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Application of EEMD-HHT Method in Fault Signal Analysis of Electric Power System in LNG Carriers

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Abstract

The unit capacity of the LNG carriers propulsion motor is almost equal to that of the electric generator, and random changes of this kind of high power load are tend to cause faults and system crashes. Therefore, the effective extraction of transient signal feature information is the core of fault diagnosis in electric propelling ship power system. Based on the Ensemble Empirical Mode Decomposition (EEMD), the method of Hilbert-Huang Transform (HHT) has solved the mode mixing problem which exists when the method of Empirical Mode Decomposition (EMD) is used during the process of fault signal diagnosis in electric power system, and HHT can successfully get the accurate position and feature information extraction of the fault time. Digital simulation analysis indicates that the method is correct and effective.

***Keyword**: Electric propelling ship, Feature extraction, Ensemble Empirical Mode Decomposition (EEMD), Hilbert-Huang Transform (HHT), Fault diagnosis*

1. Introduction

With so many advantages such as environment friendly, electric propulsion can improve the ship's maneuverability, and it now has become a mainstream of power solutions in medium-sized LNG (liquefied natural gas) carriers. But as the time goes by, the LNG carriers are developed into larger scale and higher safety level of transportation, and the electric power system is becoming more and more powerful and complex, which brings increasingly severe problems of its stability and reliability. Compared with the land infinite power system, the electric power system of electric propelling LNG carriers belongs to the independent power system with smaller capacity. Compared with the electric generator capacity, the locked rotor of propulsion motor can produce bigger impulse current, causing voltage sag. In addition, the power grid transmission distance is so short that the short-circuit current could influence the electric generator and the whole power system whenever there happens a short circuit fault. Thus, how to timely and accurately obtain the dynamic operation state of LNG carriers' power system, and how to predict and diagnose potential and existing fault to guarantee the continuous power supply when the fault happens has become an urgent problem to be solved.

When a fault occurs in ship power system, it is quite difficult for generators to keep a constant frequency and voltage, which will cause the transient process of the dynamic changes. At this specific moment, transient signal contains abundant information of power system characteristics, because of which, it is critical to ensure the completion of the identification, processing and feature extraction of transient signal when diagnosing fault from power system. At present, the most common method using in the field of transient signal analysis in power system is the Fourier Transform (FT) and Wavelet Transform (WT). Although the Fourier Transform can get higher resolution in its frequency domain, it has no resolving power in time domain, which leading to its lack of non-stationary transient signal detection. While the Wavelet Transform can obtain high

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resolution both in time and frequency domain, but the basic function needs to be determined in advance by human beings, which is directly related to the signal decomposition effect. In other words, the practicality and optimality of decomposition cannot be guaranteed. [1]

The Hilbert–Huang Transform (HHT) is a way to decompose a signal into so-called intrinsic mode functions (IMF), and obtain instantaneous frequency data. It is designed to work well for data that is non-stationary and non-linear. It is an adaptive signal decomposition method, proposed by Chinese American Huang N.E. in 1996 in the basis of the thorough research to the concept of instantaneous frequency. [2] This method not only draws the advantage of multivariate analysis from WT, but also avoids the difficulty in selecting wavelet base, and it has good local adaptability as well. So far, HHT method has achieved certain positive results in several fields including power quality analysis, condition monitoring [3-5] and mechanical signal analysis [6,7], *etc*. The HHT method contains two parts, the first part is the Empirical Mode Decomposition, referred to as EMD; the second part is the Hilbert Spectrum Analysis, referred to as HSA. While EMD decomposition has shortcomings that it can may appear mode mixed phenomenon, especially when the signal is not pure white noise. Reference [8] has made improvements to the EMD method, using the white noise EEMD method, an effective solution to EMD the mode mixed phenomenon. In this paper, the method EEMD-HHT is applied to analyzing electric power system fault signal of LNG carriers, and the results show that this method is simple and effective. It not only solves the problems of mode mixed phenomenon, but also realizes the accurate positioning and feature extraction of fault time.

2. Hilbert-Huang Transform based on EEMD

2.1. EMD and EEMD

The EMD is essentially a screening process [9], assuming the original signal is $x(t)$, after decomposition process, signal $x(t)$ was decomposed into n Intrinsic Mode Function (IMF) components $c_i(t)$ and a remainder $r_n(t)$, and the time series are:

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

The n IMF $c_i(t)$ attained from the equation, is ordered from highest frequency to lowest, and a remainder $r_n(t)$ is a non-oscillatory monotone sequence. Mode mixed phenomenon of EMD confused the physical meaning of the IMF components, incorrectly displaying the signal time-frequency distribution as well. Mr. Huang and his fellows [10] held the view that the mode mixed phenomenon is signal's intermittence, related to the choice of extremum point.

EEMD is an improved algorithm, proposed to analyze noise assisted data, aiming at the shortcoming of EMD. This algorithm essentially superimposes the Gauss white noise on the original signal and takes the average value of IMF components as the final result after its multiple EMD decomposition. Using the statistical properties of the white Gauss noise, the signal added with noise can be provided with continuity in different frequency range when considering the presence of white noise, frequency mixed phenomenon can be overcome. And the noise will be eliminated as if test had gone through enough times [11-12].

Perform the following steps to decompose an arbitrary signal $x(t)$ with the method of EEMD:

a. Set the initial value of assemblage as M, noise amplitude coefficient as k, $m=1$.

b. Add noise to signal $x(t)$

$$x_m(t) = x(t) + n_m(t) \tag{2}$$

c. Use EMD to decompose the noise signal $x_m(t)$, getting I IMF components $c_{i,m}$

d. If $m < M$, then $m = m+1$ and repeat the steps b and c.

e. Average $c_{i,m}$ $\quad \overline{c_i} = \sum_{m=1}^{M} c_{i,m} / M \quad i = 1,2,\cdots,I;\ m = 1,2,\cdots,M$ (3)

f. Take $\overline{c_i}$ as the final IMF components

2.2. Hilbert-Huang Transform and Marginal Spectrum

Hilbert-Huang Transform is a way to calculate the instantaneous frequency. For any kind of original signal, HHT's definition is as follows:

$$Y(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{X(t)}{t-\tau} \mathrm{d}\tau \tag{4}$$

Inverse transformation:

$$X(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{Y(\tau)}{\tau - t} \mathrm{d}\tau \tag{5}$$

The analytic signal:

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta(t)} \tag{6}$$

In the equation, $a(t)$ is instantaneous amplitude, $a(t) = [X(t)^2 + Y(t)^2]^{\frac{1}{2}} = a(t)e^{i\theta(t)}$, $\theta(t)$ is phase, $\theta(t) = \arctan \frac{Y(t)}{X(t)}$

Instantaneous frequency: $\quad f(t) = \frac{1}{2\pi} \frac{\mathrm{d}\theta(t)}{\mathrm{d}t}$ (7)

Calculate HT Hilbert amplitude spectrum of each IMF:

$$H(\omega,t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t) e^{j\int \omega_i(t)\mathrm{d}t} \tag{8}$$

Define marginal spectrum: $\quad h(\omega) = \int_{-\infty}^{+\infty} H(\omega,t)\mathrm{d}t$ (9)

Hilbert marginal spectrum showed accumulation of amplitude distribution of the entire set of data for each frequency, the spectrum signal also has characteristics of time, frequency and energy. We can analyze the fault feature more clearly by using Hilbert marginal spectrum.

3. Simulation Examples

3.1. Detection of Fault Time

Taking a LNG carrier with electric propulsion power system as an example, this kind of power system has 4 generators, and its rated capacity is 3.125MW, main motor rated capacity is 2.5MVA, power grid rated voltage is 2.4KV, rated frequency is 60HZ. We analyze A phase current at 50KHZ frequency as sample signal respectively under the following 3 fault circumstances: single-phase grounding of power system grid, three phase grounding, and the main motor stalling. The fault moment is $t = 0.5s$. Processed A phase voltage signal under 3 possible fault situations with EEMD method, and then add random Gauss white noise with the coefficient $k = 1$, performed 100 times, getting the corresponding IMF component diagram, as shown in Figure 1-3.

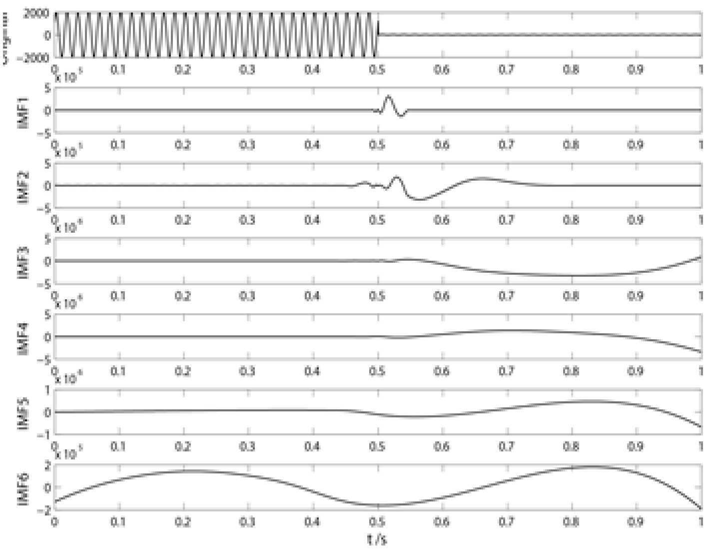

Figure 1. EEMD Decomposition of A-Phase Voltage u_a in Single-Phase Grounding Fault

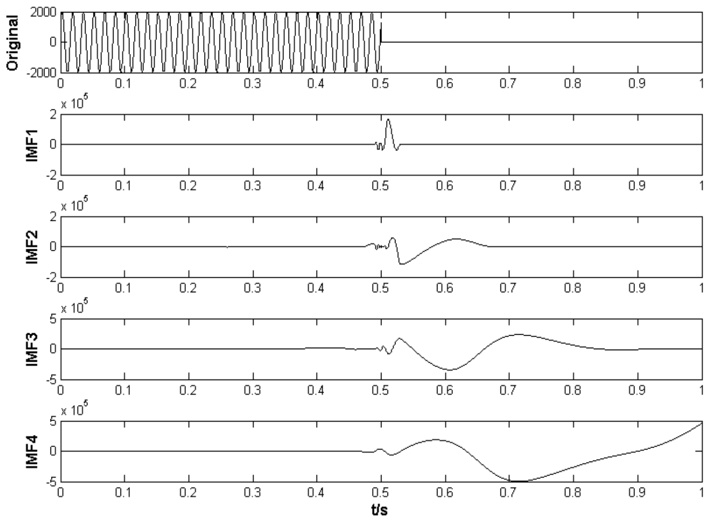

Figure 2. EEMD Decomposition of A-Phase Voltage u_a In Three-Phase Grounding Fault

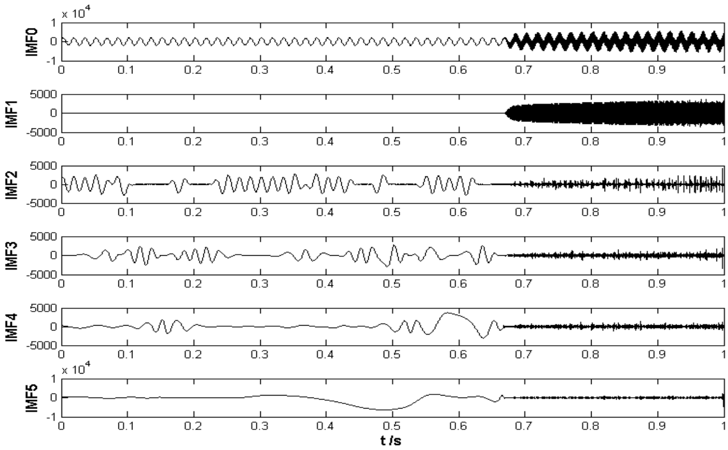

Figure 3. EEMD Decomposition of A-phase voltage u_a *in* Main Motor Stalling Fault

Normally, EEMD decomposition is used to extract the IMF component from the extremum point of the original signal, because of which, the different scale fluctuations or trends existing in real signal are decomposed according to the level from highest to lowest (from high frequency to low frequency). In addition, the time frequency of electric-propulsion power system becomes great when the fault happens, and the actual disturbance mutation information is decomposed out as the first IMF component, which can be used to test out fault moment. We can see from the Figure 1 clearly that when there was the fault of single-phase grounding or three phase grounding, the frequency of IMF1 component sharply changed at the 0.5s moment, reflecting the time of fault occurrence. When there was a main motor stalling fault, as shown in the Figure 3, the resistance moment became greater and there was no instantaneous voltage fluctuation because of the gradual loss of excitation. Instead, there was a delay of about 0.17s, which can be seen from the IMF1 component timely.

3.2. Fault Feature Extraction

According to the formula 8 and 9, we use Hilbert transform to process every IMF component of each fault signal, getting Hilbert amplitude its corresponding marginal spectrum as shown in Figure 4-6.

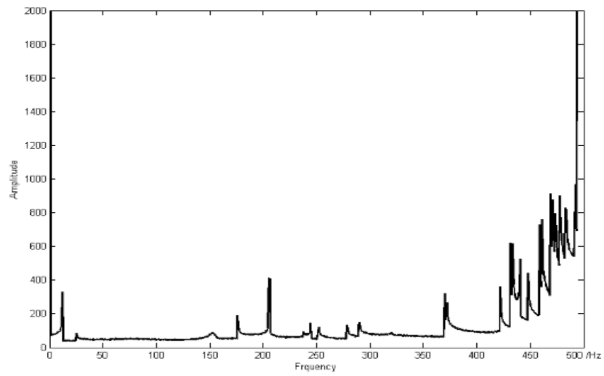

Figure 4. Marginal Spectrum of A-phase Voltage u_a in Single-Phase Grounding Fault

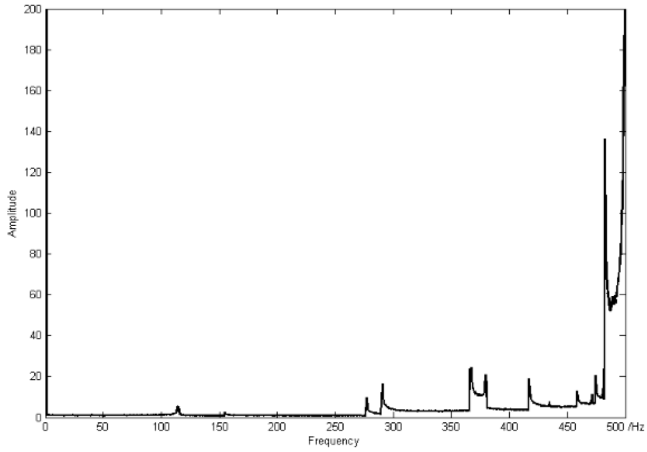

Figure 5. Marginal Spectrum of A-phase voltage u_a in Three-Phase Grounding Fault

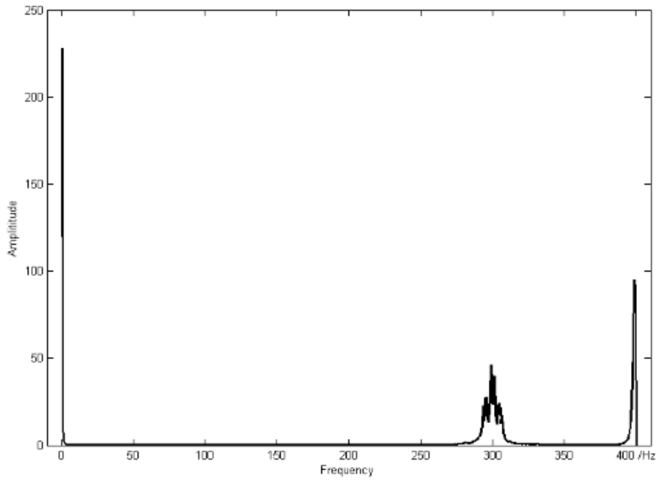

Figure 6. Marginal Spectrum of A-phase Voltage u_a in Main Motor Stalling Fault

From Figure 6 can be seen clearly, when the main motor stalling, the characteristic signal had large changes at around 300HZ (300/60 frequency), while the other two had no such changes. Compare Figure 4 with Figure 5, we can know that their amplitude values are significantly different from each other. The amplitude value of single-phase grounding is about 350db while that of three-phase grounding is about 30db. Thus, it can be seen that Hilbert marginal spectrum has higher resolution of non-stationary signal, and it is an effective way to achieve feature extraction of fault signal.

Figure 7 indicates a marginal spectrum of single-phase grounding fault obtained after decomposition, and there exists signal mode mixed phenomenon, compared with Figure 4, leading to its marginal spectrum curve tend to be smooth without clear characteristic amplitude. We clearly see that EEMD can not only effectively separate the high frequency disturbance signal and low frequency signal, but also overcome the mode mixed problem. It keeps both the adaptive characteristics of EMD decomposition and the superiority of EEMD decomposition.

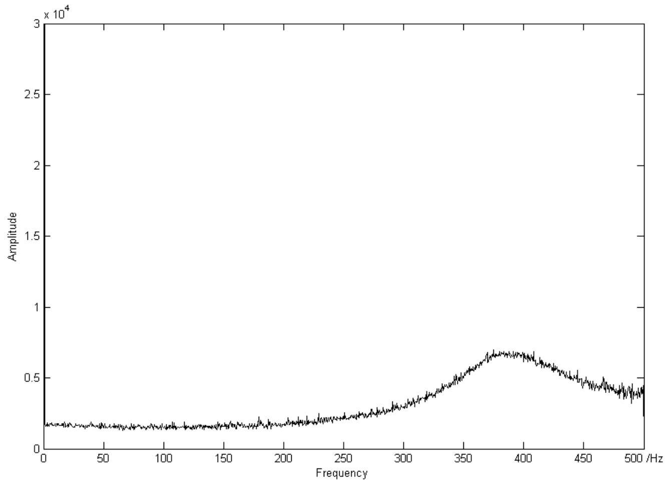

Figure 7. Marginal Spectrum of A-phase Voltage u_a in Single-Phase Grounding Fault after EMD Decomposition

4. Conclusions

(1) Experimental results demonstrate that the EEMD-HHT method has the flexibility and effectiveness analysis of transient fault signals in power system in electric-propulsion ship.

(2) Using EEMD instead of EMD decomposition largely overcome the mode mixed phenomenon. Different frequency components contained in fault signal in different IMF components given by EEMD better show hidden frequency characteristics of fault signal, and it can also accurately realize the time positioning of fault and disturbance.

(3) Select the signal IMF component containing fault information, and the corresponding marginal spectrum can be worked out through the Hilbert Transform. By analyzing the marginal spectrum of signal frequency and amplitude, we can realize the feature extraction and pattern recognition of fault signal. It turns out that the above-mentioned method can solve the problems of the low-level frequency and resolution and susceptibility to be influenced by adjacent harmonic when using traditional wavelet transform method.

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