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# An Enhanced WAMS-based Power System Oscillation Analysis Approach

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## Abstract

Modern interconnected wide-area power systems around the world are faced with serious challenging issues in global monitoring, stability, and control mainly due to increasing size, changing structure, emerging new uncertainties, environmental issues, and rapid growth in distributed generation. The present paper introduces an enhanced data processing method based on the Hilbert-Huang Transform (HHT) technology for studying the power system oscillation dynamics analysis. The addressed method could be useful to develop a new oscillation monitoring system using real-time wide-area measurement system performed by the phasor measurement units (PMUs). The present methodology analyzes power system oscillation characteristics and estimates the damping of oscillatory modes from the ambient data. The proposed method gives an indication for the damping of transient oscillations following occurred disturbances. It employs a system identification procedure that is carried out in a real-time environment. To demonstrate the effectiveness of the developed methodology, the PMU-based measured data from the Japan power system are used.

*Keywords: Power System Oscillation, wide-area measurement system, HHT technology*

## 1 INTRODUCTION

Wide area measurement system (WAMS) is an important issue in modern electric power system operation and control; and is becoming more significant today due to the increasing size, changing structure, introduction of renewable energy sources, distributed smart/micro grids, environmental constraints, and complexity of power systems. The WAMS with phasor measurement units (PMUs) provide key technologies for monitoring, state estimation, oscillation analysis, system protections and control of widely spread power systems [1]. Hilbert-Huang Transform (HHT) is a fully adaptive time-frequency analysis method, suitable for both non-linear and non-stationary signal analysis as well as for linear and stationary signal analysis [2]. The HHT applies empirical model decomposition (EMD) to decompose the low frequency oscillation signals and calculates the instantaneous parameters including frequency of model components. Then, it computes the damping ratio of each model component using the derived set of formulas. This method can be applied to analyze highly non-linear oscillation models in power systems and then the tuning of existing damping controllers.

## 2 THE ENHANCED HHT METHOD

The detail introduction of HHT method could be found in [2-4]. This paper addresses two key problems for applying the HHT method to power system oscillation characteristic analysis. Then, a method is presented to identify parameters of power system.

### 2.1 Hilbert-Huang Transformation Issues

Here, in order to show the fundamental issues of the HHT, an example is given. Consider a simple *sin* signal, as show in Figure 1,

$$x = 2\sin(2\pi * 20t) \quad (1)$$

Figure 2 and Figure 3 show that EMD result and time-domain spectrum of *sin* signal using the HHT method. Three IMF components and residue signal are achieved as shown in Figure 2. As can be seen from the signal function, it should only get one IMF component. Occurring of other two IMFs in Figure 2 is due to the problems caused by the EMD analysis process.

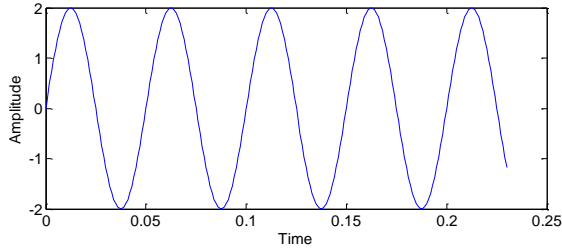


Figure 1. Test *sin* signal

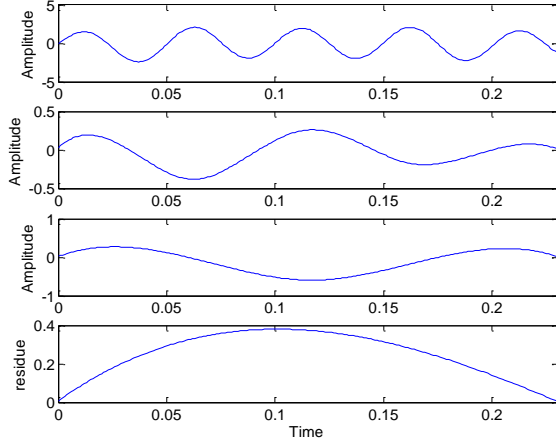


Figure 2. EMD analysis result

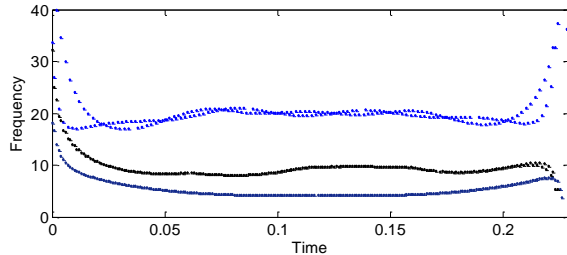


Figure 3. Time-domain spectrum of HHT (Instantaneous frequency)

Figure 3 shows the change of three instantaneous frequency components over the time. The first frequency component is around 20Hz, which is similar to the frequency of the test *sin* signal. However, distortions are appeared at the both endpoints; which this phenome is called the boundary end effect. The reason of appearance of the other two instantaneous frequency components is discussed later.

From the simple *sin* signal test, the available HHT algorithms typically include three key issues: 1) boundary end effect; 2) pseudo IMF component caused by EMD decomposition, especially for low-frequency signal; 3) parameters identification in power system oscillation analysis. These issues are briefly explained below.

#### A). the Boundary End Effect

Boundary end effect generated in the EMD process is one of the important factors that affect the quality of EMD. In general, a distortion called "Gibbs" phenomenon often appears at signal boundaries when processing signals concentrated in a limited period of time, which known as the boundary end effect. The Gibbs phenomenon exists for many integral representations [5-9] and for many series representations as well. The presence of this phenomenon is undesirable, since it is related to the behavior of the series approximating a discontinuous function  $f$  at a jump location  $t$ , implying non-uniform approximation at  $t$ ; so it is important to examine the ways to reduce or even avoid it. In [10] and [11], Gibbs phenomenon has been shown to exist for Fourier interpolation. Since most multi-resolution analyses induce sampling expansions [12], Gibbs phenomenon for wavelet sampling expansions has been examined in [13-15].

In the EMD algorithm, every time the "sieve" of a new IMF component have a certain relationship with the old IMF component. Therefore, the distortion at the endpoint will spread to the interior. As a result, the new IMF components have obviously distortion, especially for IMF lower frequency components. Seriously, this will lead to EMD decomposition results incorrect and it can also bring the endpoint distortion in Hilbert transform process which will affect the accuracy of the Hilbert spectrum analysis (HSA). Therefore, solving the boundary end effect issue for the HHT is highly important in theoretical and practical point of view.

#### B). Pseudo IMF Component

There are a lot of reasons for generating pseudo-IMF components, such as boundary end effect, termination criterion for IMF component and an unreasonable sampling frequency select. If we can solve the boundary end effect issue, pseudo-IMF component can be eliminated to some extent.

#### C). Parameters Identification

It is well known that the EMD method is based on the local characteristic time scale signal. Any signal can be decomposed into the sum of IMF components adaptively in order to make instantaneous frequency has a real physical meaning. Afterwards, each IMF component of the instantaneous amplitude and instantaneous frequency can be calculated by the Hilbert transform. In this research, the least squares method is employed to combine the HSA and to perform a power system low frequency oscillation parameter identification algorithm.

In power system, the oscillation mode component can be written as:

$$P(t) = Ae^{-\lambda t} \cos(\omega t + \psi) = Ae^{-\lambda t} \cos(2\pi f t + \psi) \quad (2)$$

The time response function of the oscillation mode component

can be also represented as follows:

$$P(t) = Ae^{-\xi\omega_0 t} \cos(\omega_0\sqrt{1-\xi^2}t + \psi) = Ae^{-\xi\omega_0 t} \cos(\omega_d t + \psi) \quad (3)$$

The  $A$  is initial amplitude,  $\psi$  is initial phase,  $\lambda$  is damping coefficient,  $\omega$  is oscillation angular frequency,  $f$  is oscillation frequency,  $\omega_0$  is un-damped angular frequency,  $\omega_d$  is damped angular frequency, and  $\xi$  is damping ratio. Comparing the equation (2) and (3), gives:

$$\begin{cases} a(t) = Ae^{-\lambda t} = Ae^{-\xi\omega_0 t} \\ \theta(t) = 2\pi f t + \psi = \omega_d t + \psi \end{cases} \quad (4)$$

For identification of frequency oscillation signal, it is necessary to accurately extract the amplitude of the oscillation component and damping coefficient, and then calculate the damping ratio, which depends on the oscillation frequency and damping factor.

Frequency oscillation signal exists in the decomposed IMF components as an oscillation mode component. Therefore, the parameter identification is needed. In order to obtain more accurate identification results, two issues should be considered. The least squares method is used to improve the accuracy of damping coefficient and oscillation amplitude. It also needs to make some changes in the analytical signal form, as show in equation (5). Damping coefficient ( $\lambda$ ) identification uses the least squares through the logarithmic curve of instantaneous amplitude function of a single IMF component.

$$\begin{cases} \ln a(t) = -\lambda t + \ln A = -\xi\omega_0 t + \ln A \\ \omega(t) = \frac{d\theta}{dt} = 2\pi f = \omega_d = \omega_0\sqrt{1-\xi^2} \end{cases} \quad (5)$$

On the other hand, reducing the IMF component data is also noteworthy. Since the data for parameter identification is obtained from the IMF component, the boundary end effect caused by the EMD is suppressed, but is not eliminated. At the same time, the endpoint distortion come from the Hilbert transform is also not completely eliminated. Therefore, IMF can improve identification accuracy by removing small amounts of data at the both ends. In this work, 10% - 90% of the IMF component source is used for the identification algorithm.

## 2.2 The Enhanced HHT Method

As mentioned in [3][4], the HHT algorithm is divided into EMD process and HSA process. Removing direct current (DC) and a band-pass filtering steps are need to be preprocessed

before applying the HHT algorithm. Since the low frequency oscillations (LFO) or generator rotor angle oscillations having a frequency between 0.1-2.0 Hz [16], the band frequency range is from 0.1Hz to 2Hz. The proposed improved HHT algorithm is summarized in Figure 4.

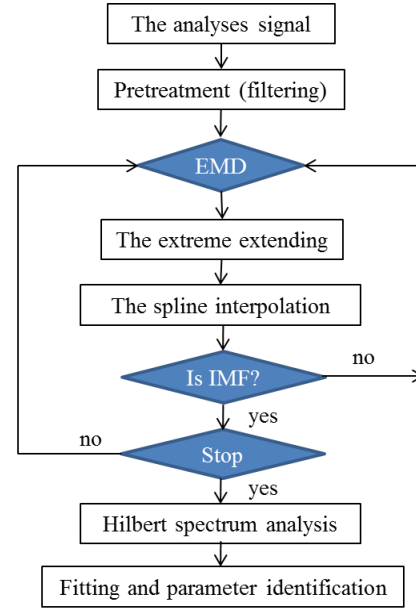


Figure 4. Oscillation mode extraction algorithm

The oscillation signal analysis in power system is normally decomposed into the low-frequency oscillation analysis and sub-synchronous oscillation analysis. The IMF components decomposed by the EMD process should have actual physical meaning. Therefore, the decomposition process must include spline interpolation algorithm (cubic spline interpolation function), endpoint extension algorithm (alternatively direct continuation and mirror extension algorithm, etc.), termination constraint selection, and monotonic constraints (e.g., stop EMD screening process if extreme point is less than 3 and considered residual function is monotonous).

## 3 ALGORITHM EVALUATION

### 3.1 Case I

The effectiveness of the proposed algorithm is used by application on the given oscillation signal in (6). This signal contains power system frequency components including inter-area oscillation (0.1Hz-1Hz), local oscillation (1Hz-2Hz) and noise oscillation (over 2Hz).

$$\delta = 5 \sin(2\pi * 0.1t) + 2 \sin(2\pi * 0.4t) + 1.5 \sin(2\pi * 2t) + 0.5 \sin(2\pi * 5t) + 0.2 \sin(2\pi * 15t) + 15 \quad (6)$$

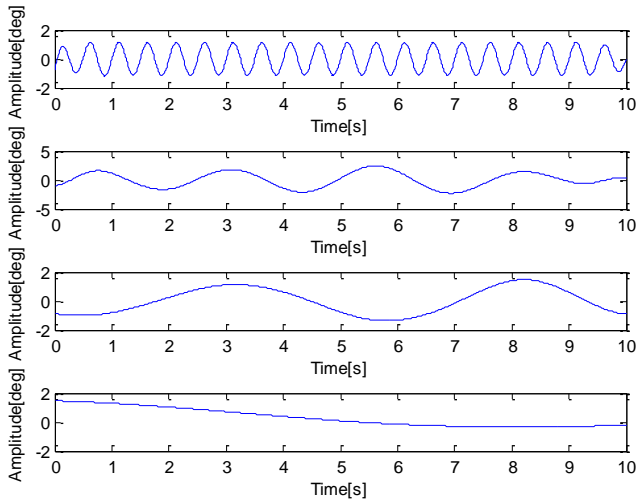


Figure 5. Pre-treatment EMD result (sampling time 0.01s)

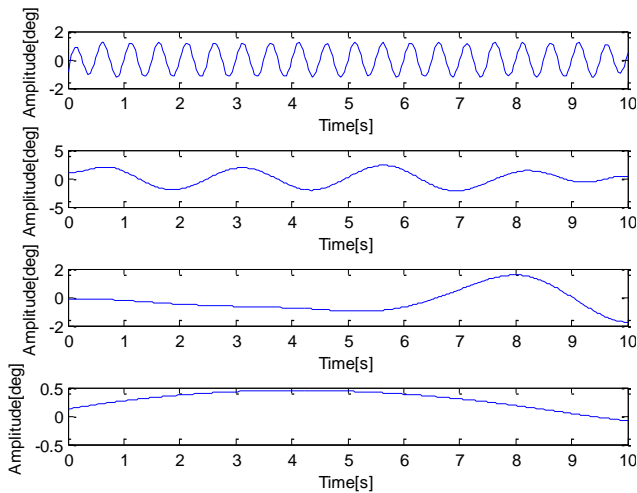


Figure 6. Pre-treatment EMD result (sampling time 0.033s)

This section also addresses the effect of the sampling time applied by the enhanced EMD algorithm. The results are shown in Figures 5 and 6, with sampling time of 0.01s and 0.033s, respectively. Both figures include three oscillation modes and one residue. The frequencies of IMF components from high to low are 2Hz, 0.4Hz, and around 0.1Hz. Comparing two results with different sampling times, it is easily to find that serious distortion happened in low frequency component with sampling time of 0.033s (Figure 6), especially in the lowest frequency of 0.1Hz. The reason of this distortion is due to the Gibbs phenomenon in the performed butterworth filter processing.

It is well known that low frequency oscillation in power system is much more threatening than high frequency oscillation. In order to inhibit the distortion caused by butterworth filter processing, we try to analysis signal without

per-treatment. Figure 7 for sampling time of 0.01s and Figure 8 with sampling time of 0.033s shows the EMD result without per-treatment.

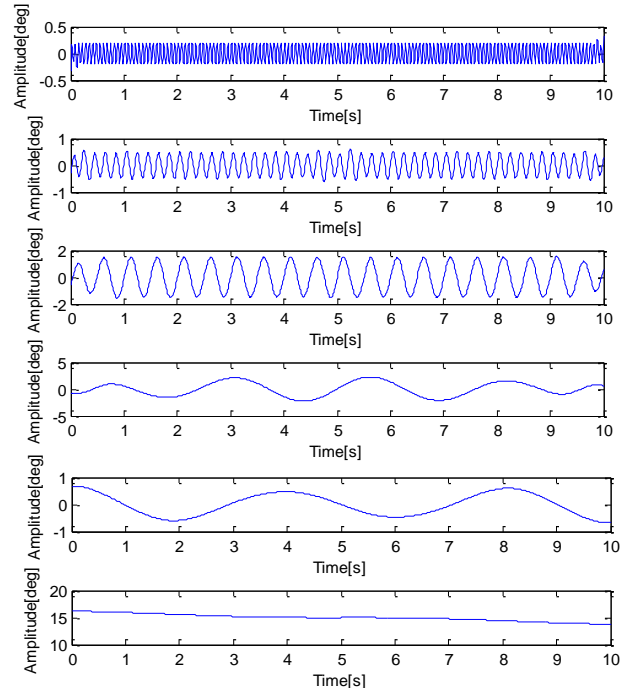


Figure 7. EMD result (sampling time 0.01s)

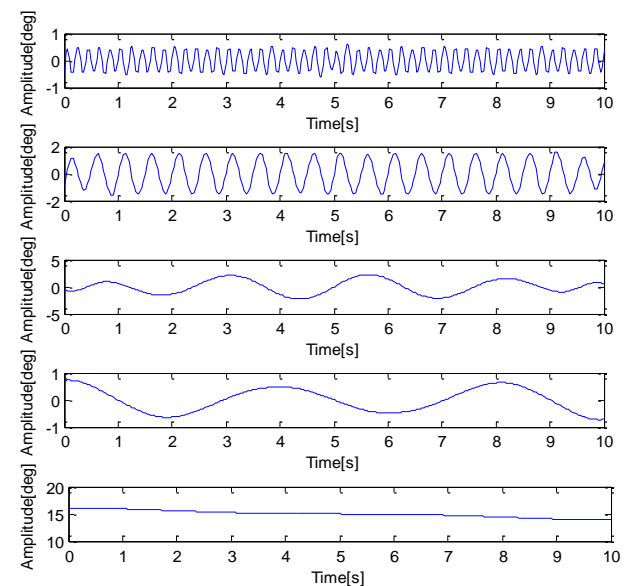


Figure 8. EMD result (sampling time 0.033s)

Figure 7 includes five oscillation modes and one residue in sampling time of 0.01s. The frequencies of IMF components from high to low are 15Hz, 5Hz, 2Hz, 0.4Hz, and around 0.1Hz. The residue DC component is 15. Figure 8 includes four

oscillation modes and one residue in sampling time of 0.033s. The frequencies of IMF components are 5Hz, 2Hz, 0.4Hz, and around 0.1Hz. The residue DC component is 15. It can be found that, regardless the sampling time, there are not serious distortions in the low frequency component. However, high frequency component cannot be observed in the low sampling time cases.

From Figs. 5 and 6, it can be seen that the pre-treatment process can help to cut down noise performance and high frequency components, properly. In the low sampling time cases, pre-treatment process is worked but without high accuracy in low frequency components (see Figs. 7 and 8).

In conclusion, these two comparisons indicate that effects on the analysis results by applying pre-treatment are removed in the high sampling time situation, while in the low sampling time situation, high frequency component cannot be observed but low frequency distortion is happened. If we want to observe low frequency components in high sampling time truly, pre-treatment process is needed. On the contrary, the pre-treatment process should not be applied if we want to observe low frequency components clearly in low sampling time situation.

### 3.2 Case II

In this case, a construct oscillation signal including damping coefficients is considered:

$$x = 3e^{-0.15t} \sin(2\pi * 2t) + 6e^{-0.2t} \sin(2\pi t) + e^{-0.1t} \sin(2\pi * 0.4t) + 15 \quad (7)$$

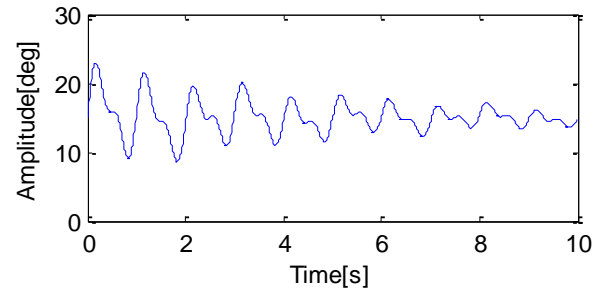


Figure 9. Oscillation signal

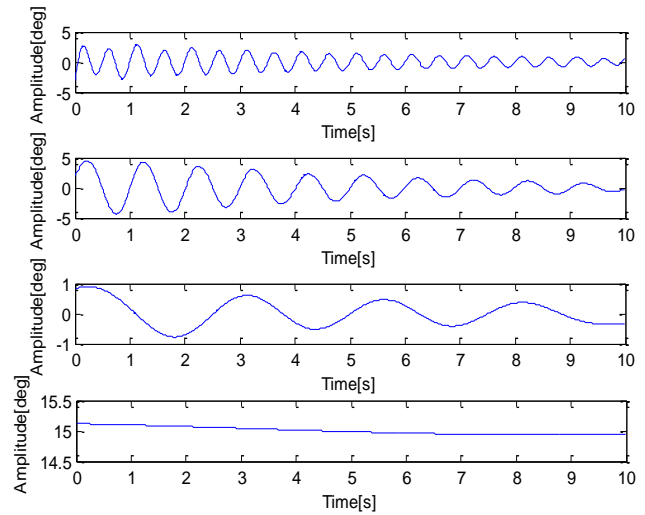


Figure 10. EMD result

Table 1 Parameters identification result

Mode	Frequency		Damping Coefficient		Damping Ratio	
	0.01	0.033	0.01	0.033	0.01	0.033
1	2.0800	2.0766	-0.1490	-0.1516	0.0118	0.0120
2	0.9936	0.9951	-0.1948	-0.1978	0.0310	0.0315
3	0.3917	0.3903	-0.1032	-0.1000	0.0419	0.0407

This oscillation signal shown in Figure 9 contains three decay competent, which damping coefficients are -0.15, -0.2, and -0.1 and the frequencies are 2Hz, 1Hz, and 0.4Hz; with DC component of 15. Then, we can get the IMFs by applying the improved EMD algorithm (Figure 10).

Table 1 shows the identified parameters for every IMF components. We can see that the improved HHT method can estimate the frequencies, damping coefficient and damping ratio of three modes quite accurately. Moreover, the estimation results are not affected by the sampling time.

From the results, it can be concluded that the improved HHT algorithm effectively decomposes the low-frequency oscillation signal mode. Without concerning the sampling time,

the correct oscillation parameters can be obtained from the decomposed modal signal. This is an effective method for low frequency oscillation signal analysis as long as it can be correctly extracted.

### 3.3 Application to Real Data Measurements

Here, the Japan power network is used as a case study. Due to its longitudinal structure of this network, there are some significant low-frequency oscillation modes among whole the system. Recently, a joint research project among some universities in Japan to develop an online wide area measurement of power system dynamics by using

synchronized phasor measurement technique [1] has been presented.

To establish a real WAMS, several PMUs are installed in universities/institutes in different geographical locations of Japan. The PMUs are synchronized by the global positioning system (GPS) signal. This project was started to develop a WAMS covering the whole power system in Japan as a collaborative research called *Campus WAMS*. The PMUs measured voltage phasors in the monitoring location (laboratory) of assigned the university campuses over 24-hour schedules [1].

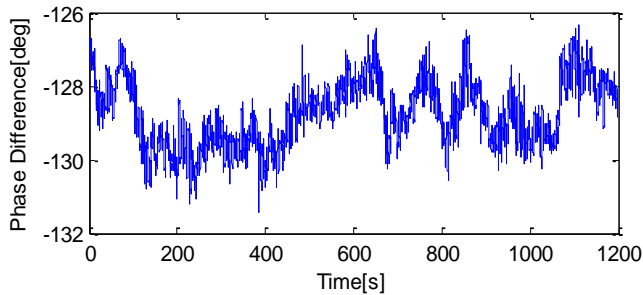


Figure 11. Waveforms of phase difference between Miyazaki University and Nagoya Institute of Technology University stations

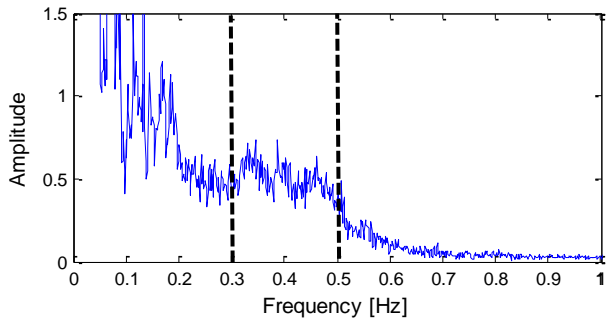


Figure 12. Hilbert marginal spectrum

Figure 11 shows the waveforms of phase difference between Miyazaki University and Tokushima University stations. The HMS is shown in Figure 12. The oscillation mode can be extracted in the frequency range of 0.3Hz to 0.5Hz. Then, the maximum amplitude value is extracted from the oscillation mode frequency range which is shown in Figure 13. Figure 14 describes the extracted oscillation mode. Figure 15 shows the time domain data from the extracted oscillation mode in the maximum point, which can be used to estimate power system oscillation parameters. As a result, the estimated parameters values of power system frequency oscillation are angular frequency (3.4344 rad/s), damping coefficient (-0.06891), and damping ratio (0.0820).

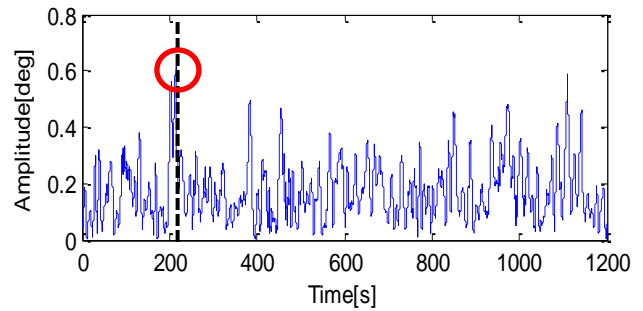


Figure 13. Amplitude of the extracted oscillation mode

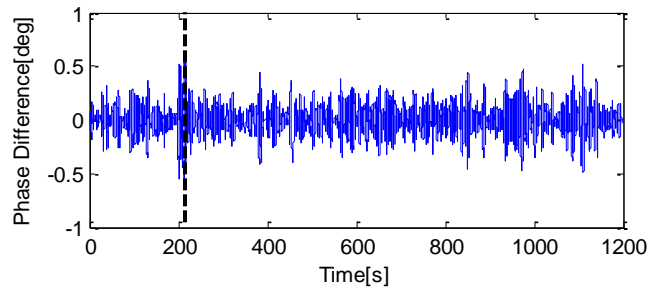


Figure 14. Extract the oscillation mode

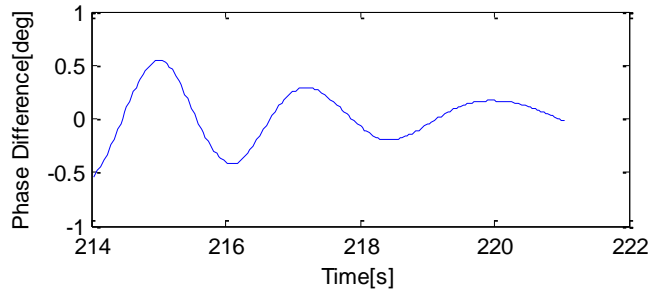


Figure 15. A short time data from the extracted oscillation mode

#### 4 SUMMARY

In recent years, detecting and analyzing the low frequency oscillation phenomenon in power system has become an attractive research topic. For this reason, many experts and scholars around the world have done valuable research works in the field of the power system time-frequency analysis and have developed numerous processing methods on the oscillation signals.

In the present paper, an integrated scheme based on enhanced HHT algorithm for monitoring and detecting low-frequency oscillations is introduced. Several key signal-processing techniques are implemented to improve HHT method. It can determine the center range frequency of the concerned mode automatically and accurately, which is then be used to determine the parameter of the extraction. The extracted frequency mode, damping and mode shape can be detected by this oscillation monitoring system.

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