# Analysis of Non-Stationary and Nonlinear Low-frequency Oscillation of a Realistic Bulk Power System in a Time-Frequency Perspective

LI Peng, Zhang Yong, Liu Hongtao, Zhao Yong, Du Zhaobin

***Abstract*--This paper focuses on study of time evolving dynamic of interarea oscillation modes in a realistic bulk power system – China Southern Grid (CSG). Three time-frequency methods, Ensemble Empirical Mode Decomposition (EEMD), Hilbert Vibration Decomposition (HVD) and Wavelet Transform (WT), are applied and compared in oscillation events of CSG in recent years. It is found that time varying features do exist in some oscillation events of CSG, which can be captured by HVD and WT exactly. EEMD is limited in the scenario due to mode mixing, and traditional Prony method can't give meaningful results at all. It is proposed that HVD, WT and Prony should be complementary to each other during analyzing oscillation events in CSG.**

***Index Terms*—interarea oscillation, Hilbert transform, Walelet Transform.**

## I. INTRODUCTION

Interarea oscillations always threaten the security of interconnected grid like China Southern Grid (CSG) [1]. There are three critical oscillation modes in CSG, ranged from 0.4 HZ to 0.8 Hz. Eight oscillation events occurred in last six years. CSG take many measures to enhance the damping of critical modes, including developing wide-area damping control system, strengthening the management of PSS of generators [2].

Proper understanding of the oscillatory dynamic relies on proper analysis techniques. Traditionally CSG use mode analysis to evaluate the risk of oscillation from power system model and data, and use Prony method to account for ringdown data from PMU/WAMS. These techniques, however, rely on the assumption of linearity and assume that the data are strictly periodic or stationary in time which limits their applicability to bulk power systems.

More and more studies show that oscillation of power systems may display nonstationary characteristics [3-5]. Mode analysis and Prony are not effective in these situations. Recently, nonlinear and nonstationary analysis techniques based on the Hilbert–Huang transform (HHT) [6-8] have been used to analyze data from nonlinear and nonstationary processes. The cornerstone to the whole HHT procedure, empirical mode decomposition (EMD), decomposes a signal into a set of intrinsic mode functions (IMF) that can be associated with different oscillation modes. A problem that has remained existing in the EMD process is the mode mixing. EMD can't separate two components which frequency lies within an octave of each other [9, 10]. Typical frequency of the critical oscillation modes range from 0.4 Hz to 0.8 Hz, and EMD can't separate the modes via IMF if there two or more modes are excited.

To improve the EMD method, the ensemble empirical mode decomposition (EEMD) method has been recently proposed to eliminate mode mixing [11]. Hilbert vibration decomposition (HVD) is another Hilbert-based signal process method which was proposed in 2006 [12, 13]. HVD is dedicated to the same problem of decomposition of non-stationary wideband vibration.

Wavelet Transform (WT) also allows the recognition of dominant modes of oscillation. Moreover, the Complex Morlet WT is able to preserve damping information in the time-frequency domain [14].

This research investigates temporal behavior of CSG's interarea oscillation, with method including EEMD and HVD. WT is also used as a benchmark. All methods are applied on three oscillation events. The results demonstrate that time-varying oscillation do exist in CSG, while HVD together with WT are promising techniques to capture temporal characteristics of oscillation components. EEMD works better than EMD, while it can't separate closely spaced modal components in CSG.

## II. APPROACHES FOR EVOLUATING OSCILLATION BEHAVIOR

Prony is the routine technique of CSG's operation and planning departments to assess the oscillation risk. HVD and EEMD are both novel Hilbert-based method to detect frequency variations through instantaneous frequency, which are proposed in 2006 and 2008 respectively and initially applied in various fields including sound processing and mechanical systems. WT is used to monitoring power system oscillations in recent years.

---

LI Peng is with CSG EHV, Canton (e-mail: li.peng@csg.cn).

Zhang Yong, Liu Hongtao is with CSG Dispatching Center, Canton, (e-mail: zhangyong@csg.cn, liuht@csg.cn).

Zhao Yong is with CSG TRC(zhaoyong@csg.cn).

Du Zhaobin is with South China University of Technology(epdzb@scut.edu.cn)

### A. *Prony*

The Prony analysis is a method that decomposes time-domain signals into a sum of damped sinusoids, each characterized by four parameters: frequency, damping, amplitude and phase. The Prony method is able to deal with the nonlinearities of power systems and can also be applied to field measurements.

### B. *Wavelet Transform*

The Wavelet Transform (WT) represents a valid alternative tool for direct spectral analysis. Wavelet algorithms process data with different scales, stretching or compressing the basic wavelet function, providing a multi-resolution analysis in both frequency and time. The adoption of short time intervals for high-frequency components and long intervals for low frequency components allows doing a complete and efficient spectral analysis without loss of precious information. Wavelet Transform is appropriate for non-stationary and nonperiodic signals analysis. In power systems, the WT have been successfully applied for power quality assessment, fault location, power system relaying applications and electromagnetic transient analysis [15-18].

### C. *Ensemble Empirical Mode Decomposition*

To alleviate the problem of mode mixing in EMD, ensemble empirical mode decomposition (EEMD), an improved method of EMD, is presented by Wu and Huang [9] recently. Essentially, it repeatedly decomposes the signal into IMFs by using the EMD method. During each trial of the decomposition process, white noise of finite amplitude is added to the original signal. The ensemble means of the corresponding IMFs generated from each trial are subsequently treated as the IMFs of the EEMD method. Since white noise is added throughout the entire signal decomposition process, no missing scales are present, and mode mixing is effectively eliminated by the EEMD process.

### D. *Hilbert Vibration Decomposition*

HVD estimates the non-stationary frequency of the largest component as an average function of the instantaneous frequency of the oscillation record, and the corresponding envelope is estimated according to synchronous demodulation. HVD can detect different monocomponents in an oscillation signal with slow varying instantaneous amplitude and frequency.

## III. ANALYSIS OF OSCILLATION EVENT ON AUG. 25TH, 2008

### A. *Prony Result and WT Result*

On the Aug. 25th 2008 CSG experienced an oscillation event, which lasted for 4 min and peak-to-peak amplitude of oscillation in 500 kV tie-line was 129 MW as well as 168 MW in 500 kV transformer at Yanshan. The oscillation was monitored in tie-lines between YN and CSG's backbone grid. It was caused by an oscillatory instability of Wenshan regional grid, which is part of YN Grid and directly connected to CSG's backbone. The oscillation didn't lead to any load loss and generator shedding, and it was damped out after the operator took actions.

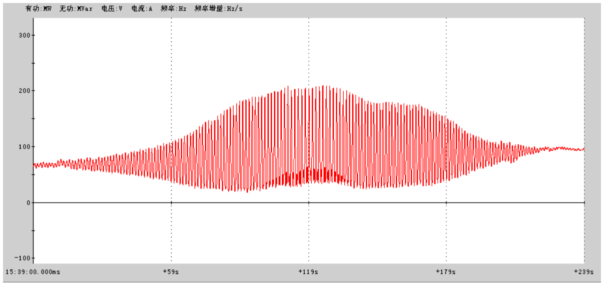

Fig. 1. PMU record of active power of transformer at Yanshan Station

The PMU record in Fig. 1 has been analyzed by means of the Prony analysis. In Tab. 1, results of mode frequency and damping obtained by means of Prony method are shown.

TABLE I
RESULTS OF PRONY ANALYSIS

| Time window | Mode A | | Mode B | |
|---|---|---|---|---|
| | Frequency(Hz) | Damping ratio(%) | Frequency(Hz) | Damping ratio(%) |
| 48-68s | 0.774 | 0.625 | 0.764 | -0.701 |
| 78-98s | 0.733 | -0.179 | 0.689 | 0.204 |
| 108-128s | 0.655 | -0.011 | 0.739 | 1.966 |
| 138-158s | 0.762 | 0.112 | 0.663 | 1.135 |
| 168-188s | 0.820 | -0.229 | 0.620 | 4.256 |

It is shown that damping and frequency of two critical are changing sharply as time window sliding, and the Prony results don't give any clear interpretation of the oscillation process.

The wavelet transform is then used to analysis the same signal of Fig. 1. In Fig. 2, results of wavelet spectral by Complex Morlet are shown. The wavelet chart shows the time-frequency behavior of the oscillation modes hidden into the signal.

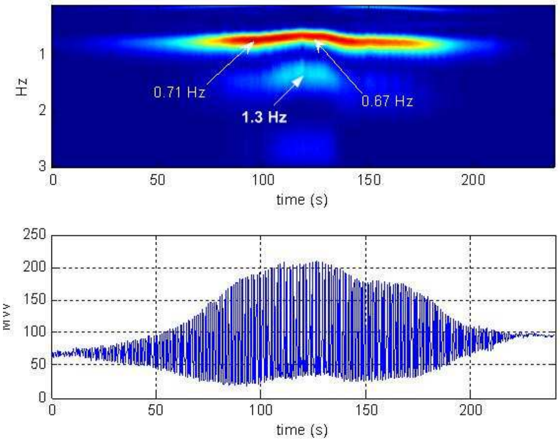

Fig. 2. Wavelet Transform of active power of transformer at Yanshan Station

From the wavelet chart, two main modes of oscillation, respectively around 0.8 Hz and 1.4 Hz, were identified. The first mode, called 'Mode A' hereafter, has the feature of time varying frequency. At the initial phase of oscillation, the frequency of Mode A is 0.8 Hz. The frequency keeps decreasing as the amplitude of oscillation increasing. After 2 min. of the initial phase, the oscillation reveals the largest amplitude as well as the frequency of Mode A reaches the lowest value of 0.67 Hz. Frequency of Mode A goes back to 0.8 Hz as the oscillation damping out. Time evolution of Mode A can't be captured by Prony and other linear methods. Classifying the Mode A is difficult. 0.8 Hz is typical frequency of mode between YN grid and Wenshan Grid, whereas 0.6 Hz is typical frequency of mode between YN and CSG's backbone grid. The phenomenon seems to hint that a regional mode (0.8 Hz) can evolve to an interarea mode (0.6 Hz) gradually and smoothly. The phenomenon is not reported in literatures and should be studied further in future.

The second mode, called Mode B, belongs to the range of local or plant modes of oscillation. The investigation of the event shows that the origin of the oscillation on Aug. 25th 2008 is onset of instability at a small hydro generator at Wenshan area, and eigenvalue analysis shows that the mode frequency is just around 1.4 Hz.

## B. *EMD and EEMD Results*

It is expected that EMD extracts different IMFs corresponding to different oscillation modes. Because the oscillation signal in Fig. 1 consists of closed spaced scales, i.e. the frequencies of two components (o.8 Hz and 1.4 Hz) lie in an octave of each other, mode mixing occurs when EMD is applied to decompose the signal. This is shown in Fig. 3, where the first six IMFs extracted following original EMD algorithm are shown and the two components are mixed together in one IMF.

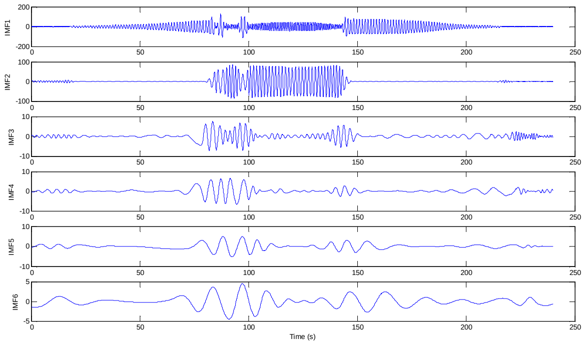

Fig. 3. The decomposition result with EMD

To overcome the problem of mode mixing, EEMD is used to decompose the oscillation signal in Fig. 1. The results are shown in Fig. 4 together with Fourier spectrum of IMFs. The number of ensemble trails is fixed as 100, and the amplitude of the added noise is chosen as 0.01. The signal can be effectively decomposed into three IMFs. Frequency components peaking on the Fourier spectrum indicates whether IMF is a monocomponent. It is seems that results of EEMD is better than EMD. IMF1 corresponds to Mode B around 1.4 Hz basically, while there are a few energy of Mode A mixed in IMF1. Both IMF2 and IMF3 correspond to Mode A from Fourier spectrum. Although EEMD work better than EMD to decompose the oscillation signal, it still recognizes the Mode A as two different IMFs, which may lead to misunderstanding of oscillation process of the event.

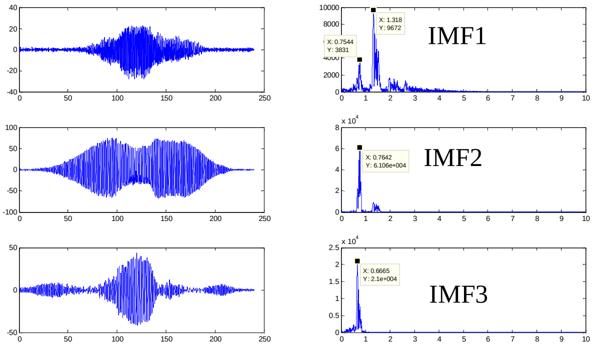

Fig. 4. The decomposition result with EEMD and Fourier spectrum

## C. *HVD Results*

The results of HVD include different components and its Hilbert instantaneous frequency, as illustrated in Fig. 5 and Fig. 6. After application of HVD method we will receive two main components of the oscillation, termed X1 and X2 respectively. The X1 is around 0.8 Hz after it's excited, and the frequency decays to 0.67 Hz after 120 seconds. The X2 is around 1.5 Hz initially, and goes to 1.3 Hz after 120 seconds. It's obvious that X1 corresponds to Mode A in wavelet transform and X2 corresponds to Mode B. The non-stationary process of the oscillation obtained from WT is consistent with that from HVD.

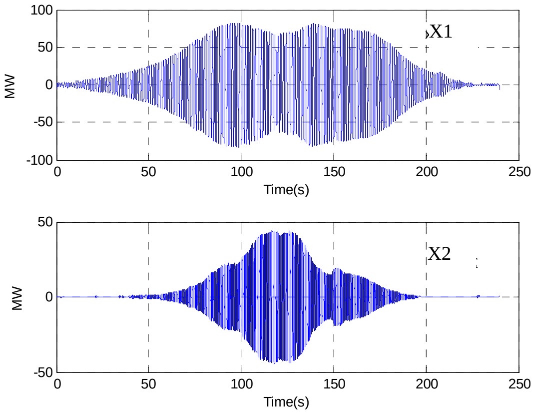

Fig. 5. The decomposition result with HVD

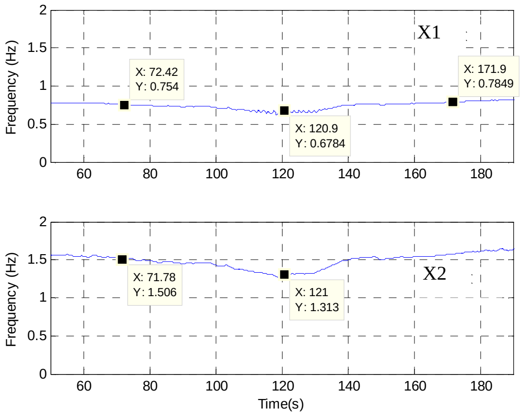

Fig. 6. Instantaneous frequency of separated components from HVD

## D. *Remarks*

It is shown that non-stationary and nonlinear oscillations do exist in a bulk power system like CSG, although the reason behinds the frequency evolution in this event is not clear yet. Traditional tools like Prony used in CSG can't explain this kind of oscillation. WT and HVD can perfectly capture the non-stationary feature and describe the time evolution of the oscillation. EEMD give more meaningful results than EMD, whereas EEMD may separate energy of one mode into two IMFs which leading to misunderstanding of the oscillation.

## IV. ANALYSIS OF OTHER TWO OSCILLATION EVENTS

### A. *Oscillation on Aug. 29th, 2006*

The oscillation event occurred on Aug. 29th 2006 and lasted for 7 minutes. Peak-to-peak amplitude of oscillation in 500 kV tie-line was 200 MW. Fig. 7 gives the PMU record of the event. The oscillation was triggered by instability inside YN grid.

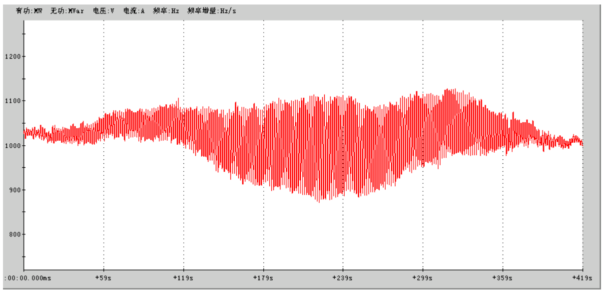

Fig. 7. PMU record of active power in 500 kV line of Luoma

WT is used to analysis the event as shown in Fig. 8. Different from oscillation event is previous section, this event has a stationary process and the frequency fixed around 0.63 Hz.

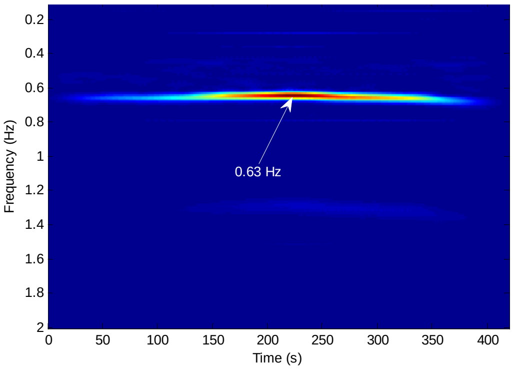

Fig. 8. Wavelet Transform of active power in Luoma line

EEMD is also applied and the first six IMFs are shown in Fig. 9. The first IMF is associated with the critical oscillation mode. Since there is only one critical mode during this oscillation, EEMD gives good result as mode mixing problem avoided. HVD also detects that the oscillation has only one monocomponent, as shown in Fig. 10. Hilbert instantaneous frequency is fixed around 0.64 Hz, as identified by WT in Fig. 8.

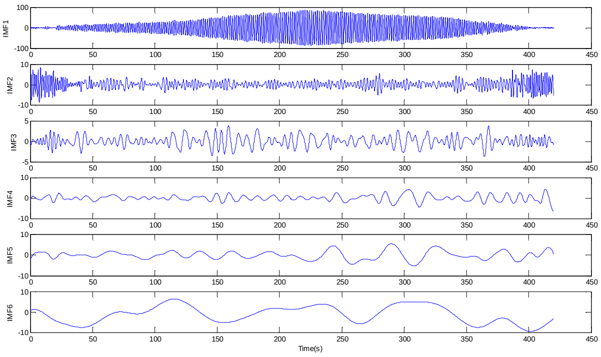

Fig. 9. The decomposition result with EEMD

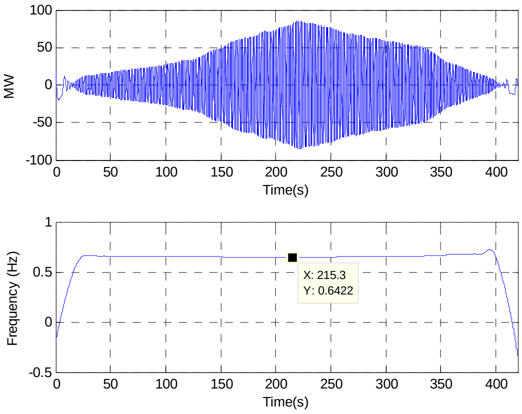

Fig. 10. The decomposition result with HVD and its instantaneous frequency

### B. *Oscillation on Apr. 21st, 2008*

The oscillation event occurred on Apr. 21st 2008 and lasted for 4 minutes. Peak-to-peak amplitude of oscillation in 500 kV tie-line was 30 MW. Fig. 11 gives the PMU record of the event. The oscillation was triggered by a generator losing stability due to governor system.

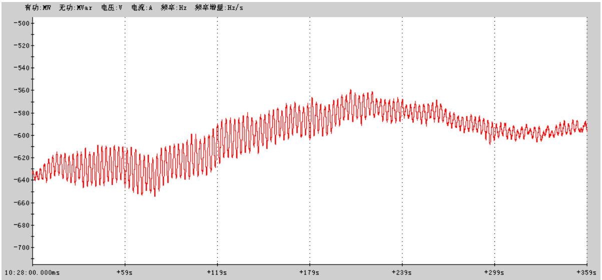

Fig. 11. PMU record of active power in 500 kV line of Wuluo

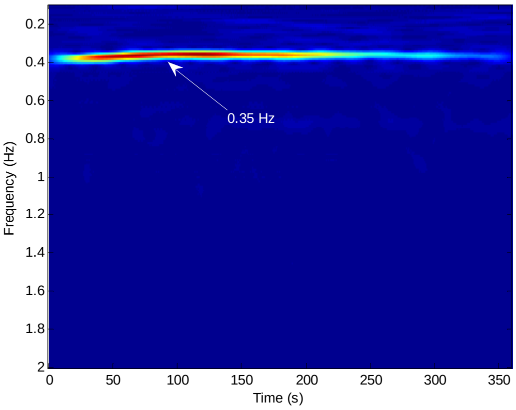

Fig. 12. Wavelet Transform of active power in Wuluo line

Analysis results from WT, EEMD and HVD are illustrated in Fig. 12, Fig. 13 and Fig. 14 subsequently. It's obvious that this oscillation event is the similar with the oscillation in 2006 and has a stationary feature. There is only one mode excited during the event, and the frequency of the oscillation is fixed throughout the event.

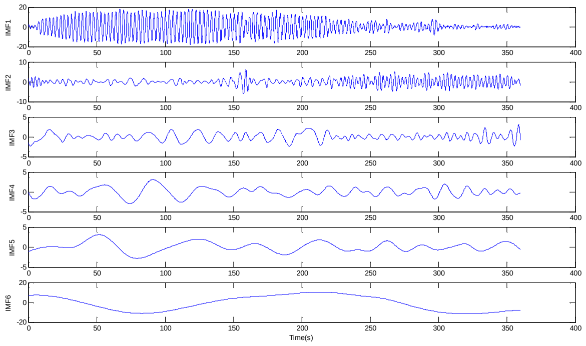

Fig. 13. The decomposition result with EEMD

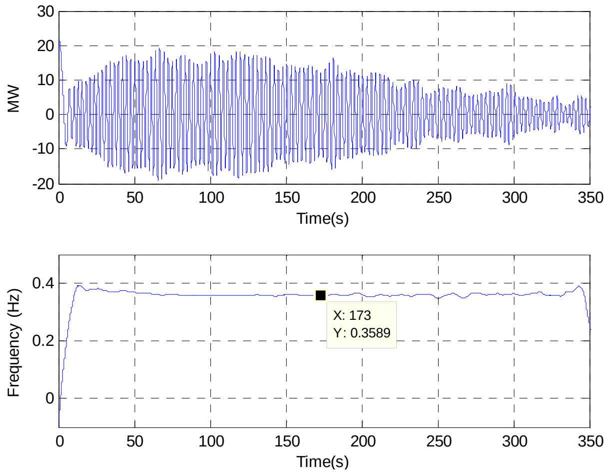

Fig. 14. The decomposition result with HVD and its instantaneous frequency

## V. CONCLUSION

In this paper, several novel signal processing techniques are used to analysis to PMU record of some oscillation events in CSG recently. It is found that oscillations in CSG may have two kinds of characteristics: stationary and non-stationary. The non-stationary one is not being aware of by CSG before, and further study is needed to explore the mechanism behind the frequency evolution.

Traditional tools like Prony don't manage to non-stationary situations. Wavelet transform and HVD are powerful tools to tracing time evolution of oscillation with multiple components exactly, while EEMD mainly is suited to relatively simple situation. It is suggested that WT and HVD should be used as complement to Prony and mode analysis in CSG's oscillation analysis and evaluation.

## VI. REFERENCES

[1] Mao Xiao-ming Zhang Yao Guan Lin Wu Xiao-chen, "Coordinated control of interarea oscillation in the China Southern power grid," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 845-852, 2006

[2] Li Peng, Wu Xiaochen, Lu Chao, et. Al., " Implementation of CSG's Wide-Area Damping Control System: Overview and experience," in *Proc. IEEE Power Systems Conference and Exposition*, pp. 1-9, 2009

[3] J. F. Hauer and J. G. DeSteese, "A Tutorial on Detection and Characterization of Special Behavior in Large Electric Power Systems," Pacific Northwest Nat. Lab., Rep. PNNL-14655. Richland, WA, 2004.

[4] Xue Yusheng, Hao Sipeng, Liu Junyong, et. Al, "A Review of Analysis Methods for Low-frequency Oscillations," *Automation of Electric Power Systems*, Vol. 33, No. 3, pp. 1-8, 2009

[5] S. Liu, A. R. Messina, and V. Vittal, "Characterization of nonlinear modal interaction using Hilbert analysis and normal form theory," in *Proc. IEEE Power Eng. Soc. Power Systems Conf. Expo.*, New York, Oct. 2004.

[6] A. R. Messina, Vijay Vittal, "Nonlinear, Non-Stationary Analysis of Interarea Oscillations via Hilbert Spectral Analysis," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1234-1241, 2006

[7] Dina Shona Laila, Arturo Roman Messina and Bikash C. Pal. A, "Refined Hilbert–Huang Transform With Applications to Interarea Oscillation Monitoring," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 610-620, 2009

[8] A. R. Messina, Vijay Vittal, Daniel Ruiz-Vega, and G Enríquez-Harper, "Interpretation and Visualization of Wide-Area PMU Measurements Using Hilbert Analysis," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1763-1771, 2006

[9] Zhaohua WU, Norden E. HUANG, "Ensemble Empirical Mode Decomposition: A Noise Assisted Data Analysis Method," *Advances in Adaptive Data Analysis.* Vol. 1, No. 1, pp. 1-41, 2008

[10] Gabriel Rilling, Patrick Flandrin, "One or Two Frequencies? The Empirical Mode Decomposition Answers," *IEEE Transaction on Signal Processing*, vol. 56, no. 1, pp. 85-95, 2008

[11] M. Feldman, "Analytical basics of the EMD: Two harmonics decomposition," *Mechanical Systems and Signal Processing*. Vol. 23, pp. 2059-2071, 2009

[12] M. Feldman, "Time-varying vibration decomposition and analysis based on the Hilbert transform," *Journal of Sound and Vibration*. Vol. 295, pp. 518-530, 2006

[13] M. Feldman, "Theoretical analysis and comparison of the Hilbert transform decomposition methods," *Mechanical Systems and Signal Processing*. Vol. 22, pp. 509-519, 2008

[14] Bruno, S., De Benedictis, M., La Scala, M, "Taking the pulse of Power Systems: Monitoring Oscillations by Wavelet Analysis and Wide Area Measurement System," in *Proc. Power Systems Conference and Exposition*, pp. 436 – 443, 2006

[15] S. Santoso, P. Hofmann, "Power quality assessment via wavelet transform analysis", *IEEE Transactions on Power Delivery*, Vol. 11, No.2, pp. 924-930, April 1996.

[16] F. H. Magnago, A. Abur, "Fault location using wavelets", *IEEE Transactions on Power Delivery*, Vol. 13, No. 4, pp. 1475-1480, October 1998.

[17] D. Chanda, N.K. Kishore, A.K. Sinha, "Application of wavelet multiresolution analysis for identification and classification of faults on transmission lines", *Electric Power Systems Research*, Vol. 73, pp. 323–333, 2005.

[18] D. C. Robertson, O. I. Camps, J. S. Mayer, W. B. Gish, "Wavelets and electromagnetic power system transients", *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, pp. 1050-1057, April 1996.

## VII. BIOGRAPHIES

**LI Peng** received his B.E. and Ph. D degree in electrical engineering from Tianjin University, China, in 1999 and 2005, respectively. He then joined CSG (China Southern Power Grid) Technology Research Center. As a senior research engineer in the field of power system operation analysis and control, he is involved in the design of special protection systems and stability analysis. He led research activities in the field of wide-area monitoring and control, and developed the first wide area damping control system of CSG which commissioned in 2008. He then joined CSG EHV Power Transmission Company in 2009 and now responsible for operation, maintenance and study of Protection and Control system of HVDC/UHVDC and HVAC systems.