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Research Article

A Novel Multidimensional Frequency Band Energy Ratio Analysis Method for the Pressure Fluctuation of Francis Turbine

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The pressure fluctuation has multiple influence on the steady operation of Francis turbine, and the impact degree varies with the operation condition. In this paper, for the analysis of pressure fluctuation in the Francis turbine, a novel feature extraction method of multidimensional frequency bands energy ratio is proposed based on Hilbert Huang Transform (HHT). Firstly, the pressure fluctuation signal is decomposed into intrinsic mode functions (IMFs) by EEMD. Secondly, the Hilbert marginal spectrum is utilized to analyze the frequency characteristics of IMFs. Then, according to the inner frequency of IMFs, each of them is divided into high, medium, or low frequency band which are constructed based on the frequency characteristic of the pressure fluctuations in the Francis turbine. Afterward, the energy ratio of each frequency band to the original signal is calculated, which is to realize the feature extraction of multidimensional frequency band energy ratio. Actual applications verify that this method not only can extract the time-frequency characteristics but also can analyze the condition feature of the pressure fluctuation. It is a novel method for extracting the feature of pressure fluctuation in the Francis turbine.

1. Introduction

Hydropower accounts for the largest proportion of renewable energy sources and plays an important role as a clean energy in the world's energy structure [1]. Due to the inherent structural characteristics of Francis Turbine, once it works at certain off-design conditions, the flow will be unsteady, so there will be a positive or negative circulation in the runner exit. Moreover, some hydraulic instability phenomenon such as runner inlet and outlet flow separation, channel vortex, and draft tube vortex will appear. Therefore, the Francis turbine can only operate stably in a certain load range, which is one of its inherent characteristics [2]. The draft tube vortex is one kind of hydraulic instability phenomenon, which occurs when the Francis turbine is running out of optimum conditions, especially under the partial load condition [3]. The pressure fluctuation caused by the draft tube vortex is one of the most important vibration sources of Francis turbine and has an important influence on the stability of operation [4, 5]. When the pressure fluctuation passes through the flow passage parts and structures, the vibration of the unit, the period swing of the shaft, and the vibration of the head cover of the Francis turbine may be caused [6, 7]. When the pressure fluctuation resonates with the water body in the pressure pipeline, it will cause the vibration, output oscillation of the hydropower generating unit, and even have an influence on the electric power system [8, 9]. In recent years, some large and giant Francis turbines have been put into operation, whose size and specific speed have increased, while relative stiffness has weakened; hence the hydraulic instability problems have become more serious [10]. Therefore, in order to improve the hydraulic stability of Francis turbine, it is necessary to research the inherent mechanism and performance characteristics of the pressure fluctuation and their influences on the operation stability of Francis turbine [11].

At present, there are many methods used to the pressure fluctuation signal processing, such as short-time Fourier transform and wavelet transform. However, their essential flaws limit their performance [12]. The actual measured pressure fluctuation signal has a distinct nonlinear and nonstationary characteristic. FFT assumes that the signal is linear and stationary, so it has an insurmountable limitation for the signal with strong shock mutations and nonstationary characteristics, which may lead to harmonic distortion problem. Wavelet analysis is an important method of time-frequency analysis; however, the selection problem of primary function still exists. HHT is a new method for nonlinear and nonstationary signal analysis. It can decompose signal into different scale fluctuations adaptively and produces a series of data sequences with different characteristic scales. Compared with FFT, HHT can deal with nonstationary and transient problems, and, compared with wavelet transform, HHT has the advantage of multiresolution, and there is no selection problem of primary function [13]. Currently, HHT analysis methods are used in many areas, like gear fault diagnosis [14, 15], bearing fault diagnosis [16, 17], wind power characteristics analysis [18], pneumatic conveying flow characteristics analysis [19], and so on. In the aspect of pressure fluctuation analysis and feature extraction, Feng and Chu used HHT method to analyze the pressure fluctuation signal in the draft tube during the start-up process and confirmed that the HHT method can effectively extract the low frequency and unsteady characteristics of the pressure fluctuation signal [20].

There are many kinds of pressure fluctuations in the Francis turbine, which have different effects on the operation reliability of the unit [21, 22]. At present, most of the analysis methods of pressure fluctuation signal focus on the extraction of amplitude and frequency characteristics, without considering its condition features. Moreover, the frequency characteristics of different pressure fluctuation have not been analysed specifically. In this paper, a multidimensional frequency band energy feature extraction method for the pressure fluctuation of Francis turbine is proposed. The HHT was performed on the pressure fluctuation signal for the time-frequency analysis, and a multidimensional frequency band concept for pressure fluctuation of Francis turbine is proposed, which helps to find out the underlying mechanism affecting the pressure fluctuation amplitude and proved the feasibility of this method on the pressure fluctuation analysis of Francis turbine.

2. Multidimensional Frequency Band Energy Ratio Feature Extraction Method

Pressure fluctuations in the Francis turbine may have different frequencies and operating condition features. In terms of frequency characteristics, there are several kinds of frequencies related to vortex, rotation, and the blades [23]. In recent years, it has been continually found some kinds of pressure fluctuations with other frequencies existing in some large Francis turbines, for example, pressure fluctuation with a frequency of 1 to 4 times the rotation frequency [24–26] and frequency related to the number of the leaf and the rotation frequency [21]. In terms of operating condition feature, under low partial load, pressure fluctuation with rotation frequency and other higher frequencies may appear [26, 27]. Under the partial load condition, the draft tube vortex pressure fluctuation with a low frequency is taken as the main factor of the pressure fluctuation which may occur in the flow channel [10]. Under the high load area, Karman Vortex, channel vortex, higher part load pressure fluctuation, and so on may appear [28, 29]. Thus, it can be seen that there will be different types of pressure fluctuation under diverse operating conditions, and their frequency characteristics are also different. Therefore, the analysis of pressure fluctuation is not only for the extraction of the amplitude and frequency characteristics, but also for the analysis of the condition feature.

The most common method of the pressure fluctuation partition for the Francis turbine is to divide it into three parts of low, medium, and high according to their frequency characteristics [21, 27]: low frequency pressure fluctuation (it is generally about 1/6~1/2 times of the rotational frequency); medium frequency pressure fluctuation (it is about 1~4 times of the rotational frequency, most of which are caused by the rotation of the runner); high frequency pressure fluctuation (the frequency may be related to the number of guide vanes, the number of blades, and the rotation speed of the unit). Therefore, this paper constructs the high-medium-low three frequency bands according to the frequency characteristics of the pressure fluctuation which may occur in the Francis turbine. By means of mode analysis combined with Principal Component Analysis (PCA), the energy ratios of pressure fluctuation belonging to different frequency bands are computed. Thus, the amplitude and frequency characteristics of the pressure fluctuation components are extracted, and the condition feature of the pressure fluctuation can be analyzed. Based on this method, the dominant frequency components that increase the amplitude of the pressure fluctuation can be analyzed.

According to the above-mentioned frequency characteristics of pressure fluctuation, three bands are constructed: the low frequency band of 0~2.5 Hz (the rotation frequency of the test Francis turbine) representing the low frequency vortex pressure fluctuation of the draft tube; the medium frequency band with a range of 2.5 Hz~10 Hz representing the frequency of higher part load pressure fluctuation and analogous rotational pressure fluctuation; and the high frequency band whose frequency is more than 10 Hz representing leaf number of frequency of pressure fluctuation.

The measured pressure fluctuation signal contains several vibration modes. In this paper, the HHT algorithm is used to analyze the mode components of the pressure fluctuation and do the time-frequency analysis. The HHT algorithm includes two parts [30]: Empirical Mode Decomposition (EMD) and the Hilbert transform. A signal can be decomposed into a finite set of IMFs by using the EMD without a priori basis assumption. The first extracted IMF corresponds to the highest frequency component of the signal, whereas the lower frequency components are represented by higher-order IMFs. The result of EMD decomposition may have the problem of mode mixing [31]; that is, an IMF contains extremely different characteristic time scales, or similar feature time scales are distributed in different IMFs. EEMD is an improved method of EMD, which can well solve the modal aliasing problem of EMD [32]. Therefore, EEMD is utilized to decompose the pressure fluctuation signal in this paper.

After mode decomposition, the original signal $y(t)$ can be expressed as a combination of a certain number of IMF components and a residual component, as shown in

$$y(t) = \sum_{i=1}^{n} \mathrm{IMF}_i(t) + r_n(t). \quad (1)$$

Then, the frequency characteristic of each IMF component is analyzed by Hilbert marginal spectrum. As the IMF component is stable, it has the physical meaning to calculate the instantaneous frequency of the IMF component by the Hilbert transform [30]. The equation can be expressed as

$$h(\mathrm{IMF}_i(t)) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{\mathrm{IMF}_i(\tau)}{t-\tau} d\tau. \quad (2)$$

Constructing the interpretation signal with the intrinsic mode function components,

$$z_i(t) = \mathrm{IMF}_i(t) + jh(\mathrm{IMF}_i(t)) = a_i(t) e^{j\varphi_i(t)}. \quad (3)$$

The instantaneous amplitude and phase can be expressed as

$$a_i(t) = \sqrt{\mathrm{IMF}_i(t) + h^2(\mathrm{IMF}_i(t))}, \quad (4)$$

$$\varphi_i(t) = \arctan \frac{\overline{h_i}(t)}{h_i(t)}. \quad (5)$$

Thus, the instantaneous frequency is expressed as follows:

$$f_i(t) = \frac{1}{2\pi} w_i(t) = \frac{1}{2\pi} \times \frac{d\varphi_i(t)}{dt}. \quad (6)$$

The original signal $y(t)$ without $r_n(t)$ can be expressed as the sum of all the explanatory signals' real part:

$$x(t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t) e^{j\varphi_i(t)} = \mathrm{RP}\sum_{i=1}^{n} a_i(t) e^{j\int w_i(t)dt}. \quad (7)$$

The Hilbert spectrum can accurately describe the change of the signal amplitude with the changing of time and frequency under the entire frequency domain, as it is shown in the following:

$$H(w,t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t) e^{j\int w_i(t)dt}. \quad (8)$$

Hilbert marginal spectrum can show that the signal amplitude changes with frequency in the whole frequency domain, and it can reflect the actual frequency component of the signal more accurately [33]. The magnitude of the marginal spectrum indicates that the sum of the amplitudes of the signal at each time of the frequency can not only improve the frequency resolution but also remove other uncorrelated frequency components [34]. Therefore, in this paper, the Hilbert marginal spectrum is used to extract the frequency characteristics of IMF components. The calculation formula is shown in the following:

$$h(w) = \int_0^T H(w,t)\, dt. \quad (9)$$

Finally, according to the frequency characteristics of the IMF component shown in Hilbert marginal spectrum, the IMFs are divided into the corresponding frequency band to calculate the total energy ratios of each frequency band. The pressure fluctuation multidimensional frequency band energy ratio characteristic is represented by the energy distribution coefficients P. The energy ratios of high, medium, and low frequency band are expressed by P_h, P_m, P_l. In this way, the extraction of multidimensional frequency band energy proportion characteristic of pressure fluctuation is realized. The calculation formula is shown in the following:

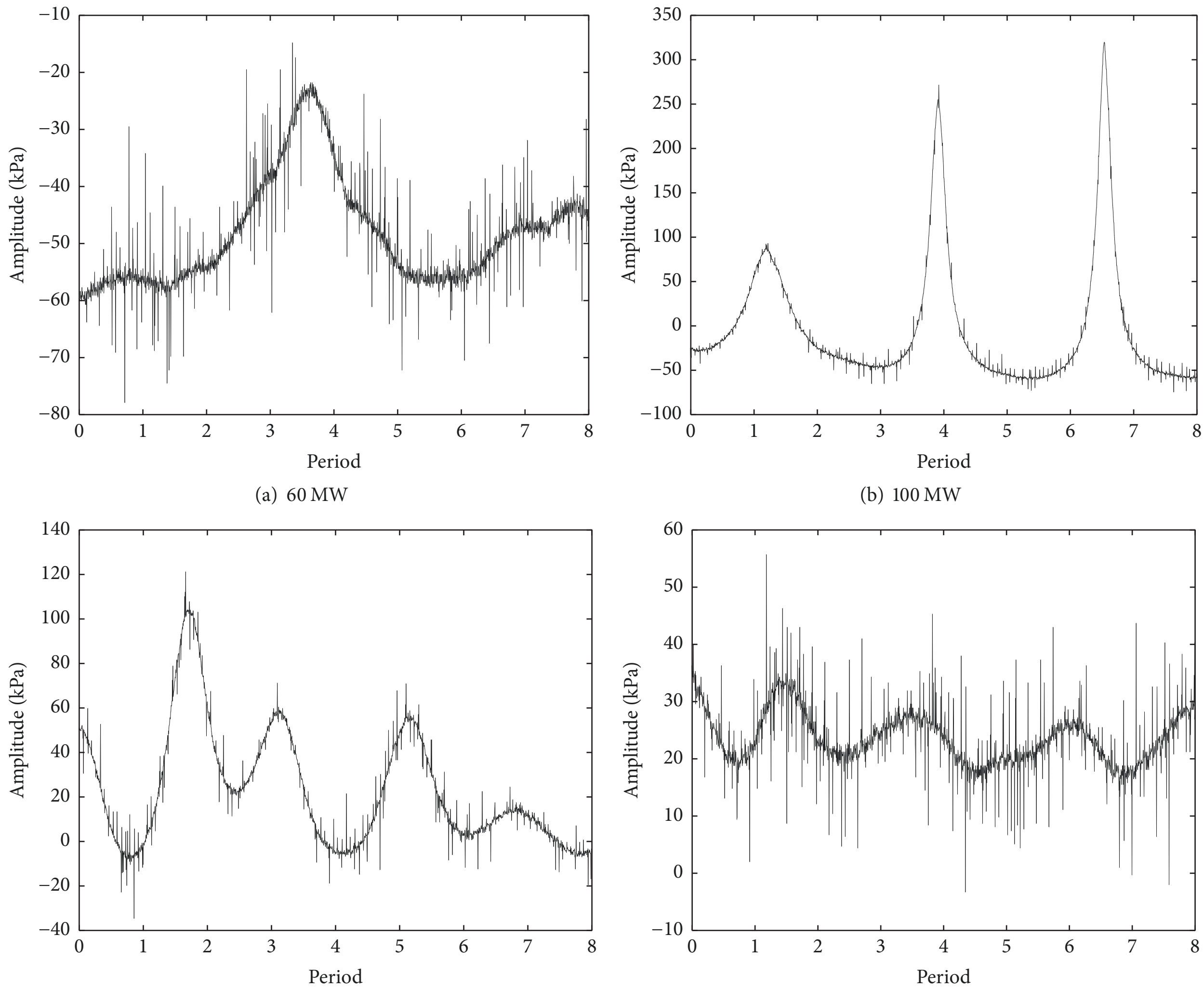
$$\begin{aligned} E_i &= \int_{-\infty}^{+\infty} \left|\mathrm{IMF}_i\right|^2 dt, \\ P_h &= \frac{E_h}{E}, \\ P_m &= \frac{E_m}{E}, \\ P_l &= \frac{E_l}{E}, \end{aligned} \quad (10)$$

where E_h, E_m, and E_l represent the energy sum of the high frequency band, medium frequency band, and low frequency band, respectively; E is the total energy of the pressure fluctuation signal, and IMF_i is the ith IMF component.

3. Case Study and Discussion

Most of the pressure fluctuations in the Francis turbine are reflected in the draft tube, in which the measured value at the taper pipe part is the most important representative of the hydraulic stability [6]. Therefore, this paper takes the measured signal from the taper pipe part of a 200 MW Francis turbine whose rotation frequency is 2.5 Hz as an example to discuss the method and analyze the inner mechanism of pressure fluctuation of large Francis turbine.

3.1. Time Domain Analysis and Multidimensional Frequency Band Energy Distribution Analysis by Using FFT. The amplitude and frequency characteristics of pressure fluctuation and their variation law can be visualized in the waves of different load signals. After analysis and comparison, the analysis results of the signals which are measured from a same working conditions are not obvious, so, in the analysis below, only one signal analysis result of all conditions is selected for display. Figure 1 shows the original waveform of the pressure fluctuation signal under load of 60 MW, 100 MW, 140 MW, and 180 MW. It can be seen from the figure that pressure fluctuation signals are obvious nonstationary, and the frequency components of the signal are changing with time. The fluctuation is much intense at 100 MW and 140 MW and tends to be stable at 180 MW. Figure 2 shows the trend curve



(a) 60 MW
(b) 100 MW
(c) 140 MW
(d) 180 MW

Figure 1: The wave of pressure fluctuations under different load.

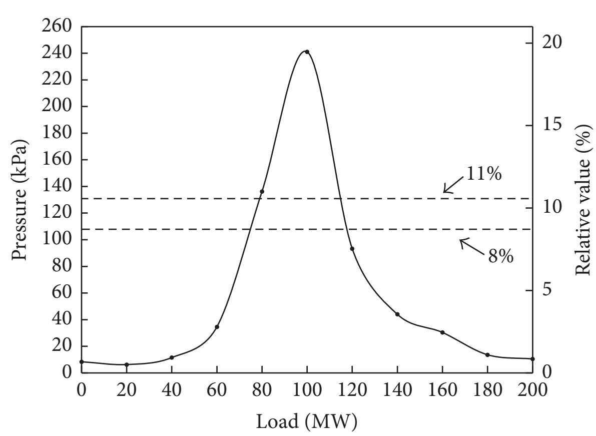
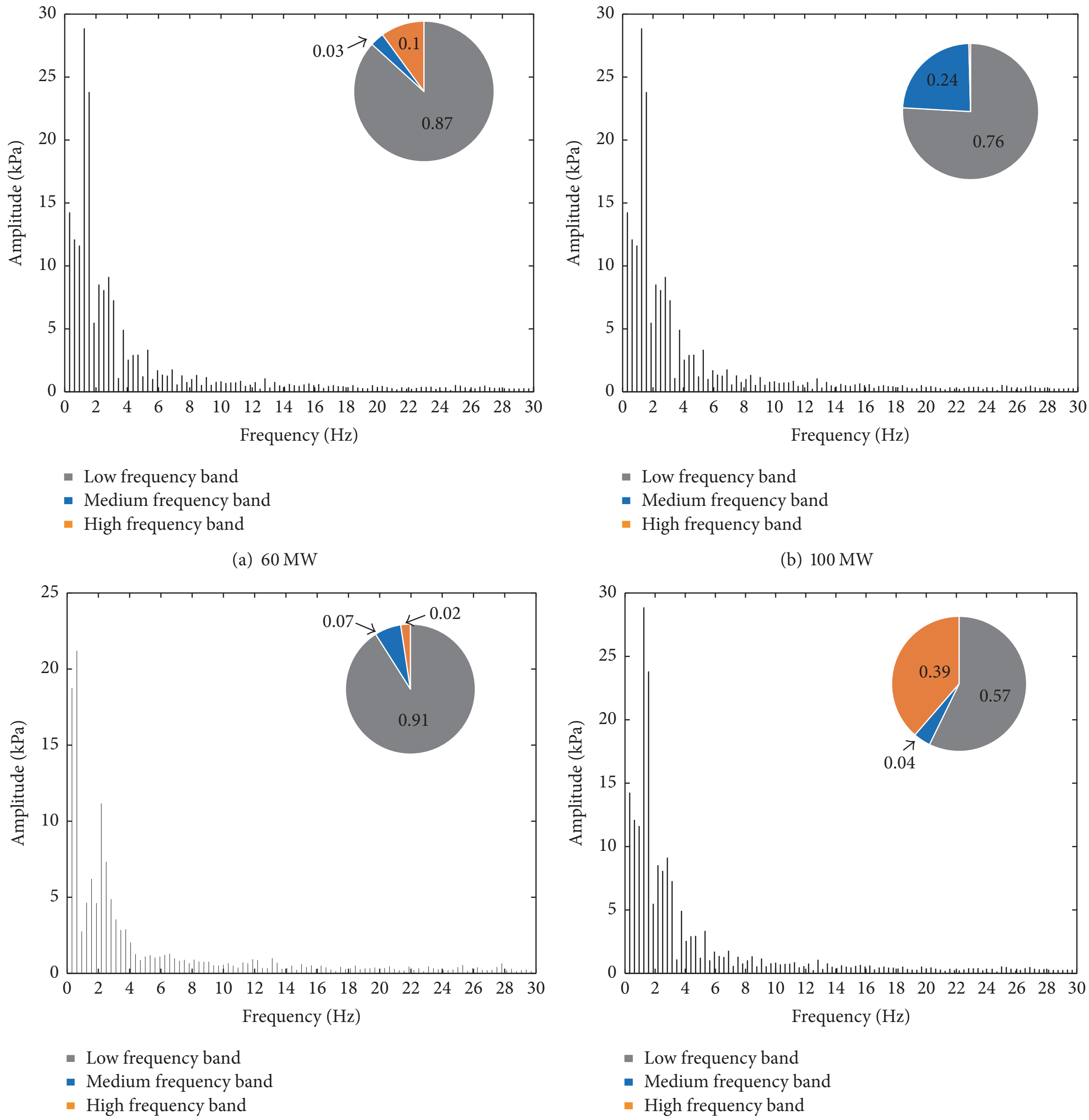


Figure 2: The curve of pressure fluctuation peak to peak values varies with the load.

of pressure fluctuation amplitude with load. It can be seen that the pressure fluctuation does not change significantly in the range of 0~40 MW, and the amplitude is smaller. The amplitude increases rapidly starting from 40 MW. The maximum point of 230 kPa occurs under 100 MW, and the relative value is 19%. The secondary amplitude of 130 kPa appears in the 80 MW with a relative value of 11%. With the load increases to full, the amplitude decreases gradually. As shown in the right Y-axis of the figure, the relative value ($\Delta H/H$) of the pressure fluctuation is less than 2% within the 0–40 MW, more than 3% from 60 MW to 140 MW, which is greater than 8% in the range of 80 MW to 120 MW and greater than 15% around the 100 MW.

Figure 3 shows the spectrum and the multidimensional frequency band energy distribution of pressure fluctuations signals under those four loads which are calculated by FFT. It can be seen that the spectrum of FFT can show the components of the signal in frequency domain, but it cannot analyze the time-frequency characteristic of the signal. From the multidimensional frequency band energy distribution, it can be seen that the signals' frequency components of 60 MW and 180 MW are mainly low frequency, but, accompanied by



(a) 60 MW (b) 100 MW (c) 140 MW (d) 180 MW

Figure 3: The spectrum and the multidimensional frequency band energy distribution of pressure fluctuations calculated by FFT.

obvious high frequency components, the overall amplitude of the frequency components is lower than 100 MW and 140 MW. Under the load of 100 MW, there are almost no high frequency components, the low frequency band energy accounts for 76%, and the middle frequency band energy accounts for 24%. At 140 MW, low frequency band energy accounts for 91% and middle frequency band energy ratio is 7% and has less high frequency band energy.

The energy distribution of multidimensional frequency bands can be obtained by using FFT. However, because of FFT's own limitations on signal linearity and stability hypothesis, it may lead to inaccurate frequency analysis of the nonlinear unsteady pressure fluctuation signal [20]. Moreover, the amplitude of a point frequency in the FFT spectrum indicates the trigonometric function component containing the frequency in the whole signal, and there may be some unnecessary harmonic components [12], which may finally lead to inaccurate analysis of the energy distribution of the multidimensional frequency band. Therefore, in order to accurately analyze the components' characteristics and accurately realize the multidimensional frequency energy ratio analysis of pressure fluctuation signal, a time-frequency analysis method which is suitable for nonlinear nonstationary pressure fluctuation signal is needed.

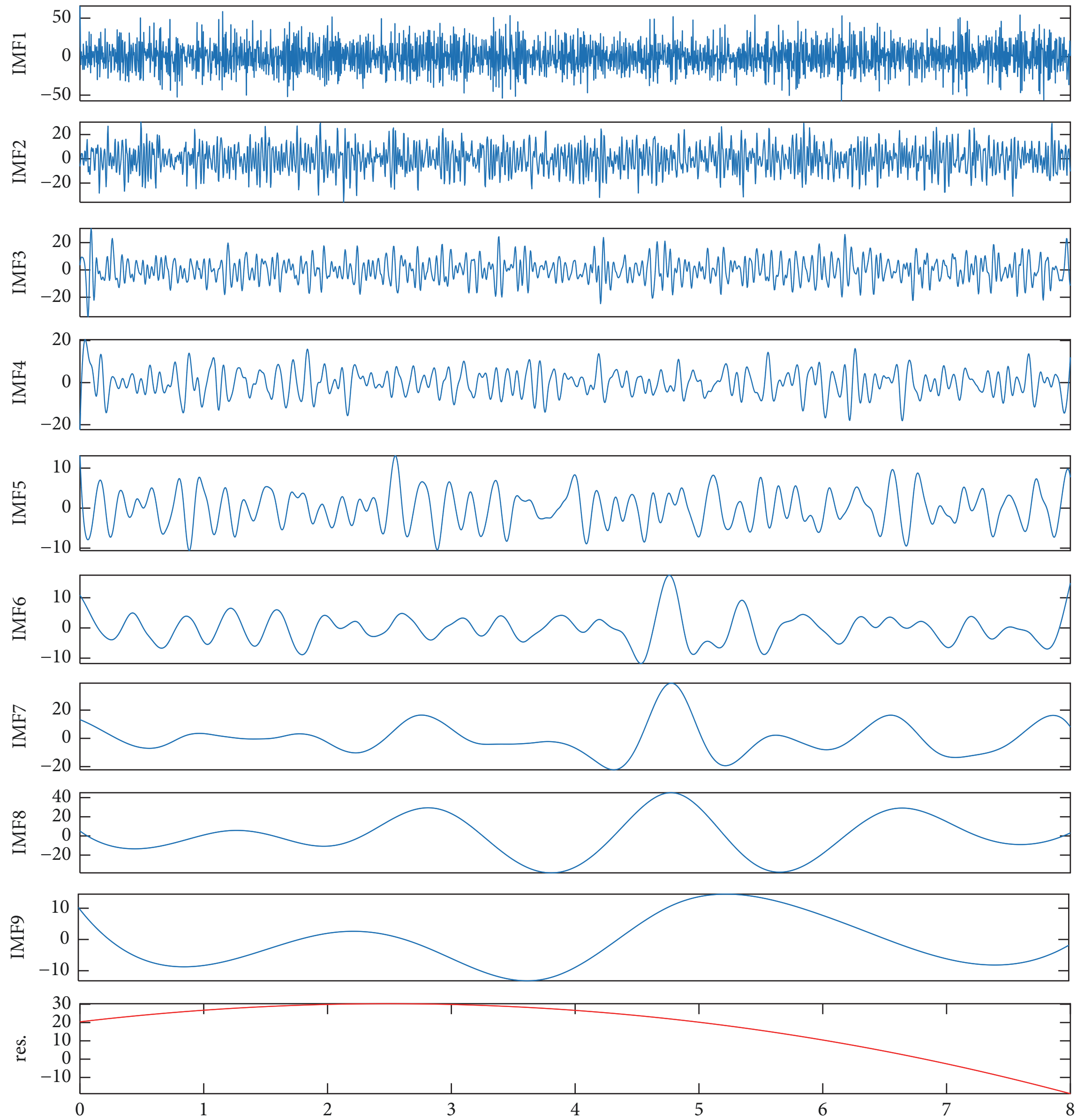


Figure 4: The results of EEMD.

3.2. Extraction and Analysis of Multidimensional Frequency Band Energy Ratio by HHT. The pressure fluctuation signal under 100 MW was used as an example to show the signal analysis process by HHT. Figure 4 is the decomposition results of the signal by EEMD (in this paper, the embedded dimension and Gaussian white noise level of EEMD are set to 100 and 0.2 [32, 35]). The coordinate points of the ordinate from top to bottom are as follows: IMF1~IMF9 are the IMF components and res is the residual component. It can be seen from the diagram that the amplitude of IMF1~IMF3 is small and the frequency is higher, which can be judged as high frequency noise components. The amplitude of IMF4~IMF9 is obvious and the energy is large, which may be the dominant component of the signal.

The Hilbert spectrum analysis of IMFs is shown in Figure 5; after the IMF components transformed by HHT, the instantaneous frequency is uniformly distributed in the low frequency region at the whole time axis. The frequencies are below 2.5 Hz, and a small amount of high frequency occurs at some time. It can be seen that the low frequency component occupies the leading position in the middle load range and the influence of the low frequency component on the pressure fluctuation should be emphatically analyzed. Compared with FFT analysis results in the above, Hilbert-Huang spectrum as a time-frequency analysis method not only can show the frequency components contained in the signal, but also has the advantage of showing the changing law of frequency components with time. So the HHT is more suitable for the analysis of nonlinear and nonstationary signal.

The Hilbert marginal spectrum analysis of the pressure fluctuation signal under 100 MW is shown in Figure 6. As it can be seen from the diagram, the main frequency of the

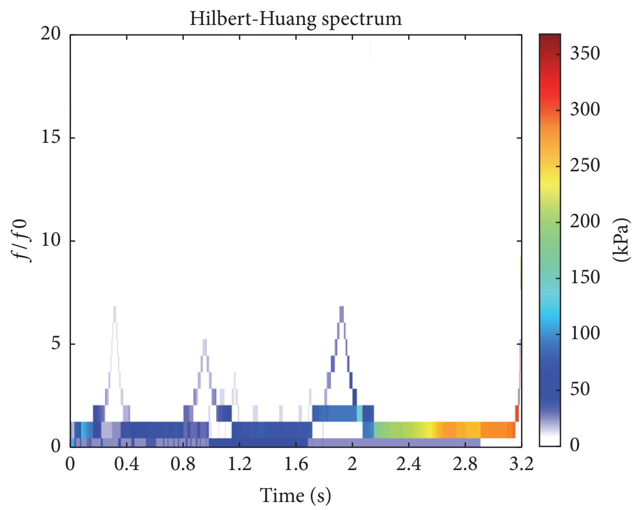


Figure 5: The Hilbert-Huang spectrum.

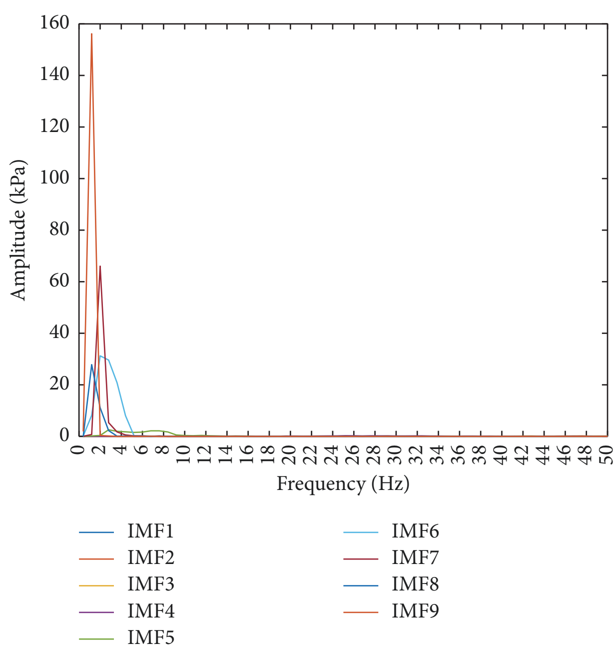


Figure 6: Hilbert marginal spectrum of IMFs.

IMF component is below 3 Hz, the amplitude of the IMF9 component is the maximum, its corresponding frequency is 1.2 Hz, the amplitude of the IMF7 is the second, and its corresponding frequency is 2 Hz. The Hilbert marginal spectrum has a clearer display of frequency components than FFT and no unnecessary harmonic components. Therefore, the HHT can better analyze the characteristics of pressure fluctuation signal.

The frequency characteristics of the IMFs are analysed by the Hilbert marginal spectrum. Then, they are divided into high, medium, and low frequency bands according to their inner frequencies. By calculating the total energy ratio of the IMFs in each frequency band to the signal energy can obtain the multidimensional frequency band energy ratio

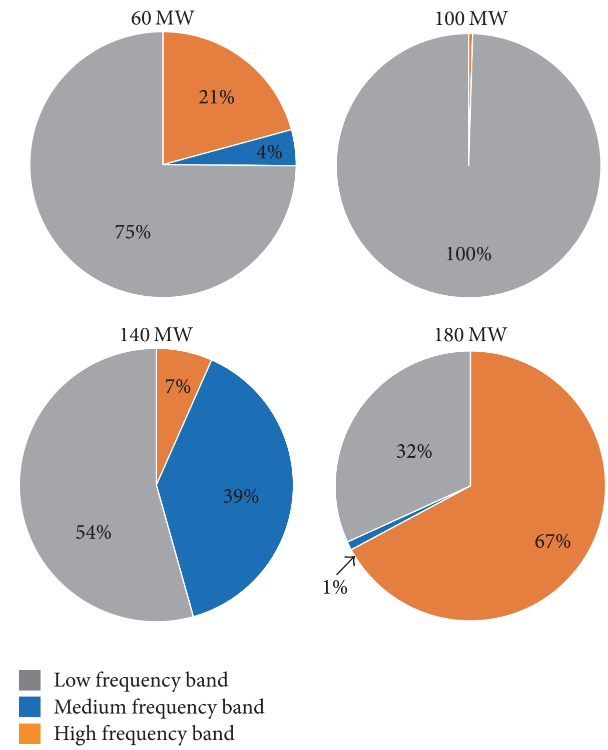


Figure 7: Different frequency bands energy distribution of pressure fluctuation under different load.

characteristics of the pressure fluctuation signal. The computation results of pressure fluctuation signals under 60 MW, 100 MW, 140 MW, and 180 MW are shown in Figure 7. It can be seen that the energy is mainly distributed in the low frequency band at 60 MW, accounting for about 2/3, and the remaining 1/3 is occupied mostly by the high band energy; the medium frequency band energy only takes up a small part. At 100 MW, the energy ratio of low frequency band is close to 100%. At 140 MW, the low frequency band energy accounts for most of the total energy, the middle band energy seizes 39%, and the high band energy occupies a small part. In the 180 MW, high frequency band energy accounts for about 2/3; low-band energy takes up the majority of the rest. It can be seen that the energy consumption of the three bands under each load is different, and the difference of the pressure fluctuation type under each load is also reflected.

The multidimensional frequency bands energy ratio calculation results of the pressure fluctuation signals at intervals of 20 MW are shown in Table 1. Figure 8 is a histogram of the calculation results and the variation trend of pressure fluctuation amplitude with load. As it can be seen from Table 1 and Figure 8, in the low part load range of 0~40 MW, the energy ratio in the high frequency band is relatively large, accounting for more than 80%, the low frequency energy is less, and there is less energy component in the medium frequency band, and the amplitude of pressure fluctuation is less. In the part load range of 60~160 MW, the energy is mainly concentrated on the low frequency band, while containing a certain medium frequency band energy, and we can see that medium frequency band energy accounted

Table 1: Different frequency bands energy ratio and the amplitude of pressure fluctuation.

Load/MW	High frequency band/%	Medium frequency band/%	Low frequency band/%	Amplitude/kPa
00	0.98	0.01	0.01	8.0
20	0.86	0.00	0.14	6.0
40	0.81	0.00	0.19	11.0
60	0.21	0.04	0.75	33.0
80	0.03	0.03	0.94	130.0
100	0.00	0.00	1.00	230.0
120	0.02	0.03	0.96	89.0
140	0.07	0.39	0.54	42.0
160	0.29	0.00	0.71	29.0
180	0.67	0.01	0.32	13.0
200	0.86	0.00	0.14	10.0

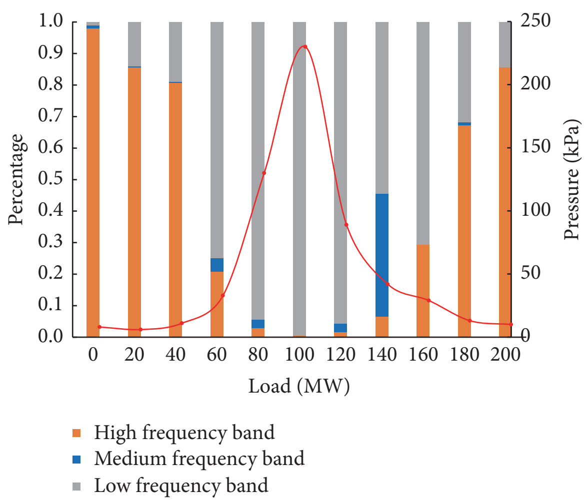


Figure 8: Different frequency bands energy distribution and the amplitude curve of pressure fluctuation.

for significant 39% in 140 MW. During this load range, the pressure amplitude is relatively larger. In the load range of 80~120 MW, low frequency energy owns the largest proportion, whose value was more than 90%, under the 100 MW, the low pressure energy ratio of the pressure fluctuation is 100%, and the amplitude of the pressure fluctuation reaches the maximum at 120 MW; here the low frequency energy ratio is 96%. In the high load area of 180~200 MW, the energy in the high frequency band increases again, but the low frequency energy also occupies a certain proportion, and the amplitude of the pressure fluctuation decreases.

Through the analysis of the multidimensional frequency band energy ratio characteristics of the pressure fluctuation, it can be seen that the main reason for the amplitude increasing is the low frequency components, and the medium frequency component also plays a certain role. By comprehensively analysing the multidimensional frequency band energy ratios of pressure fluctuations under different loads, we can see that the condition characteristics of pressure fluctuations are discrepant. The main component of the pressure fluctuation under low and high part load is high frequency components. In the partial load area, the main component is low frequency pressure fluctuations and also comes with a certain medium frequency pressure fluctuation. This method can clearly get the energy ratio of different frequency bands under each operation condition, and it has a good effect on analysing the main frequency components of pressure fluctuation signal and their effect on the pressure fluctuation amplitude. From the above analysis, it can be seen that the method proposed in this paper can well extract and analyze the amplitude-frequency and working conditions characteristics of pressure fluctuation signal of Francis turbine.

4. Conclusions

The feature extraction of the hydraulic pressure fluctuation signal is of great importance to the analysis of the mechanism of pressure fluctuation and its influence on the stability of the hydroelectric unit. In this paper, a multidimensional frequency band energy ratio analysis method for the pressure fluctuation of Francis turbine is proposed based on the summary of all possible pressure fluctuation characteristics and HHT. By the actual data analysis, three main conclusions are obtained.

(1) For the nonlinear and nonstationary characteristics of pressure fluctuation signal, the HHT which is based on EEMD and Hilbert marginal spectrum can achieve better analysis results than FFT. It can not only analyze the frequency characteristic of signal mode components changing with time but also can accurately realize the frequency characteristics extraction of different mode components.

(2) The feature extraction method of multidimensional frequency band energy ratio can not only observe the energy distribution of pressure fluctuation in different frequency bands but also analyze the condition characteristics of it by comparing the analysis results under different working conditions. It is much effective to analyze the representative frequency components contained in the signal and the mechanism behind the increase of the pressure fluctuation amplitude.

(3) The pressure fluctuation measured at the taper pipe of the Francis turbine draft tube has a large amplitude under the central load region. It is mainly due to its low

frequency components, and the pressure fluctuations in the medium frequency band also play a certain role. The specific interaction mechanism of low frequency components on the pressure fluctuation amplitude should be further studied.

However, in order to realize the specific analysis of hydraulic pressure fluctuation, the division range of multidimensional frequency band could be carried out according to the rotation frequency and hydraulic stability behavior of the targeted unit.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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