Application of Harmonic and Interharmonic Detection in Ship Power Network based on HT-SVD Transform

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Abstract

With the increase of nonlinear load, impulse load and power electronic converter connected to ship power grid, the power quality of ship power system has attracted more attention and challenges. It is very important to accurately detect the content of each harmonic in the power grid. The harmonic detection algorithm of ship power grid should not only consider the accuracy, but also directly reflect the amplitude and frequency characteristics of the waveform, and pose a new challenge to more accurately detect the type, amplitude and frequency of each harmonic for a variety of composite disturbances. In view of the above, this paper proposes a new harmonic detection method for ship power grid. According to the characteristics of ship harmonic waveform and singular value decomposition, the ship harmonic signal processed by SVD is integrated into Hilbert transform, and the amplitude and frequency characteristics of steady-state harmonic can be detected more accurately after least square fitting. Then, the effectiveness of this algorithm is verified by comparing the simulated harmonic signal with other algorithms. It has the advantages of fast operation speed, high accuracy and strong intuition; Finally, through the simulation example of the measured ship harmonic current signal, it is further proved that the proposed algorithm has higher feasibility and strong universality in the harmonic detection of ship power grid.

Keywords

Ship Power System; Singular Value Decomposition; Harmonic Detection; Hilbert Transform.

1. Introduction

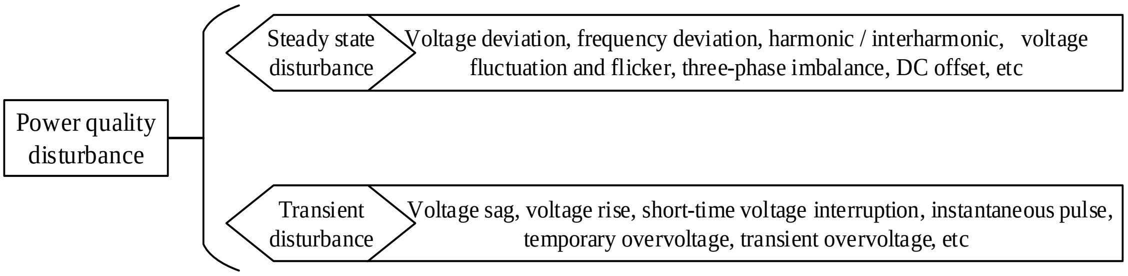


Figure 1. Power quality disturbance

"Power quality" has attracted more and more attention and challenges, mainly due to the application of a large number of power electronic devices. Power quality mainly includes harmonics, frequency deviation, three-phase imbalance, voltage sag, instantaneous pulse, etc [1][2]. Among them, harmonics are the key parameters of steady-state disturbance of ship power quality. For example, marine power electronic devices such as 6-pulse converter and 12 pulse converter produce 5 and 7 power grid current harmonics respectively, which mainly harm the ship power grid [3]. The detailed classification of ship power quality disturbance detection parameters is shown in Figure 1.

The power quality problem of new energy ship power system is mainly reflected in the input of photovoltaic inverter, frequency converter and other equipment and impulsive load into ship power grid [4][5]. Due to the integration of power generation and distribution links of ship power system, the problem of power quality is more serious, which affects the economic safety of ship operation [6].

The harmonic signal detection algorithm of ship power system is an important method to study the steady-state problem of ship power quality [7]. At present, many scholars have proposed various algorithms to detect ship harmonic and interharmonic signals, such as discrete Fourier transform (DFT), fast Fourier transform (FFT), wavelet transform, three-phase instantaneous reactive power detection method, Hilbert Huang transform (HHT), Kalman filter Singular value decomposition and so on [8]. Among them, Fourier transform is only applicable to stationary signals, and must be sampled in the whole period, otherwise it is prone to spectrum aliasing and cannot reflect the change of frequency and amplitude with time [9]. FFT is a fast algorithm of DFT, which is not suitable for the processing of detection signal of transient disturbance [10]. Wavelet transform has good detection effect on time-frequency domain localized information processing, and the processing of transient index is better than that of steady state. However, the effect of noise processing varies due to the selection of wavelet basis function, which can not ensure high accuracy [11][12].

The three-phase reactive power detection based on $i_p - i_q$ operation can better separate the fundamental and harmonic components, but it can not distinguish the harmonic number. It is often limited by low-pass filter (LPF) and has a certain degree of delay. It is mostly used for real-time harmonic detection of active power filter [13][14][15]. HHT transform is a modern adaptive harmonic detection algorithm, which is not limited by the basis function. However, the core EMD will have the problems of endpoint effect and mode aliasing [16], so the accurate separation of each harmonic will be affected by the change of harmonic amplitude and frequency, which is suitable for some specific non-stationary signals. On this basis, many researchers propose LMD, VMD and other algorithms for improvement, which will eliminate modal aliasing to a certain extent, but the accuracy will be reduced. In addition, EMD lacks strict mathematical theory support and relies more on experience for decomposition [17][18][19][20].

The above detection methods can effectively detect the harmonic and interharmonic disturbances of ship power quality under specific circumstances, but in practice, it is difficult to accurately detect and separate each harmonic and interharmonic, and the detection amplitude, frequency accuracy and variation with time are relatively insufficient.

Recently, the characteristic of singular value decomposition has unique advantages in signal denoising and feature extraction [21], especially for the application of harmonic and interharmonic detection in ship power grid. SVD is a signal analysis method without parameter adjustment. It not only has no limit on the basis function, but also can distinguish the main energy characteristics of the signal from low-energy noise [22]. Document [23] proposed a detection method combining singular value decomposition (SVD) and matrix beam algorithm. SVD is used to accurately locate the sudden change time, decompose the transient disturbance signal into multiple stationary signals, and then calculate the modal parameters by matrix beam algorithm, which has strong practicability. According to the characteristics of SVD, document [24] a new method for eliminating EMD mode aliasing of equal amplitude superimposed signals, which is mainly used for stationary signals and has high accuracy. Document [25] proposes a new method of power quality disturbance detection based on improved HHT based on SVD, which can better eliminate modal aliasing for disturbance signals with noise and high-frequency discontinuous signals, and can be applied to complex non-stationary disturbance signals and steady-state signals in a small range. It can not accurately reflect time-frequency information, and the applicability of signals is not extensive. However, SVD is mostly used to detect the start and end time of transient disturbance, but it can not reflect the amplitude, frequency and other characteristics of disturbance.

This paper presents a general disturbance detection algorithm for harmonic and interharmonic of ship power quality. The detection is realized by fusing SVD and Hilbert transform. Firstly, the disturbance waveform signal is transformed by FFT to determine its dominant frequency; Secondly, SVD is used to decompose the disturbance signal, and the number of separated signals is determined according to the number of dominant frequencies; Then Hilbert transform each separated waveform to obtain the instantaneous amplitude and frequency of each separated waveform; Finally, the instantaneous amplitude and frequency are fitted by least square to obtain more accurate instantaneous amplitude and frequency characteristics. According to the instantaneous amplitude and instantaneous frequency, the parameter detection of harmonic and interharmonic in ship power grid can be realized. Through the simulation analysis of an example, it is verified that the algorithm in this paper can accurately detect the harmonic and interharmonic parameters of ship power grid, and has certain universality in ship.

2. Separation Method of Harmonic and Interharmonic Disturbances based on SVD

2.1 Basic Theory of SVD [26]

For any $m \times n$ order real matrix A, there must be $m \times m$ order unitary matrix U and $n \times n$ order unitary matrix V (which can be regarded as real orthogonal matrix in the real number field), so that the following formula holds:

$$A = U \Lambda V^{\mathrm{H}} \tag{1}$$

Where, the diagonal matrix $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, \cdots \lambda_k)$, where k refers to the minimum value of m、n. And in the range of real numbers, V^{H} and V^{T} are equivalent. The elements in the diagonal matrix are singular values and have the property of $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \cdots \geq \lambda_k \geq 0$.

In order to better reflect each harmonic signal, it can be written in the vector form of each component:

$$A_i = \lambda_i u_i v_i^{\mathrm{H}} \tag{2}$$

Where: UI is the ith column vector of the matrix; VI is the ith column vector of the matrix; Yi is its corresponding singular value.

Then $m \times n$ matrix A can be expressed as:

$$A = \sum_{i=1}^{k} \lambda_i u_i v_i^{\mathrm{H}} \tag{3}$$

2.2 Harmonic and Interharmonic Separation Method based on SVD

According to two characteristics of SVD method: one is that each frequency component in the signal corresponds to two approximate singular values [27]; Second, the magnitude of the singular value corresponding to the frequency in the signal is directly proportional to the amplitude of the frequency, but has nothing to do with the frequency [24]. Based on these two characteristics, it is found that the characteristics of harmonic in ship power grid are almost in line with this. The amplitude of harmonic decreases with the increase of frequency, and the singular values obtained after SVD are arranged in descending order, and the corresponding amplitude will also be arranged in descending order, which does not exactly correspond to the harmonic characteristics under the Fourier order model. However, recently, most researchers use SVD method to deal with the positioning time of signal mutation time. According to the characteristics of SVD, it is very suitable for analyzing stationary harmonic and interharmonic signals.

Let $y(i)$ be the detected ship harmonic and interharmonic disturbance signal, where $i=1,2,\cdots,\mathrm{L}$. The steps of harmonic and interharmonic separation detection based on SVD are as follows:

①The reasonable sampling of the original signal $y(i)$ needs to meet the Shannon sampling theorem, and the number of samples should be more than 1000 to ensure the original trend of the waveform.

②The signal $y(i)$ is constructed in the form of Hankel matrix, because the Hankel matrix can retain the characteristics of the original waveform. The form of construction matrix A is as follows:

$$A=\begin{bmatrix} y(1) & y(2) & \cdots & y(N-n+1) \\ y(2) & y(3) & \cdots & y(N-n+2) \\ \vdots & \vdots & & \vdots \\ y(n) & y(n+1) & \cdots & y(N) \end{bmatrix} \tag{4}$$

Where: A is $m\times n$ matrix; N is the number of original signals $y(i)$; n is the number of rows of the matrix; $(N-n+1)$ is the number of columns of the matrix.

In order to ensure the accuracy of detection, the Hankel matrix constructed by $n=\frac{N}{2}$ is the best.

③The Hankel matrix A composed of signals is decomposed by singular value decomposition $A=U\Lambda V^{\mathrm{H}}$, and the orthogonal matrix U、V and many singular values distributed in descending order are obtained.

It should be noted here that $y(i)$ harmonic signal is composed of fundamental signal and interference component (including noise). Due to the descending arrangement of singular values, it can show the energy concentration distribution of fundamental signal and interference signal. The first group of largest singular values corresponds to fundamental signal, the first $k-1$group of singular values corresponds to harmonic disturbance signal, and the later $\frac{n}{2}-k$ group of singular values with smaller values corresponds to interference component, By setting the small singular value part to zero, the interference component (including noise) in the disturbance can be removed [19].

④According to the characteristics of singular value, find out the energy concentration singular value matrix corresponding to the fundamental wave and its harmonics respectively:

Fundamental singular value matrix Λ_1: only the first two rows, the first group of data, are retained, and the singular values of the other rows are set to zero.

Harmonic singular value matrix Λ_i: only two rows $2i-1$、$2i$, i.e. group i data, are reserved, and the singular values of other rows are set to zero.

Here: $1\le i\le m$, where m depends on the dominant frequency number r in the FFT decomposition result, i.e. $m=r$, and the rank of the corresponding singular value matrix is $2r$, which is an integer.

⑤Reconstruct the signal matrix corresponding to the energy of fundamental wave and each harmonic component:

$$\begin{aligned} &A_1 = U\Lambda_1 V^{\mathrm{H}} \\ &A_2 = U\Lambda_2 V^{\mathrm{H}} \\ &\vdots \\ &A_i = U\Lambda_i V^{\mathrm{H}} \end{aligned} \tag{5}$$

Where: i is the dominant frequency r in the FFT result. Where, the total harmonic matrix $A_h = A_2 + \cdots + A_i$.

⑥According to the singular value matrix corresponding to the fundamental wave and each harmonic component, the waveform signal y_{inew} corresponding to the fundamental wave and each harmonic component is obtained respectively. Here: $1 \le i \le m$, m, which depends on the number of dominant frequencies r in the result after FFT decomposition, i.e. $m = r$.

The above can realize the accurate separation of ship power quality fundamental wave and each (inter) harmonic. However, the amplitude and frequency characteristics can not be seen directly after the accurate separation of each harmonic, so Hilbert transform needs to be introduced.

3. Hilbert Transform Theory and Instantaneous Frequency

Assuming that the real part signal is $x(t)$, the Hilbert transform is recorded as $X(t)$, and Hilbert transform is performed on each component of the harmonic signal after SVD decomposition:

$$X(t) = H[x(t)] = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{x(\xi)}{t-\xi} d\xi \tag{6}$$

Hilbert transform does not change the amplitude and energy of the real signal $x(t)$, but only the phase.

For a long time, the definition of instantaneous frequency has been controversial. At present, the recognized instantaneous frequency is the definition method of constructing complex function and calculating phase derivative with the help of Hilbert transform.

The complex function is constructed according to HT Transformation:

$$z(t) = x(t) + jX(t) \tag{7}$$

The instantaneous amplitude and phase can be calculated:

$$a(\mathrm{t}) = \sqrt{x^2(t) + X^2(t)} \tag{8}$$

$$\theta(t) = \arctan\frac{X(t)}{x(t)} \tag{9}$$

Then, the instantaneous frequency of the original signal $x(t)$ can be obtained by deriving the phase:

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \tag{10}$$

Using equations (8) and (10), the instantaneous amplitude frequency characteristics of ship disturbance harmonic and interharmonic signals can be calculated to detect the relevant characteristic information of harmonic signals.

Combining SVD harmonic separation with Hilbert transform will be very convenient to get a new algorithm for harmonic detection of ship power grid.

4. Harmonic Detection of Ship Power Network based on Hilbert-SVD Algorithm

Considering that the characteristics of singular value decomposition are very similar to those based on Fourier series harmonic model, and SVD is mostly used to determine the start and end time of transient disturbance, it is not used for steady-state harmonic separation of ship power quality. SVD detection also has some disadvantages: it can only separate each (inter) harmonic, but can not intuitively express the corresponding amplitude, frequency and other characteristics. Therefore, this paper combines Hilbert transform with SVD to propose a new steady-state harmonic disturbance detection algorithm for ship power grid. The algorithm is simple to use, does not need to determine the basis function, and has certain universality, which overcomes the shortcomings of the original SVD separation. The flow of ship (inter) harmonic disturbance detection algorithm proposed in this paper is shown in Figure 2.

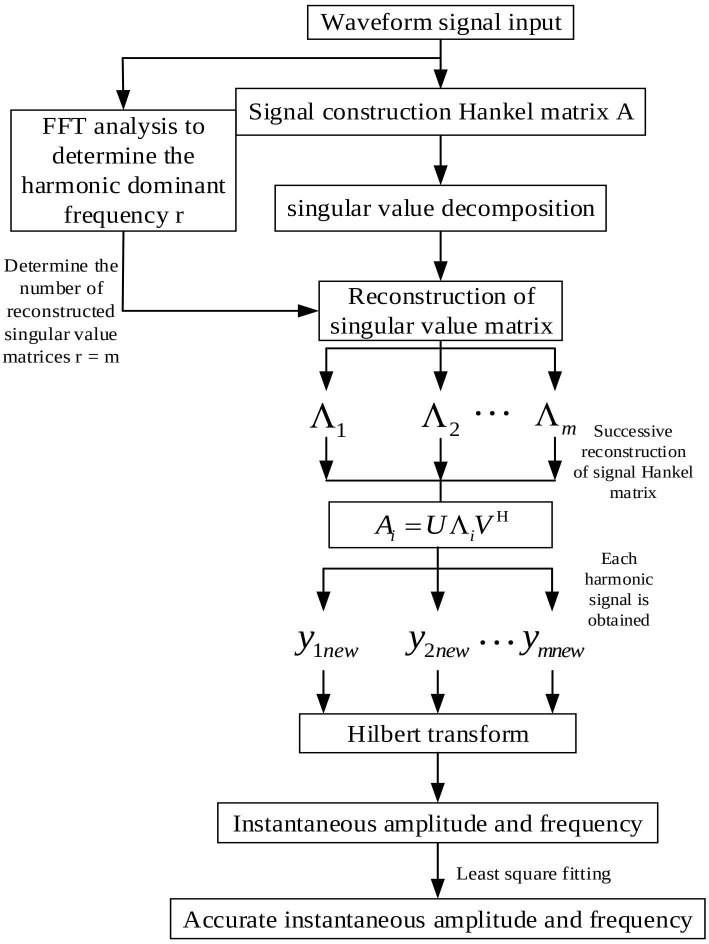


Figure 2. The flow chart of ship (inter) harmonic disturbance detection algorithm in this paper

The detailed steps of ship (inter) harmonic disturbance detection algorithm in this paper are to calculate the instantaneous amplitude and frequency based on SVD ship harmonic separation process and Hilbert transform process. The SVD harmonic separation and HT transformation process has been given in detail above, and will not be repeated here. Here is a brief description of the least squares fitting method.

The harmonic is separated by SVD above, and then the instantaneous amplitude and frequency are obtained after Hilbert change. However, these instantaneous amplitude and frequency are not a straight line, but will fluctuate to a certain extent. Using least square fitting, the average value of the fluctuation can be taken for smoothing, which will further improve the detection accuracy and be more intuitive.

The mathematical model of the selected simulation signal is:

$$f(t) = 220\sin(2\times 50\times \pi \times \mathrm{t}) + 60\sin(2\times 150\times \pi \times \mathrm{t}) + 40\sin(2\times 250\times \pi \times \mathrm{t}) \tag{11}$$

The simulation is carried out according to the above algorithm, in which the dominant frequency R is taken as 3, and the instantaneous frequency diagram of the simulated 5th harmonic is taken out separately, as shown in Figure 3.

According to the simulation waveform shown in Figure 3, the theoretical value of the fifth harmonic frequency is 250Hz, but the instantaneous frequency obtained after HT transformation is not a straight line, but a sine like wave with small amplitude fluctuation. At this time, the smoothing effect of least square fitting is more accurate. The least square fitting equation can be displayed intuitively. The difference between 249.97hz and 250Hz is only 0.03hz, and the accuracy is very high. This method is suitable for smoothing in this algorithm.

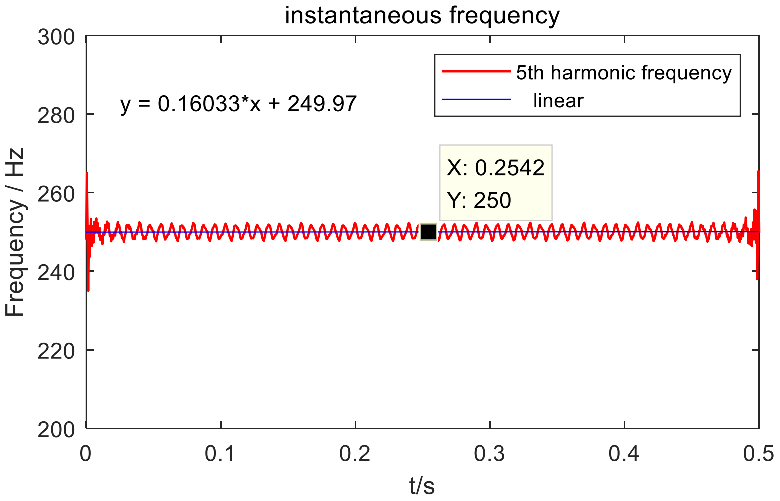


Figure 3. Effect drawing of least square fitting smoothing

5. Simulation Analysis

In order to verify the accuracy and effectiveness of this algorithm in detecting ship power grid (inter) harmonics, this paper uses the mathematical model data of simulating ship power grid harmonic current to carry out the simulation experiment, and the experimental program is written and run in MATLAB 2018a.

Taking the steady-state non integer current harmonic compound disturbance in ship power grid as an example, marine power electronic devices are widely used. The current harmonic number of ship power grid is mostly 6n ± 1, of which the 5th and 7th harmonics are the most serious, generally excluding the integer multiple harmonics of 3. Considering the situation of interharmonics, the selected mathematical model of simulation signal is:

$$\begin{aligned} f(t) &= 220\sin(2\times 50\times\pi\times \mathrm{t}) + 66\sin(2\times 250\times\pi\times \mathrm{t}) + 45\sin(2\times 375\times\pi\times \mathrm{t}) \\ &+20\sin(2\times 550\times\pi\times \mathrm{t}) \end{aligned} \tag{12}$$

The composition of the original signal is shown in Figure 4:

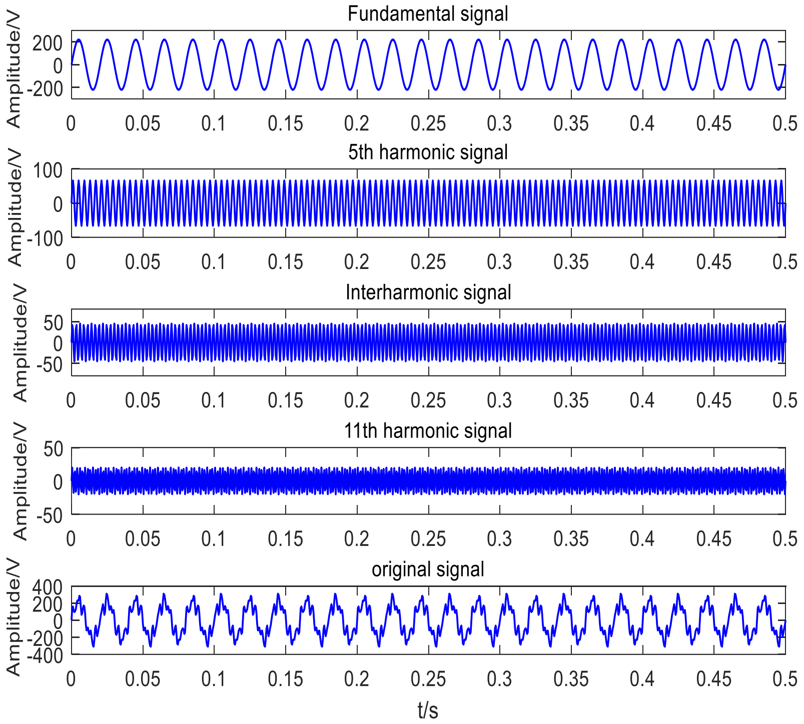


Figure 4. Original harmonic signal model

The new algorithm is compared with the traditional FFT transform and HHT transform, and the simulation results are shown in figures 5 to 7.

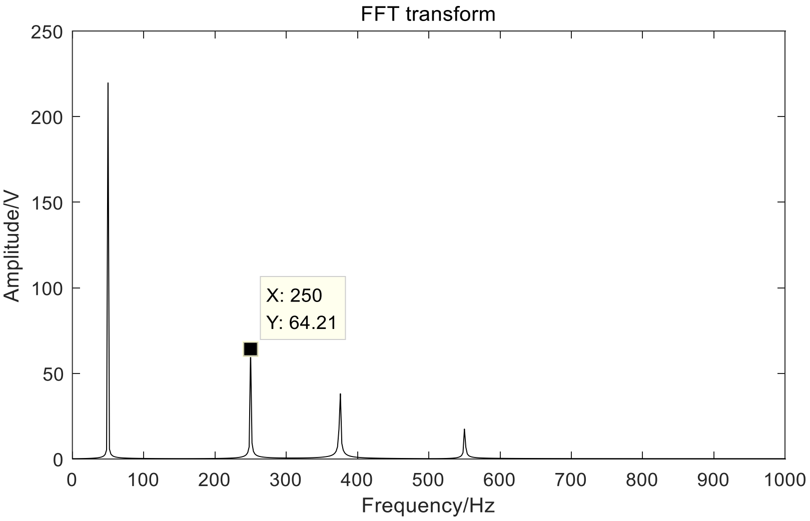
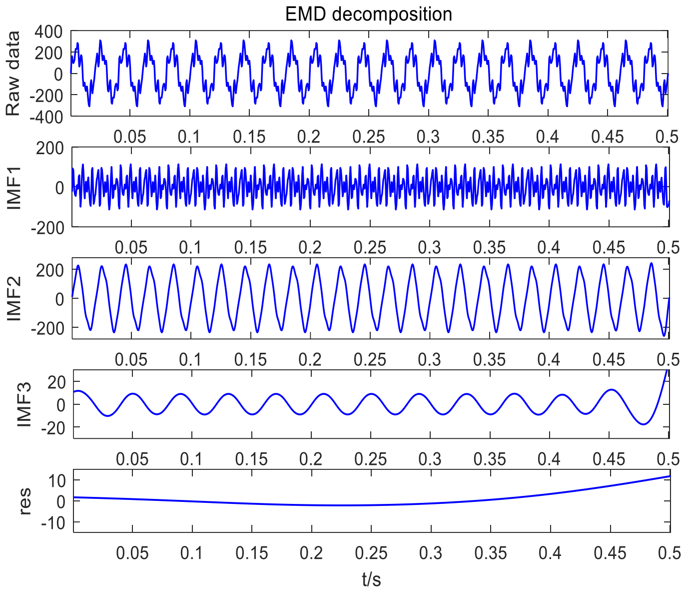
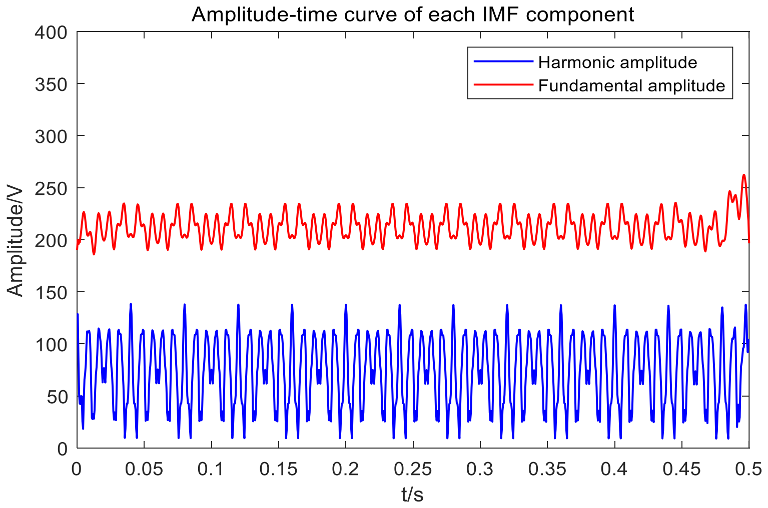


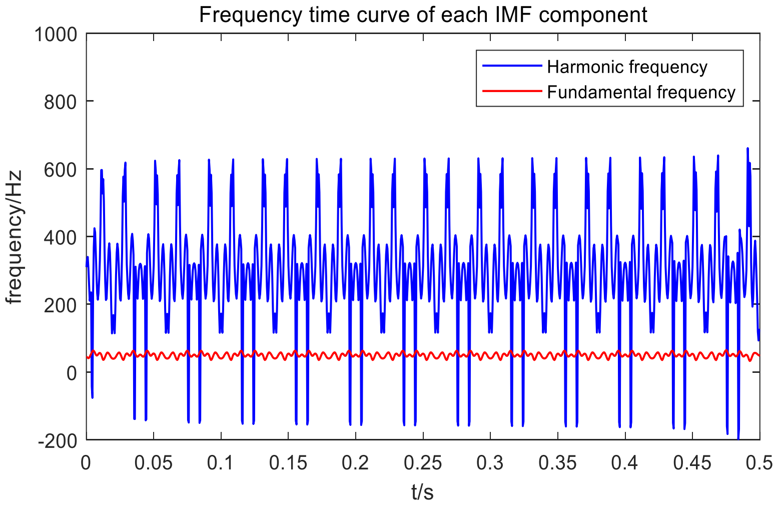
Figure 5. FFT transform harmonic detection diagram



a). EMD exploded view



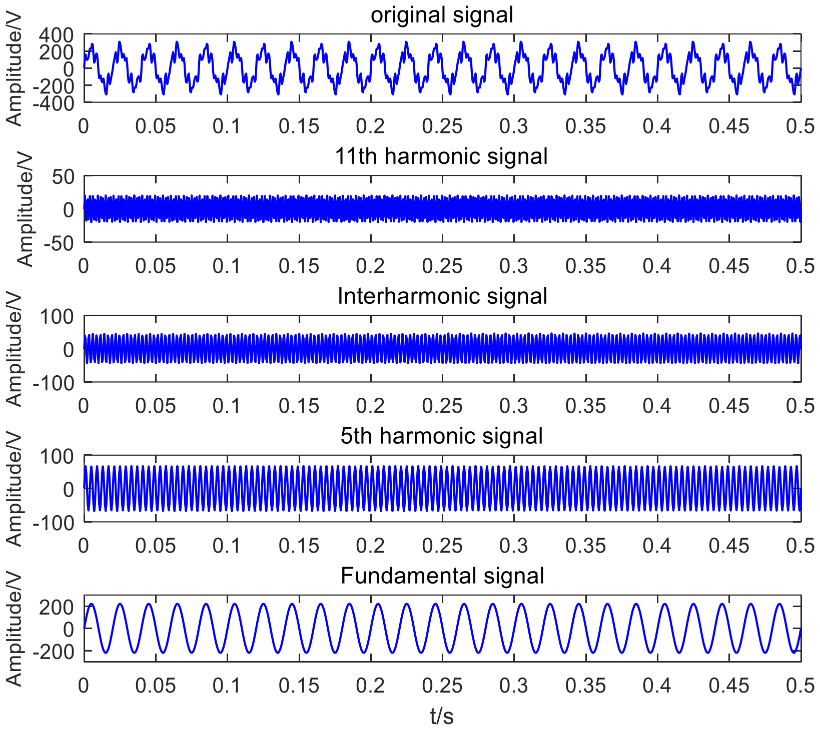
b). Instantaneous amplitude diagram of each harmonic



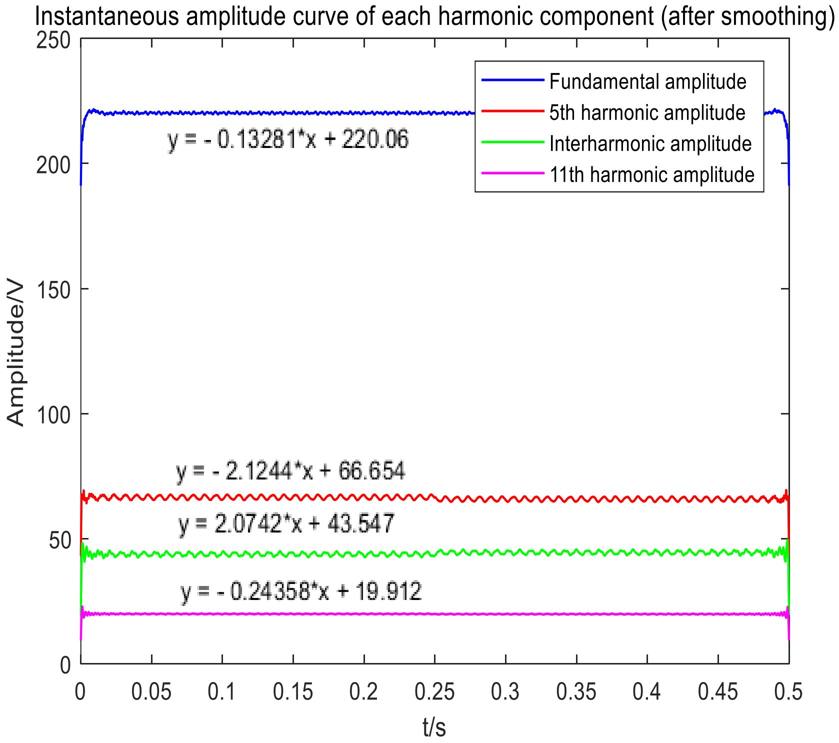
c). Instantaneous frequency diagram of each harmonic

Figure 6. HHT transform harmonic detection

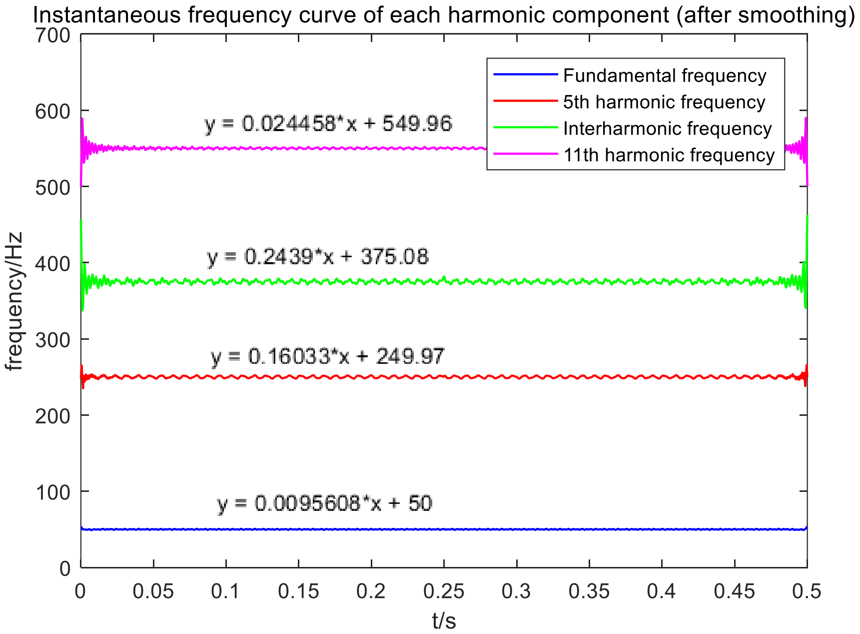
According to Fig. 5, the number of dominant frequencies r of FFT transformation is 4, and the number of reconstruction matrices m is also 4. The simulation of harmonic detection algorithm based on HT-SVD transform is as follows:



a). Waveform diagram decomposed by SVD



b). Instantaneous amplitude of each harmonic component (after smoothing)



c). Instantaneous frequency of each harmonic component (after smoothing)

Figure 7. Harmonic detection based on HT-SVD transform

According to the above figures, the harmonic detection effects of the three methods are shown in Table 1:

Table 1. Comparative analysis results of non integer harmonics

Steady state harmonic detection method	Harmonic number	Instantaneous amplitude / V	Amplitude error	Instantaneous frequency / Hz	Frequency error
Theoretical value	Fundamental wave	220	-	50	-
	5rd	66	-	250	-
	Interharmonic	45	-	375	-
	11rd	20		550	
FFT detection	Fundamental wave	219.7	0.14%	49.95	0.1%
	5rd	64.21	2.71%	250	0
	Interharmonic	38.07	15.4%	376	0.267%
	11rd	17.46	12.7%	549.5	0.01%
HHT detection	Fundamental wave	212.23	3.53%	49.91	0.12%
	5rd	Modal aliasing	-	Modal aliasing	-
	Interharmonic		-		-
	11rd		-		-
Hilbert-SVD detection	Fundamental wave	220.06	0.027%	50	0
	5rd	66.654	0.99%	249.97	0.012%
	Interharmonic	43.547	3.23%	375.08	0.02%
	11rd	19.912	0.44%	549.96	0.007%

According to the analysis of simulation and list 1 results, the original signal is composed of fundamental, 5th harmonic, interharmonic and 11th harmonic combined signals in Figure 4. The harmonic analysis using FFT transform in Figure 5 can accurately reflect the spectrum diagram, but it is found that there is a large difference between the amplitude of interharmonic and 11th harmonic and the theoretical amplitude, with errors of 15.4% and 12.7%, and the detection accuracy effect is poor. In the HHT algorithm adopted in Fig. 6, serious mode aliasing occurs in EMD decomposition. At the same time, it is found that the instantaneous amplitude and frequency of fundamental wave and total harmonic fluctuate greatly, the fundamental error reaches 3.53%, and the resolution and accuracy are too poor; It shows that HHT transform can effectively separate specific steady-state waveforms, but modal aliasing is an important part that limits the development. HHT is better than steady-state for the detection of transient power quality signals. The detection method based on Hilbert-SVD transform can not only accurately separate each harmonic, but also accurately obtain the instantaneous amplitude and frequency. Among them, the interharmonic error is 3.23%, and the other subharmonics are not more than 1%. It is found that the instantaneous amplitude and frequency of interharmonic and 11th harmonic using this method do not fluctuate, the effect is very obvious, the accuracy is improved compared with the other two methods, and the error can be basically ignored.

6. The Feasibility of HT-SVD Algorithm is Verified under the Ship Power Grid Model

The harmonic source model of ship power grid is established by using Simulink in MATLAB 2018a, as shown in Figure 8.

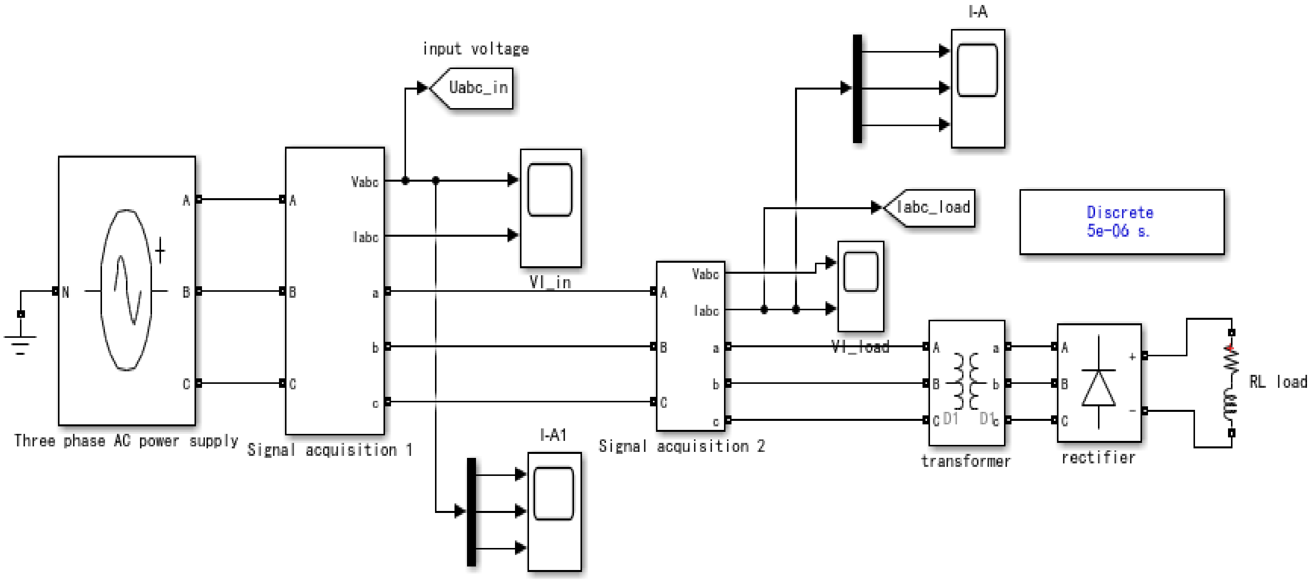


Figure 8. Generation model of ship harmonic source

The main parameters used in the above figure are shown in Table 2.

Table 2. Main parameters of ship harmonic source

Operating parameters	Value size
Ship power grid	380V(wire), 50Hz
Nonlinear load	R=20Ω, L=0.001H

After operation, the distorted waveform of three-phase load current is shown in Figure 9. The current waveform of phase a of the load is extracted into Matlab, the sampling frequency is 2000Hz, and the number of sampling points is 1001. The waveform of phase a after sampling is shown in Figure 10.

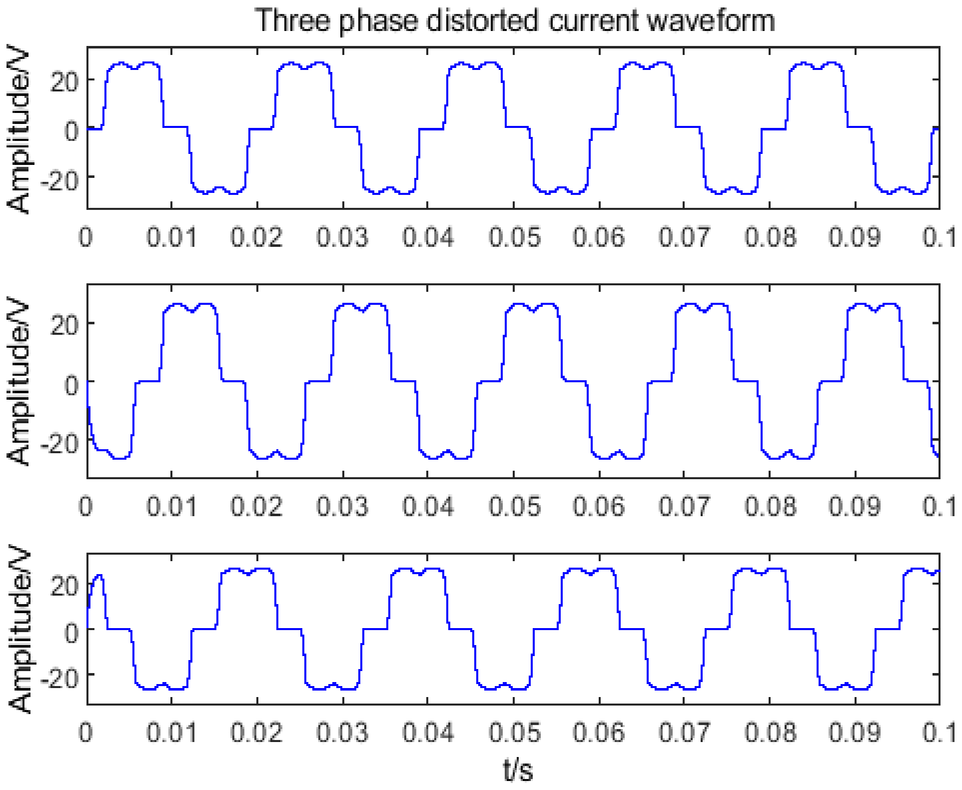


Figure 9. Distortion waveform of ship three-phase harmonic current

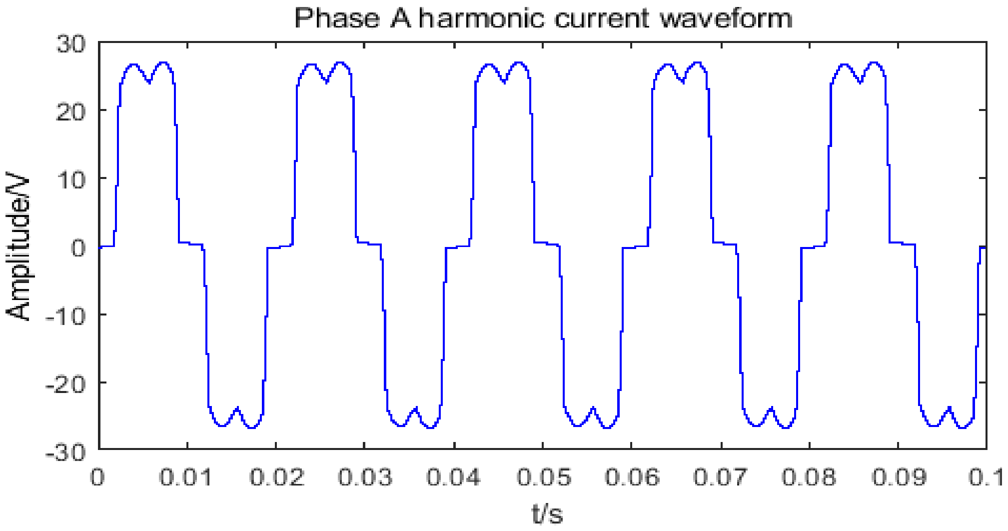


Figure 10. Harmonic current waveform after ship phase a sampling

The sampled A-phase distortion current is used as the original data signal, the data is exported for harmonic analysis, and the detection algorithm in this paper is used for simulation verification. The sampling frequency is 2000Hz, the sampling time is 0.5s, and the number of samples is 1001. The detection results are shown in figures 11 to 12.

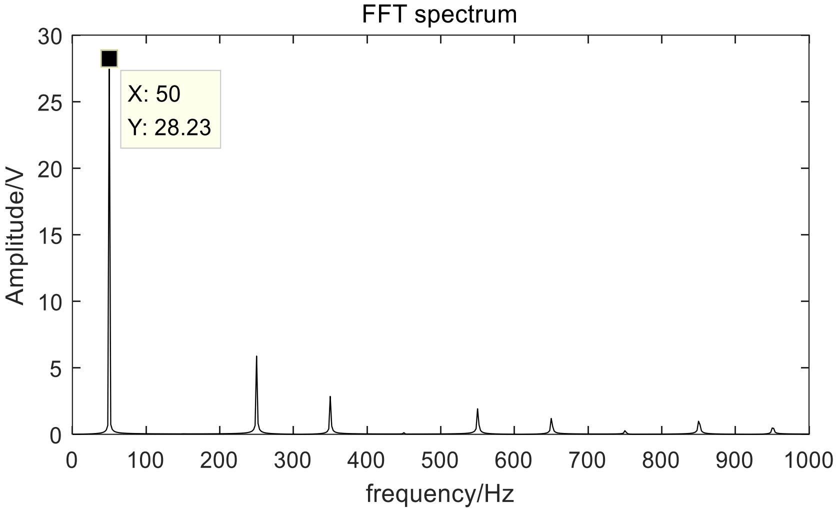
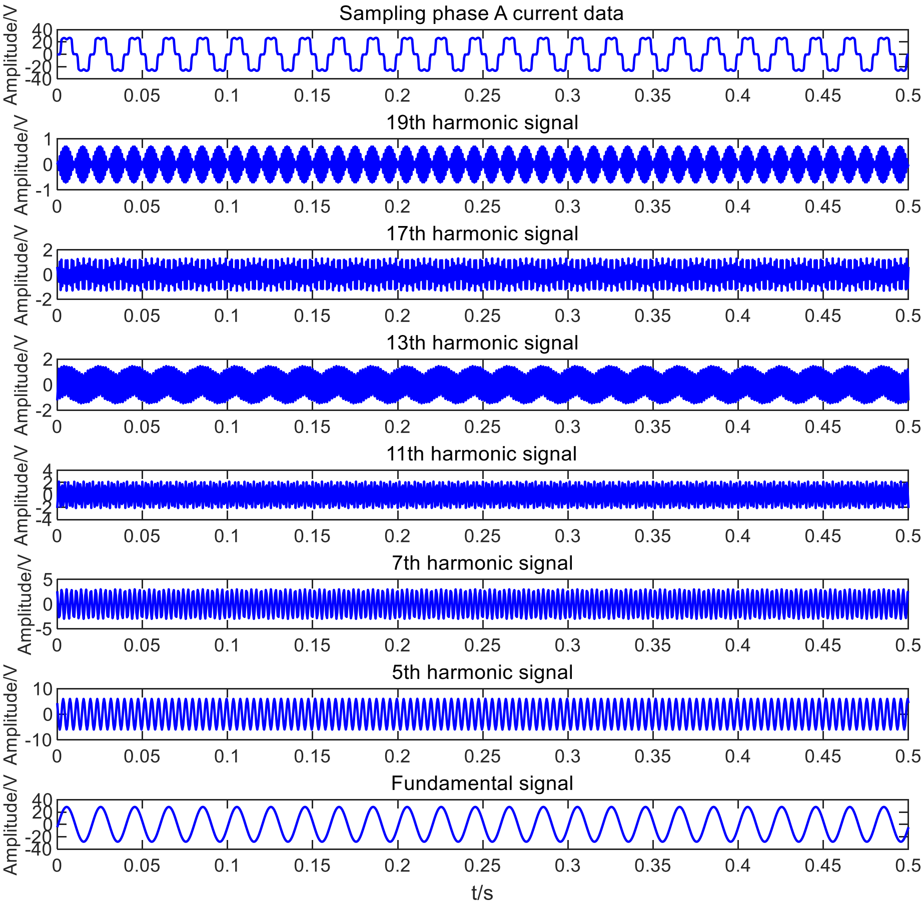
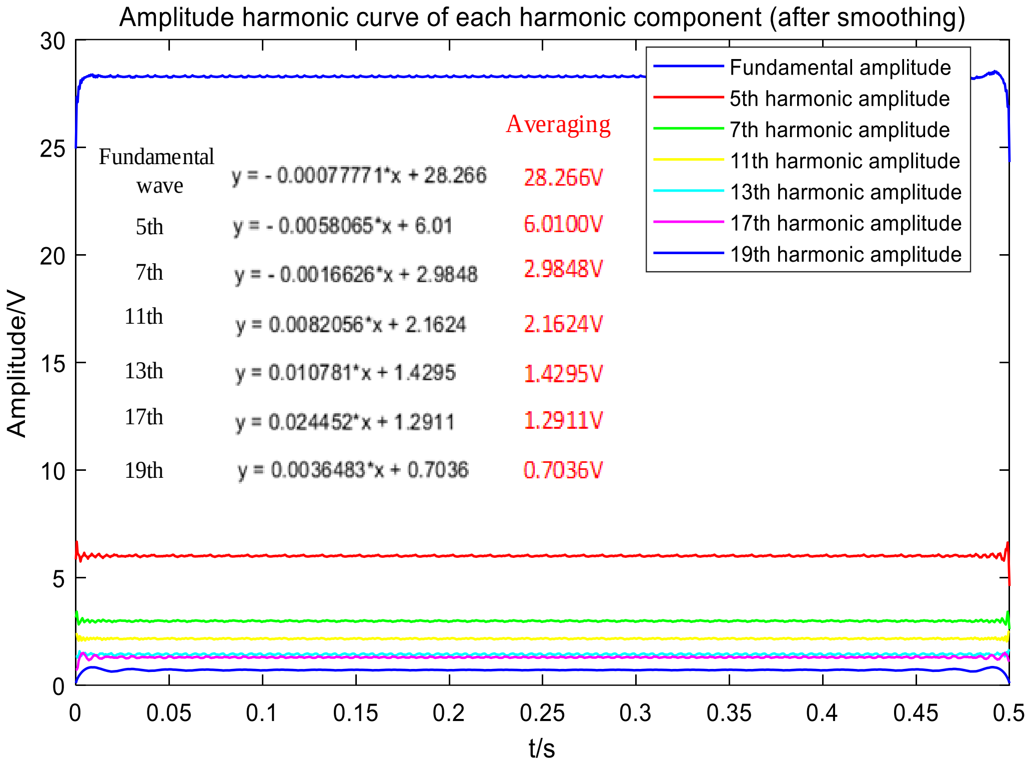


Figure 11. FFT transform harmonic detection diagram

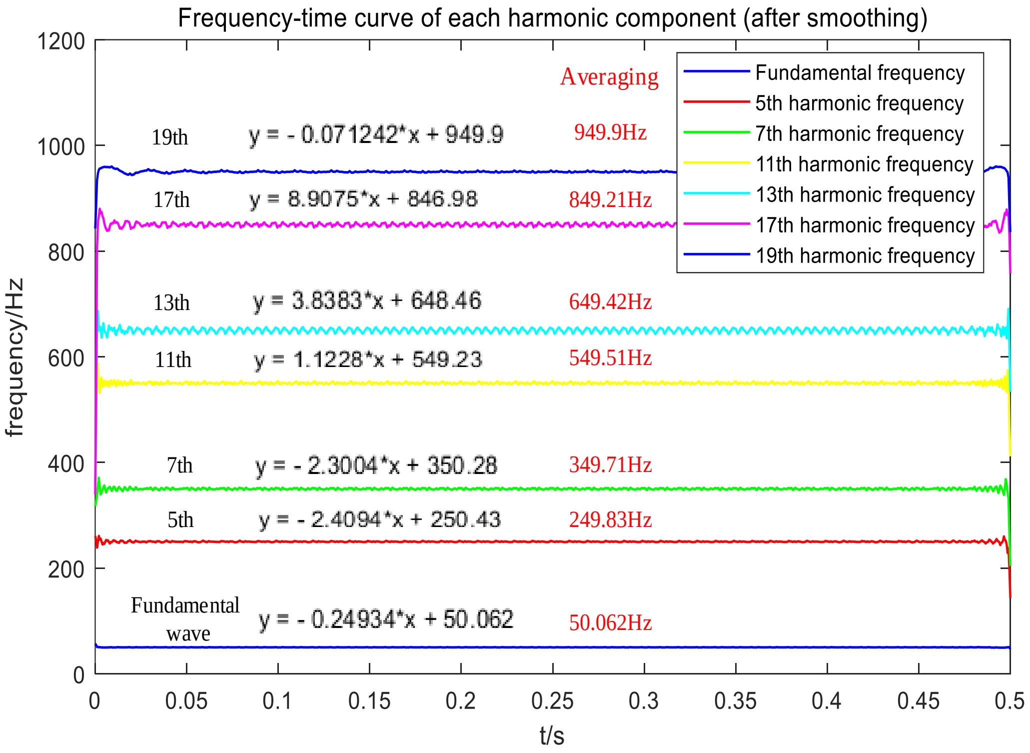
According to Fig. 11, the number of dominant frequencies r of FFT transformation is 7, and the number of reconstruction matrices m is also 7. The simulation of harmonic detection algorithm based on HT-SVD transform is as follows:



a). Waveform diagram decomposed by SVD



b). Instantaneous amplitude of each harmonic component (after smoothing)



c). Instantaneous frequency of each harmonic component (after smoothing)

Figure 12. Harmonic detection based on HT-SVD transform

According to the above simulation results, the detection error of this algorithm for ship load harmonic current is shown in Table 3:

Table 3. Comparative analysis results of ship load current harmonics

Steady state harmonic detection method	Harmonic number	Instantaneous amplitude / V	Amplitude error	Instantaneous frequency / Hz	Frequency error
FFT detection	Fundamental wave	28.23	-	49.95	0.1%
	5rd	5.878	-	249.8	0.08%
	7rd	2.85	-	349.7	0.086%
	11rd	1.92	-	549.5	0.091%
	13rd	1.193	-	649.4	0.092%
	17rd	0.9843	-	849.2	0.094%
	19rd	0.4732	-	949.1	0.095%
Hilbert-SVD detection	Fundamental wave	28.266	0.036	50.062	0.124%
	5rd	6.01	0.132	249.83	0.068%
	7rd	2.9848	0.1348	349.71	0.083%
	11rd	2.1624	0.2424	549.51	0.089%
	13rd	1.4295	0.2365	649.42	0.089%
	17rd	1.2911	0.3068	849.21	0.093%
	19rd	0.7036	0.2304	949.9	0.011%

Ccording to the analysis of simulation and table 3 results, the harmonic analysis using FFT transform in Figure 11 can accurately reflect the spectrum characteristics. It is found that it is more accurate in frequency detection, but there is an error between the current amplitude detection and the algorithm in this paper. The detection method based on Hilbert-SVD transform can accurately separate each harmonic and obtain better instantaneous amplitude and frequency. Compared with FFT transform, the current amplitude difference is 0.036, 0.132, 0.1348, 0.2424, 0.2365, 0.3068, 0.2304 and so on. It can be inferred from the accuracy with theoretical value above that the result of this algorithm is more accurate and has certain universality.

7. Conclusion

Traditional harmonic detection algorithms have good detection effect to some extent, but they have some limitations more or less according to different problems. According to the characteristics of ship power quality harmonics, a new method suitable for ship steady-state harmonic disturbance detection is proposed in this paper. According to the comparative analysis of the effect of algorithm simulation, this paper draws the following conclusions:

1) At present, the application of SVD mostly focuses on the positioning of the start and end time of transient signal, but it may be more durable for stationary signal. The decomposition characteristics of SVD are extremely similar to those of harmonic composition, which is very consistent with the separation of (inter) harmonics. This algorithm overcomes some defects of Fourier transform, wavelet transform and HHT. For example, the whole period sampling is not required, which can reflect the intuitive change of amplitude and frequency with time; There is no need to set wavelet basis function; Even the characteristics of SVD can provide assistance for EMD mode aliasing.

2) According to the characteristics of SVD, this paper applies it to ship (inter) harmonic separation, overcomes the deficiency that SVD steady-state detection can not reflect the amplitude frequency

characteristics, and combines Hilbert transform to form a new harmonic detection algorithm of Hilbert-SVD for ship power grid, which is also the innovation of this paper. However, the ship power grid (inter) harmonic detection method based on Hilbert-SVD has relatively weak noise resistance. When the noise intensity increases and the waveform obviously deviates from the trend of the original waveform, it will lead to large deviation in the detection results. According to the instantaneous amplitude frequency characteristics, the change of amplitude frequency offset with time can be seen intuitively. The detection based on Fourier transform will affect the accuracy according to the change of data length and selected detection length, but the algorithm in this paper is not affected by it.

3) This algorithm can separate and detect various steady-state harmonics of ships, and can separate and detect various harmonic types. It not only has high separation and detection accuracy for single integer harmonics, but also is suitable for composite inter-harmonic signals. Finally, this paper uses the ship harmonic source model for data extraction, so as to better separate and detect the components and accurate amplitude of ship (inter) harmonics.

This paper simulates the harmonic analog signal of ship power grid, and proves that the algorithm in this paper is applicable to the accurate separation and detection of (inter) harmonics in ship power system, and is superior to FFT 'transform and HHT transform to a certain extent. Of course, there are still many shortcomings in this algorithm. For example, how to accurately separate each harmonic with a large amount of noise, it needs to be improved on the basis of this algorithm; In addition, the detection of ship harmonic initial phase is not considered; Finally, the algorithm is only verified by simulation. In the follow-up work, the application of the algorithm in the power quality monitoring platform of ship power grid will be further studied.

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