in the value of one variable means an increase in the value of the other, meaning that the components or oscillatory modes move together. On the other hand, a negative correlation coefficient indicates that the components are in opposition, and in our test case (inter area modes) they oscillate out of phase.

The second selected test system is the NE bus 39 test system with ten generators (Fig. 4). In order to test the proposed approach, TFSC at bus 31 is simulated. TFSC at bus 31 is selected for a comparison with the results of the research presented in [16] and [25], where the authors use the same test system and simulate the same disturbance. After simulating TFSC, oscillations occur in the system. The rotor-angle oscillations of all ten generators are plotted in Fig. 5. For the simulated TFSC on bus 31, the results of the proposed approach are presented in Table 3.

Table 3. The most important (significant) correlations between IMFs for the signals in Fig. 5

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
G1	x	0.610	0.486	-0.799	-0.797	-0.842	-0.708	0.501	-0.581	0.462
G2		x	0.428	-0.831	-0.801	-0.782	-0.857	0.456	-0.431	-0.651
G3			x	-0.681	-0.695	-0.779	-0.387	-0.417	-0.588	0.313
G4				x	0.980	0.943	0.741	-0.275	0.450	0.301
G5					x	0.919	0.750	-0.316	0.626	-0.329
G6						x	0.791	0.514	0.322	0.520
G7							x	-0.786	0.765	-0.572
G8								x	-0.924	0.824
G9									x	-0.926
G10										x

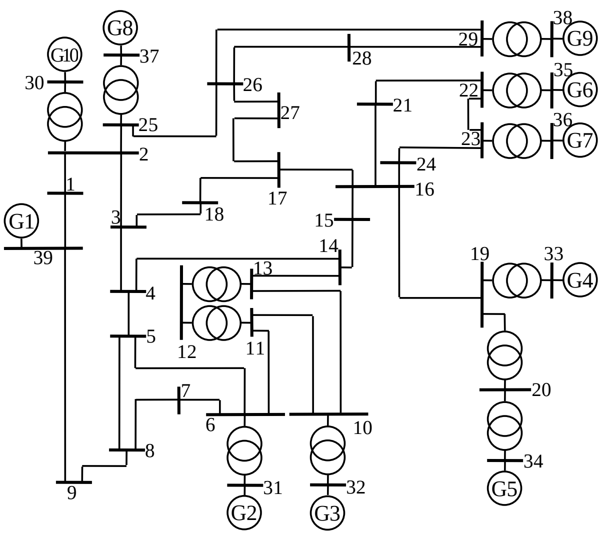

Figure 4. NE bus 39 test system [3]

The most important and significant (positive) correlation coefficients are identified between generators G4, G5, G6 and G7, and also between generators G8 and G10. Generator G9 has a significant positive correlation with generator G7 (0.765), but with other generators from the first identified group it has no significant correlation and is for that reason not classified in that group.

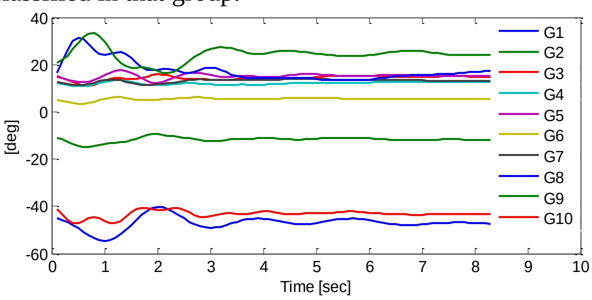

Figure 5. Generator rotor-angle oscillations due to TFSC on bus 31

Also, because of its significant but negative correlations of G9 with G10, it is not classified in to the second group neither.

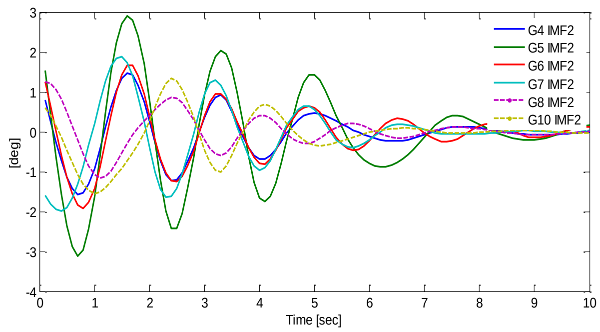

Figure 6. IMFs 2 as a basis for the identified coherent group (presented in Table 3)

Other values of the correlation coefficients between IMFs of other generators have no significant positive values (Table 3). A more detailed analysis of the correlation coefficients between IMFs presented in Table 3 shows that the significant values of the correlation coefficients (in the range from ±0,7 to ±1) come from IMFs 2. For the coherent groups identified in this example and grouped according to the proposed approach, specific IMFs are selected and presented in Fig. 6. It is clear that the IMFs 2 components which come from the signals of generators G4, G5, G6 and G7 move together, while IMFs 2 which come from the signals of generators G8 and G10 move together with a very similar amplitude (Fig. 6). Also the frequencies of those components are about 0.6 Hz which represents the inter-area mode frequency for this test system (Fig. 6)

Generators G4, G5, G6, and G7 in all three compared works are identified in the same coherent group. Also, generators G8 and G10 are in the same coherent group due to the compared various approaches, but according to the approach in this research generators G8 and G10 cannot be classified in the group with generators G4, G5, G6 and G7.

Table 4. A comparison with the results presented in Refs. [15] and [24]

	Coherent-generator groups
This work	(G8,G10) and (G4,G5,G6,G7)
Ref. [24]	(G1,G3,G4,G5,G6,G7,G8,G9,G10)
Ref. [15]	(G4,G5,G6,G7,G8,G9,G10)

4 Conclusion

Power-system coherency generator identification has been attracting a significant attention of the scientific community for many years. For this reason there has been a considerable number of scientific approaches to this issue suitable for the analysis and processing of non-stationary and nonlinear signals with presentation in the time frequency plain.

In this paper, an approach is proposed based on the Huang's EMD and correlations between IMFs. A practical application carried out on two test systems offers a satisfactorily result. One of the good features of this approach is that there is no need to identify the dominant (inter-area) modes to define with it coherent-generator groups. However, based on the analysed examples, it is found that the most important correlation values are just between these components (inter-area modes).

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