Ship Power Quality Detection based on Improved Hilbert-Huang Transform

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***Abstract*—Hilbert-Huang Transform (HHT) and its improved method are introduced to detect and analyze power quality in ship power system for the first time, in this paper. The HHT method is used to detect surge current, voltage sag and swell, voltage interruption, etc. of the ship power system. By means of Hilbert-Huang transform, Beginning time, ending time, time-frequency, time-amplitude of the disturbance signal can be obtained accurately.**

Because the fundamental energy is bigger than other single harmonic's, mode mixing occurs when using empirical mode decomposition (EMD) method to decompose harmonic signal in ship Power system, and consequently, each single harmonic component cannot be effectively extracted from the complex original signal. The improved HHT method based on Fourier transform is used to solve the mode mixing problem in this paper. By means of the improved HHT method, complex harmonic signal can be decomposed into single harmonic component, and time-amplitude and time-frequency of harmonics can be obtained accurately.

In MATLAB/Simulink platform, harmonic source model is established according to characteristics of the ship power system to simulate harmonic current signal. And the improved HHT method and wavelet packet transform are applied in analyzing the harmonic current signal. Simulation results show that the improved method has better performance in harmonics analysis than wavelet packet transform.

***Index Terms*—Hilbert-Huang Transform (HHT), Fourier transform (FT), EMD, Power quality detection, Harmonic detection, Ship power system**

I. INTRODUCTION

Ship power system is an independent system with a small capacity. Because of the greater use of impact loads in ship, the power quality problems, such as transient pulse, surge current, voltage sag and swell, etc. are becoming serious. The ever increasing number and power of "polluting" loads (non-linear loads such as time-variant loads, navigation equipment, etc.) connected to the ship power system, causes a significant distortion in the line voltage and line current, which causes serious time-varying harmonic. And its direct consequence is that the sensitive equipment can't run normally, and even worse, it may have a significant impact on the stability of ship power grid which will eventually affect the normal sailing and the normal operation of equipment [1-3]. Therefore, detecting effectively power quality problems and taking corresponding measures are of great significance to the normal operation of ship power system.

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A. Overview of Power Quality Detection Method

The conventional power quality detection methods are as follows: Fast Fourier Transform (FFT) [4], Short Time Fourier Transform (STFT), d-q transform and three-phase instantaneous reactive power theory. FFT is suitable to analyze stationary signal, but is powerless to analyze nonlinear and non-stationary signal. STFT performs satisfactorily for stationary signals whose properties do not change in time. For non-stationary signals, the STFT does not track the signal dynamics properly due to the limitations of a fixed window width [5]. Three-phase instantaneous reactive power theory and d-q transform can be used to detect harmonic and reactive current in real-time. The former's disadvantage is that the detection results contain larger error when the voltage contains harmonic [6, 7]. The latter's defect is that the test precision tends to be easily affected by the change of apparatus' parameters [8].

Other methods have been developed, such as wavelet analysis, which handles time-frequency resolution in a more realistic way [9]. A wavelet is a function localized in both time and frequency. Furthermore, wavelets are band-limited, i.e. they are composed of not one but a relatively limited range of frequencies [10]. Wavelet analysis is nowadays widely used in power quality detection. This technique forces the decomposition of the signal into a fixed set of basis functions, although a more flexible and sophisticate done than mere sine-like functions. The choice of a specific wavelet (e.g. Morlet or Daubechies) is critical and may significantly affect the results of the analysis.

B. Overview of HHT and Its Improved Method

Hilbert–Huang transform (HHT) is a recently developed time–frequency method of signal analysis that has good performance in analyzing non-linearity and non-

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stationary. The HHT method is put forward by Huang, in 1998 [11], which consists of two parts: empirical mode decomposition (EMD) and Hilbert spectral analysis. Despite being empirically defined, HHT has repeatedly shown the potential to yield improvements over traditional time-frequency analysis methods. Unlike Fourier transform and wavelet analysis, HHT does not rely on a pre-defined set of basis functions. Instead, it searches for intrinsic oscillatory modes contained in the signal. These oscillatory modes, called intrinsic mode functions (IMFs) are the result of the EMD, and they can show variable amplitude and frequency across time [12].

Firstly, EMD is applied to decompose the non-stationary signals into several intrinsic mode functions (IMFs). Secondly, Hilbert transform is carried out to each IMF component to get the instantaneous frequencies and instantaneous amplitudes. Finally, the instantaneous frequencies and amplitudes are reassembled to obtain the Hilbert spectrum. In signal analysis, time scale and the energy distribution along with the time scale are the two most important parameters to signals. The EMD method can be used to decompose the complex signals into a number of IMF components. Since the decomposition is carried out according to the signals itself, the number of resulting IMF components is usually limited and each IMF component can reflect the intrinsic and real physical information of the signals. Therefore, the Hilbert-Huang transform has been widely used in many fields, such as the analysis of EEG oscillations [13], storm waves [14], damage detection [15], and the fault diagnosis of machines, etc. [16, 17].

In this paper, Hilbert-Huang transform [11, 18, 19] and its improved method are applied for analyzing the ship power quality, which is a new method used to analyze nonlinear and non-stationary signal. It is regarded as a huge breakthrough in linear and steady spectrum analysis which is based on Fourier transform.

Because the fundamental energy is stronger than other single harmonic's, mode mixing occurs by using EMD directly to decompose the harmonic signal, and all single harmonic components cannot be effectively decomposed. In this paper, the improved method, HHT method based on Fourier transform, is used to overcome the mode mixing problem. Firstly, signal is filtered according to Fourier spectral. Then, the output signal through band pass filter is decomposed by EMD method, and accurate IMF components are obtained. Lastly, Hilbert transform is used to transform the IMF components. Complex harmonic signal can be decomposed into single harmonic component by this improved HHT method, and the time-amplitude and time-frequency of harmonics can be obtained accurately. The improved HHT method effectively solves the problem that local characteristics of the signal can't be obtained by Fourier transform, and that the mode mixing occurs when EMD is directly used on harmonic analysis.

HHT and its improved method provide a new approach in ship power quality analysis.

II. HILBERT-HUANG TRANSFORM

A. EMD Method

The empirical mode decomposition is the first step of Hilbert-Huang transform. EMD method separates a time-series into a finite number of its individual characteristic oscillations. The essence of EMD is to identify the intrinsic oscillatory modes by their characteristic time scales in the data and then decompose the data accordingly. Each series is named intrinsic mode function (IMF), which gives prominence to the different local character of original data.

In order to define a meaningful instantaneous frequency (IF), each IMF has to satisfy the following two conditions [11]:

(1) In the whole data set, the number of extrema and the number of zero crossing must either equal or differ at most by one.

(2)At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

However, most time series do not meet these criteria. At any given time, a signal may involve more than one oscillatory mode. Therefore, it is necessary to extract the oscillatory modes from the signal, by means of the EMD procedure, which is implemented by an algorithm comprising the following five steps:

A general overview of EMD and its implementation is presented in [12], but EMD method will be briefly summarized here. Given a source signal *x (t)*:

1) Identify all local maxima and minima of signal *x (t).*

2) Interpolate between all minima (resp. maxima) to yield an envelope $e_{min}(t)$ (resp. $e_{max}(t)$)

3) Compute the mean envelope

$$m(t)=\left[e_{min}(t)+e_{max}(t)\right]/2 \tag{1}$$

4) Extract the detail $c_i(t)$

$$c_i(t)=x(t)-m(t) \tag{2}$$

5) Check if $c_i(t)$ satisfies the conditions of IMF, if not repeat steps 1-4 with $c_i(t)$ as the input signal $x(t)$, if so, $c_i(t)$ is the *i*th IMF.

So the given signal can be reconstructed by $c_i(t)$.

Based on the above algorithm, the original signal x*(t)* can thus be expressed as follows:

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

where *n* is the number of IMFs, r_n is the final residue which can be either the mean trend or a constant, and functions $c_i(t)$ are nearly orthogonal to each other, and all have zero means. By means of EMD method, signal is decomposed into *n* fundamental components, each with distinct time scale. More specifically, the first component has the smallest time scale, which corresponds to the fastest time variation of data. Since the decomposition is based on the local characteristic time scale of the signal

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to yield adaptive basis, it is applicable to non-linear and non-stationary data in general and in particular.

B. Hilbert Transform

The second step of the HHT is Hilbert transform. After the decomposition step, Hilbert transform is utilized to defined instantaneous frequency. Given an IMF, $c_i(t)$, its Hilbert transform, $H[c_i(t)]$, is defined as

$$H[c_i(t)] = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{c_i(\tau)}{t-\tau}d\tau \tag{4}$$

And an analytic signal $z_i(t)$ is defined as:

$$z_i(t) = c_i(t) + jH[c_i(t)] = a_i(t)e^{j\phi_i(t)} \tag{5}$$

Where $a_i(t)$ and $\varphi_i(t)$ are the amplitude and phase, respectively. In Eq. (5), $a_i(t)$ and $\varphi_i(t)$ are defined as following:

$$a_i(t) = \sqrt{c^2{}_i(t) + H^2[c_i(t)]} \tag{6}$$

$$\phi_i(t) = arctan\frac{H[c_i(t)]}{c_i(t)} \tag{7}$$

Therefore, the instantaneous frequency $f_i(t)$ can be given by:

$$f_i(t) = \frac{1}{2\pi}\frac{d\phi_i(t)}{dt} \tag{8}$$

Finally, by means of the combination of the amplitude and the derivative of the phase (i.e. the instantaneous frequency) of each component, it is possible to obtain the resulting amplitude, time, and frequency representation of the original series:

$$x(t) = Real\sum_{i=1}^{n} a_i(t)e^{j\phi_i(t)} \tag{9}$$

Here the residue, r_n is omitted because it is either a monotonic function or it might be smaller than the pre-determined threshold.

III. Transient Power Quality Analysis Based on HHT Method in Ship Power System

A. Surge Current in Ship Power Grid

Surge current is caused when electric equipment start or the operation condition is changed, which is a typical transient current. The surge current will reach its maximum in a few milliseconds, and then drop back to rating in a few milliseconds to a few minutes, which is a common power quality problem whose influence is huge.

Figure 1 (a) shows the current signal $s(t)$, which a surge current occurs in 336.4 ~ 336.45s, and its maximum amplitude is 196.7A. In Eq. (3), by means of EMD method, the first IMF, c_1 is obtained which contains the mutation information of the signal $s(t)$. In Eq. (5), the instantaneous frequency and amplitude of c_1 are obtained, which are respectively shown in figure 1 (b, c). Figure 1 (b) shows that the beginning time and ending time of surge current is 336.4s and 336.45s (without error). In figure 1(c), the maximum amplitude of surge current is 198.3A (error rate being about 0.8%). Simulation results show that the detection accuracy of surge current base on HHT method is high.

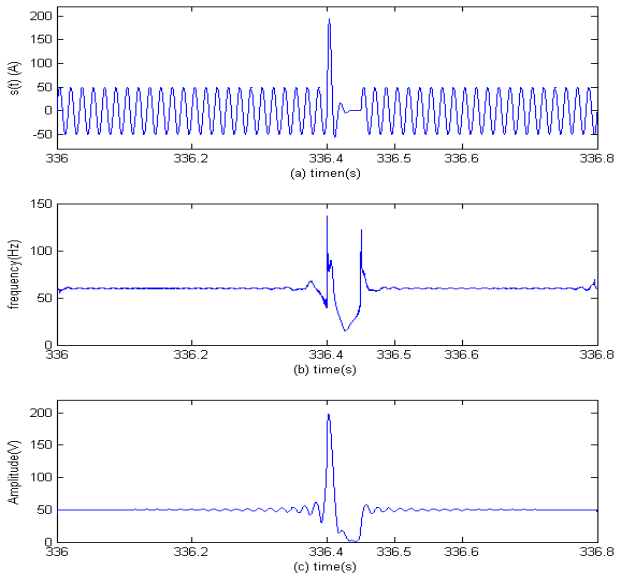

Figure 1. Surge current analysis base on HHT in ship power grid

B. Voltage Sag and Swell in Ship Power Grid

Voltage sag is the most severe power quality events, and about 80% of the power quality problems caused by voltage sags. A variety of short-circuit fault, large motor starting, transformer and capacitor switching, etc. can lead to voltage sags. Cut off large equipment that causes voltage sags.

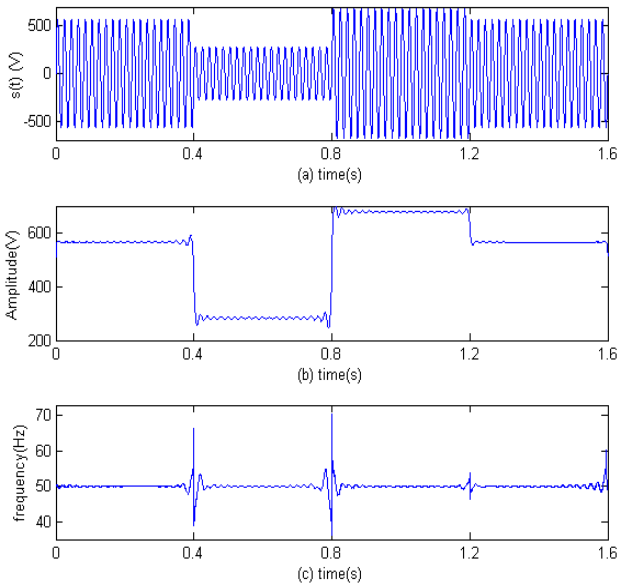

Figure 2. Voltage sags and swells analysis based on HHT in ship grid

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In figure2 (a), *s(t)* is the voltage sag and swell signal in a ship power system and its sampling frequency is 3200Hz. Here, *s(t)* is an IMF itself, because it meets the conditions of IMF. Figure2 (b) shows the instantaneous amplitude. From 0.4s to 0.8s, signal's amplitude is 282.8V, and from 0.8s to 1.2s, signal's amplitude is 681V,while during other periods, its amplitude is 566.1V. Instantaneous frequency is shown in figure 2 (c) and it mutates in 0.4s, 0.8s and 1.2s. According to the mutation frequency, we can accurately locate the beginning and ending moments of disturbance. Seen from the above-mentioned statistics, voltage sag occurs during 0.4~0.8s, and voltage swell occurs during 0.8~1.2s. This method is also applicable to detect the voltage interruption.

C. Voltage Interruption in Ship Power Grid

In figure3 (a), *s(t)* is the voltage signal whose sampling frequency is 3200Hz. Instantaneous frequency is shown in figure 3 (b), and it mutates in 611.5s and 612s. During 611.5~612s, signal's frequency is 0, and during other periods, its frequency is 60Hz. The Instantaneous amplitude is presented in figure2 (c). During 611.5~612s, signal's amplitude is 0, while during other periods, its amplitude is 564.1V. Therefore, voltage interruption occurs during 611.5~612s.

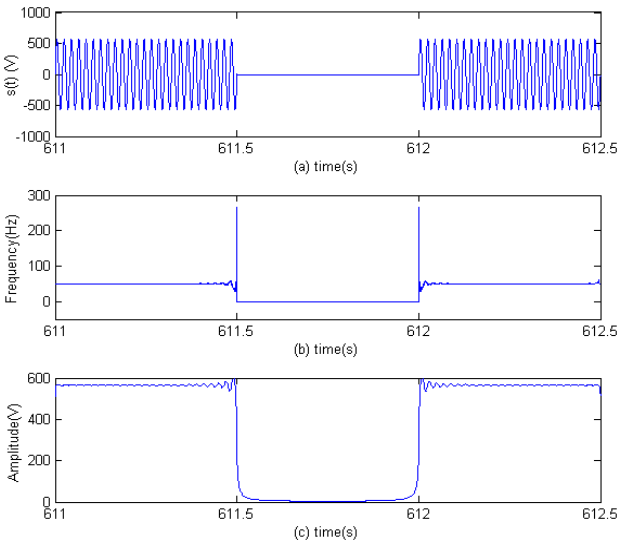

Figure 3. Voltage interruption analysis based on HHT in ship grid

D. Transient Oscillation Signal Analysis based on HHT

The phenomenon that two systems with parallel operation are out of sync is known as oscillation. Oscillation caused by many reasons, mostly due to removal of failure for too long. There are other reasons to cause oscillation, such as fault tripping, disconnect the line or equipment in weak link system.

Simulated transient oscillation signal is as follows:

$$s(t)=\sin(2\pi 60t) \qquad 0\le t\le 0.125\text{s}, 0.13<t\le 0.4\text{s}$$

$$s(t)=\sin(2\pi 60t)+0.5\sin(2\pi 600t) \qquad 0.125<t\le 0.13\text{s}$$

Figure4 (a) shows the oscillation signal *s(t)* whose sampling frequency is 3200Hz. By means of EMD, the first IMF *c1* is obtained which is shown in figure 4 (b). Instantaneous frequency is shown in figure 4 (c), and it mutates in 0.125s and 0.13s.

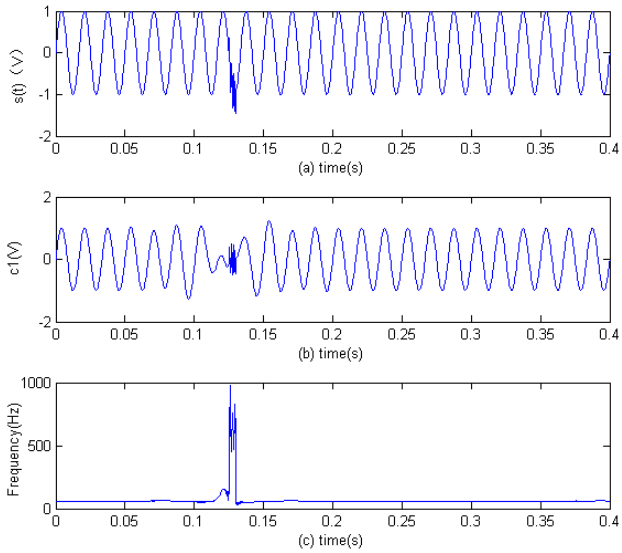

Figure 4. Transient oscillation signal analysis based on HHT

In order to extract the oscillation signal, a high-frequency signal $h(t)=0.025\sin(2\pi 720t)$, is added to the original signal *s(t)*, which is shown in figure 5 (a), and its first IMF *C1* is shown in figure 5(b). Figure 5(c) presents the second IMF. $C1-h(t)$ is the transient oscillation signal shown in figure 5(d), and its Instantaneous amplitude is presented in figure 5(e). It is can be seen that transient oscillation signal can be accurately extracted based on HHT method.

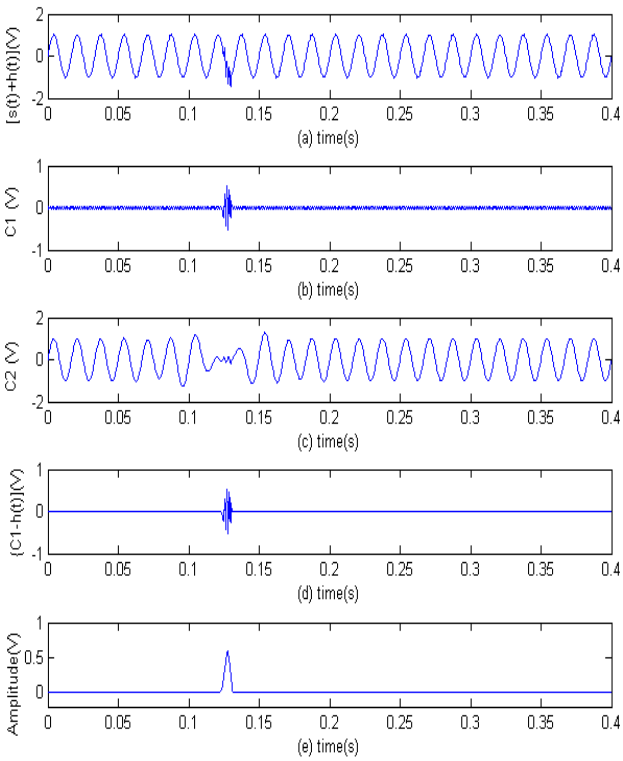

Figure 5. Transient oscillation signal extraction based on HHT

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IV. Harmonic Analysis based on HHT in Ship Power System

A. Harmonic Analysis based on HHT in Ship Power System

In the actual power system operation, because the load is changing, the amplitude, frequency and phase angle of three-phase voltage will change accordingly, and with the use of a large number of non-linear load, the waveform of voltage and current in ship power grid are distorted, which lead to the occurrence of harmonic current and harmonic voltage. Harmonic current and harmonic voltage make the power quality drop, seriously affect the normal operation of electrical equipment in the same power line, also cause interference with communications systems and equipment. Therefore, effective detection and suppression of harmonic become particularly important to the normal operation of ship power system.

Simulated harmonic current i*(t)* , is as follows:

$$\begin{aligned} i(t) &= 52\sin(2\pi 60t) + 18\sin(2\pi 180t + 50) + 15\sin(2\pi 250t + 70) \\ &+ 8\sin(2\pi 300t + 30) + 5\sin(2\pi 420t + 50) + 3\sin(2\pi 540t + 40) \\ &+ 1.8\sin(2\pi 660t + 90) \\ &0 \le t \le 0.2 \\ i(t) &= 52\sin(2\pi 60t) + 18\sin(2\pi 180t + 50) \qquad 0.2 < t \le 0.4 \end{aligned}$$

Current *i(t)* is shown in Figure 6(a), and its sampling frequency is 3200Hz. By means of EMD method, its IMF components, *c1~c7*, are obtained which is shown in figure 7, and r is the residue. It can be seen that mode mixing occurs during 0.1~0.2s, and *3*rd, *25/6*, *5*th, *7*th, *9*th and *11*th harmonic component are not effectively decomposed out because the fundamental energy is stronger than other single harmonic energy.

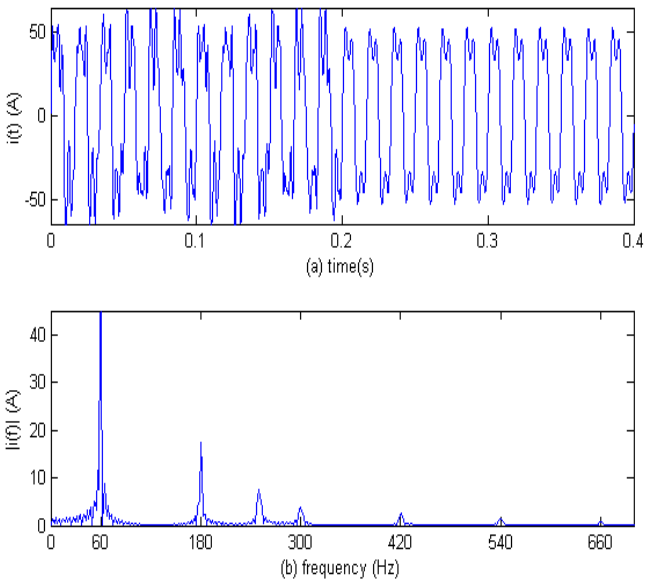

Figure 6. Harmonic current and its FFT spectrum analysis

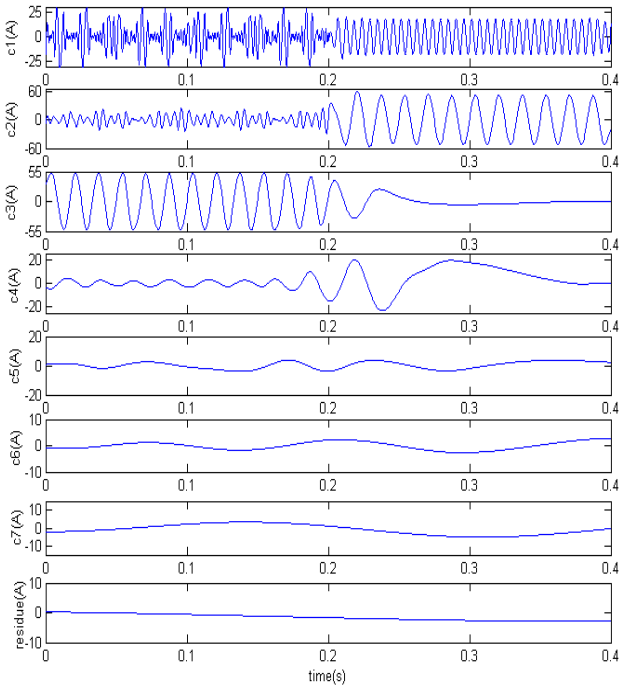

Figure 7. IMF components of harmonic current by using EMD directly

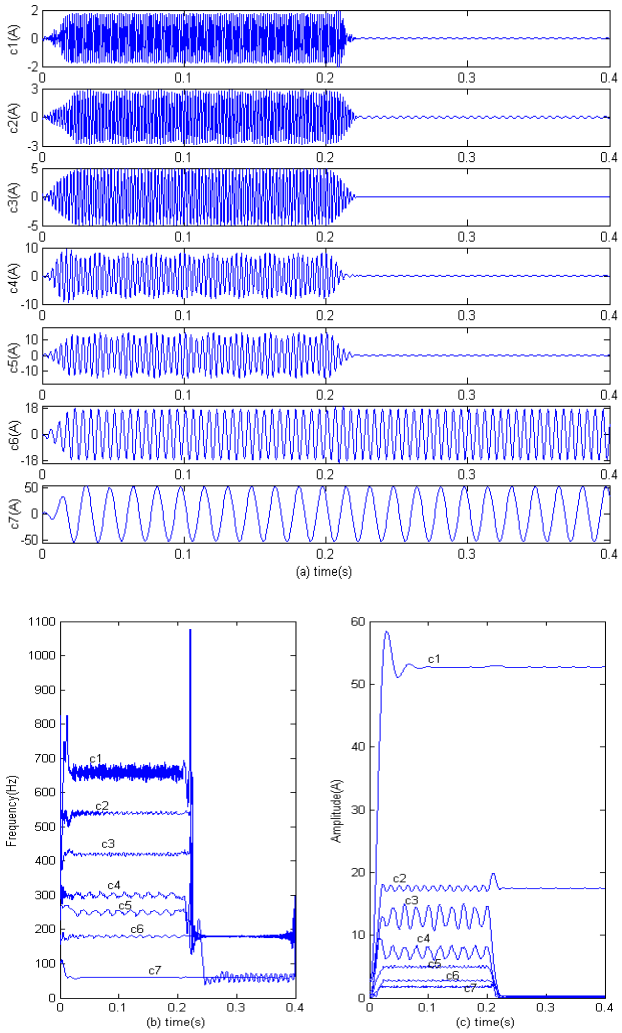

Figure 8. Harmonic current analysis base on improved HHT method

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The improved method, Hilbert-Huang transform based on Fourier transform, can eliminate mode mixing. The steps of the improved method are as follows:

1) Fourier spectrum of signal $i(t)$ is presented in Figure 6 (b), which is obtained by using Fourier transform.

2) According to frequency spectrum, select the appropriate band pass filter to filter the signal $i(t)$.

3) Use EMD method to decompose the filtered signal, and the IMF components are obtained, as is shown in figure 8 (a).

It should be noted that we have retained only the components that have physical meaning in figure 8 (a).

Figure 8 (b) presents the instantaneous frequency of IMFs , $c_1 \sim c_7$. The frequencies of $c_1 \sim c_7$ are *660, 540, 420, 300, 250, 180* and *60Hz* respectively, during *0.1~0.2s*. Figure 8(c) shows the instantaneous amplitude of the IMFs. The results are consistent with the simulated signal. In figure 8, it can be seen that end effect occurs in the border of the signal, which can be eliminated by application of the endpoint extension methods.

Figure 9 presents the result of the wavelet packet analysis of the harmonic current, $i(t)$, using *db10* wavelet with *4* layers decomposition. *RP (4,0)* - Reconstructed packet (4,0) - is the fundamental with *60Hz*, and *RP (4,1)* is the 3rd harmonic whose frequency is *180Hz*, *RP (4,2)* is the harmonic whose frequency is *250Hz*, ... , *RP (4,6)* is the *11td* harmonic whose frequency is *660Hz*.

Obviously, the improved HHT method based on Fourier transform has better effect in analyzing harmonic than the wavelet packets.

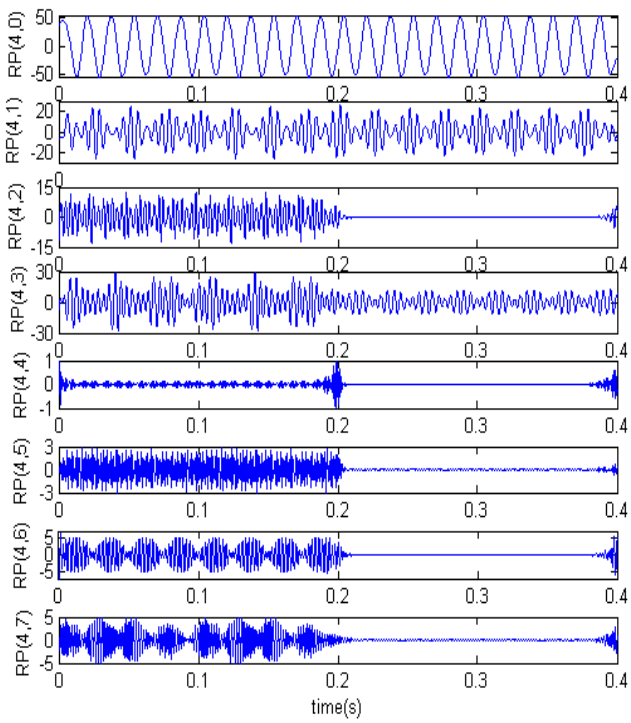

Figure 9. Harmonic current analysis based on wavelet packet

B. Harmonic Source Model in Ship Power System and Its Harmonic Analysis based on HHT

Harmonic source model is established in MATLAB/Simulink platform according to characteristics of the ship power system, which is shown in figure 10. The voltage of three-phase programmable power supply is 400, whose frequency is 60Hz. In 0.11s, the *3*rd and *5*th harmonics invade the power system. Fully-controlled three-phase bridge rectifier circuit with impedance inductive load is used as the harmonic source to obtain simulation signal. Here, harmonic current of scope 3 in figure 10 is the simulation signal, which is a phase current of load-side, as shown in Figure 11 (a), and its sampling frequency is 20000Hz. Mode mixing occurs if the signal is decomposed by using EMD method directly. Here, the improved method, HHT based on Fourier transform, is applied to solve the problem above.

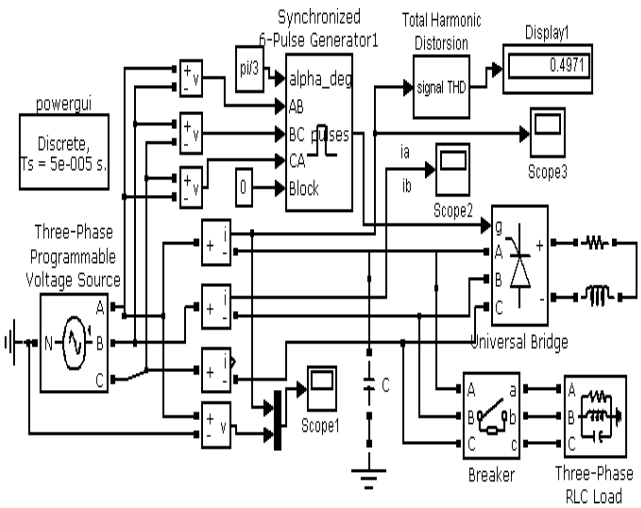

Figure 10. Harmonic source model of ship power system

Fourier spectrum of the current in Scope3 is shown in figure 11 (b), which contains *5*th, *7*th, *11*th, *13*th, *17*th, *19*th, *21*st and *23*rd harmonic component. It can be seen that the amplitude of the fundamental is far bigger than other single harmonic component's. The IMFs obtained by using the improved method, are shown in figure 11(c), which only contains the components with physical meaning and omits residue. The instantaneous frequency is shown in figure 11(d), and we can clearly see that the frequency of each IMF changes over time. The first IMF,c1, is with the highest frequency of 1500Hz, which corresponds to the *23*rd harmonic component. The instantaneous frequency of *c1* has mutated in 0.11s, due to the intrusion of harmonics into the ship power system at this time. The second IMF, *c2*, is the 21st harmonic. The third IMF, *c3*, is the 19th harmonic, and *c9* is the fundamental whose frequency is 60Hz.

Harmonic current analysis based on wavelet packet is shown in Figure 12. Here, we choose db10 wavelet with 6 layer decomposition. Obviously, the wavelet packet is not an ideal method to analyze harmonic. Wavelets are band-limited, so harmonic components are not extracted effectively. The improved HHT method based on Fourier

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transform has better effect in analyzing harmonic than the wavelet packets.

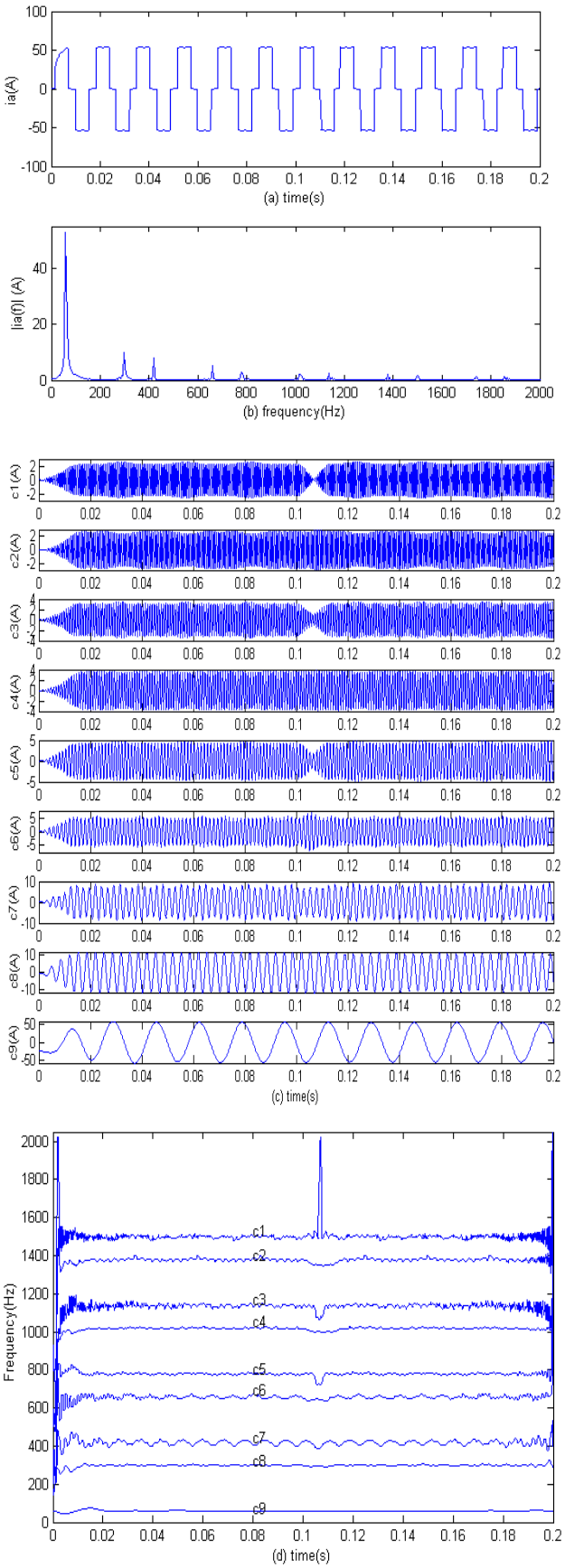

Figure 11. Harmonic analysis based on improved HHT method

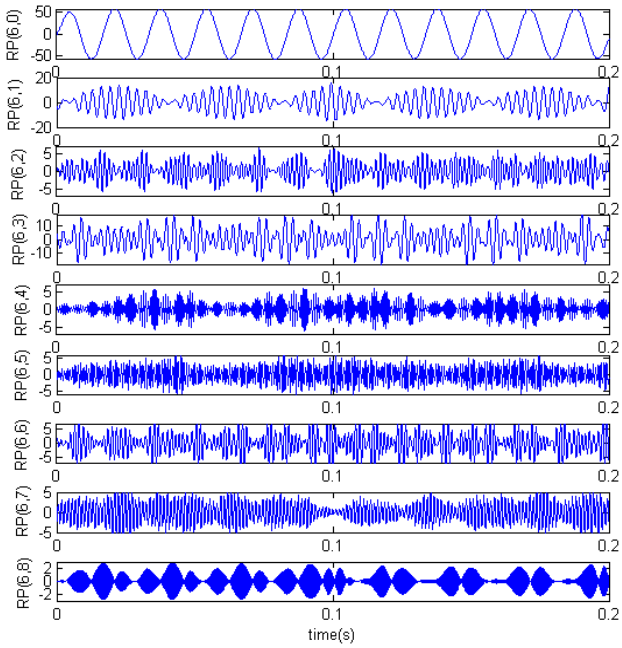

Figure 12. Harmonic analysis based on wavelet packet

V. Conclusion

The signal processing method based on Hilbert-Huang transform is considered a great breakthrough of linear and stationary spectrum analysis based on Fourier transform. In this paper, EMD method is used to decompose the time series into a set of IMFs. Then, Hilbert transform is applied to the IMFs to obtain the signal's time-frequency-amplitude spectrum. Unlike the decomposition of Fourier transform which is based on cosine function, Hilbert-Huang transform is adaptive, and has good locality. Therefore it has a good effect in analyzing nonlinear and non-stationary signal, and it could analyze linear and stationary signal, too.

In this paper, HHT method is introduced to detect and analyze the power quality in ship power system, for the first time. This method is applied in detecting transient power quality, such as surge current and voltage sag and swell, voltage interruption, and so on. The beginning time and ending time, time-frequency and time-amplitude of the transient disturbance can be accurately detected based on HHT method.

The improved method, Hilbert-Huang transform based on Fourier transform, can effectively avoid the mode mixing. By means of the improved method, all single harmonic components can be accurately decomposed from the complicated harmonics, and time-amplitude and time-frequency of harmonics are also obtained.

Compared with the Fourier transform, instantaneous frequency and instantaneous amplitude can be obtained by HHT and its improved method. Compared with the wavelet packet transform, the improved HHT method has better effects in analyzing harmonics in ship power system.

In conclusion, HHT and its improved method have good performance in analyzing power quality in ship power system.

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