Study on vibration test of SF6 circuit breaker based on wavelet packet-energy spectrum analysis in Arctic Area

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Abstract. Mechanical vibration signal of circuit breaker contains a large amount of equipment state information. Vibration monitoring is the main method of non-intrusive monitoring of mechanical fault of high voltage circuit breakers. Based on vibration monitoring of SF6 circuit breaker in arctic condition, this paper puts forward a method based on wavelet packet to process vibration signals of circuit breaker. The energy percentages on each frequency band, which are obtained by wavelet package-energy spectrum analysis, are used as the feature parameter to carry out the fault diagnosis of SF6 circuit breakers in the arctic area. And the characteristic fingerprint database of vibration signal of the SF6 circuit breaker in the arctic area was established. Wavelet packet transform can adaptively select the corresponding frequency band according to the characteristics of the signal being analysed, so that it can match with the signal spectrum to improve the time-frequency resolution of the signal processing. The signals from the wavelet packet orthogonal decomposition in each frequency band are independent and the energy in each frequency band is conserved. The measured results of vibration signals of SF6 circuit breaker show that the wavelet packet-energy spectrum is consistent with Fast Fourier Transform (FFT) spectrum analysis.

1. Introduction
In the eastern part of Inner Mongolia, the temperature in winter is low, the outdoor environment temperature will fall below -40℃, and in some areas it will even reach -50℃. The low temperature will affect the operating state of the circuit breaker, which threatens the safe operation of the circuit breaker. Because the high voltage circuit breaker is a kind of instantaneous non-stationary vibration, it will produce the characteristics of high intensity impact and high speed movement when switching operation. The driving force generated by the action can reach tens of thousands of cows, and the change of the vibration acceleration is more obvious. In a few milliseconds, the vibration acceleration can reach 100 times the magnitude of the gravity acceleration [1]. This kind of strong impact vibration provides abundant information for the condition monitoring of high-voltage circuit breakers. Therefore, it is of great significance for the fault diagnosis of circuit breakers to monitor the switching vibration signal of high voltage circuit breaker in arctic condition.
The traditional mechanical vibration signal processing method is analyzed by Fourier transform. The FFT spectrum analysis based on Fourier transform can theoretically reach infinity in the full frequency range, but the resolution of time domain is zero, so it is not suitable for the analysis of non-stationary signals [2]. At present, many time-frequency analysis methods such as short time Fourier transform, wavelet decomposition, wavelet packet decomposition (WPD) and empirical mode decomposition (EMD) are used to study the vibration signals. In the short time Fourier transform, the sampling interval between the time domain and the frequency domain is constant, and the window is fixed without adaptability. The wavelet transform has better time-frequency localization performance, but it only decomposes the low frequency components, and the high frequency components will no longer be decomposed, which causes the incompatibility of time resolution and frequency resolution. The wavelet packet decomposition develops the wavelet transform. It improves the wavelet "high frequency and low resolution" on the basis of maintaining the excellent characteristics of the wavelet orthogonal basis. It provides a more detailed analysis method for the vibration signals, and has the ability to adapt to the characteristics of different signals. The wavelet packet decomposition can select the best fundamental wave function for the signals of different frequency ranges, so it has a strong localized analysis capability. The signal after orthogonal decomposition of wavelet packet has the characteristics of signal independence and energy conservation in each frequency band, which is more suitable for time-frequency analysis and energy spectrum analysis of vibration signals [3]. Therefore, it is of practical significance to apply wavelet packet transform to the mechanical fault diagnosis of high voltage circuit breakers.

2. Wavelet packet correlation theory

The wavelet packet is a generalization of the wavelet concept. Compared with the wavelet decomposition, it can divide the frequency band into multiple levels and further subdivide the high frequency part of the signal. It adaptively selects the corresponding frequency band according to the characteristics of the analyzed signal to match with the signal spectrum, so it has better time-frequency localization capability.

2.1. Wavelet packet definition

In multi-resolution analysis, given orthogonal scale function and wavelet function, the scale relationship is:

\[ \phi(t) = 2^{1/2} \sum_{n \in \mathbb{Z}} h_n \phi(2t-n) \] (2.1)

\[ \psi(t) = 2^{1/2} \sum_{n \in \mathbb{Z}} g_n \phi(2t-n) \] (2.2)

In equation (2.1), \( h_n \) represents high pass filter coefficients in multi-resolution analysis; In equation (2.2), \( g_n \) represents low pass filter coefficients in multi-resolution analysis.

To further generalize the two-scale equations, the following recursive relationships are defined:

\[ \mu_{2m}(t) = 2^{1/2} \sum_{n \in \mathbb{Z}} h_n \mu_{m}(2t-n) \] (2.3)

\[ \mu_{2m+1}(t) = 2^{1/2} \sum_{n \in \mathbb{Z}} g_n \mu_{m}(2t-n) \] (2.4)

When \( n=0 \), \( \mu_0(t)=\phi(t) \), \( \mu_1(t)=\psi(t) \).

The set of functions defined above \( \{ \mu_n(t) \}_{n \in \mathbb{Z}} \) is a wavelet packet determined by \( \mu_0(t)=\phi(t) \).

2.2. Space decomposition of wavelet packet

Let \( \{ \mu_n(t) \} \) be the wavelet packet family for \( h_n \), considering generating subspace families in the following manner [4]. Let \( n=1,2,\cdots; j=1,2,\cdots \); And for the iterative decomposition of equation (2.3) and (2.4), there are:
\[ W_j = U_j^1 = U_j^{2^1} \oplus U_j^{3} \]
\[ W_j = U_j^{2^1} \oplus U_j^{2^2+1} \oplus \cdots \oplus U_j^{n_{max}} \oplus U_j^{2^{n_{max}+1}} \]  \( (2.5) \)

So, various decompositions of the wavelet subspace \( W_j \) are obtained, as shown in equation 2.6.
\[ W_j = U_j^{2^k} \oplus U_j^{2^k+1} \oplus \cdots \oplus U_j^{n_{max}} \oplus U_j^{2^{n_{max}}+1} \]  \( (2.6) \)

Decomposition of the subspace \( W_j \) by the wavelet packet is equivalent to dividing the frequency band of \( W_j \) into \( 2^k \) bands \([5]\). The complete decomposition of the wavelet packet subspace is shown in Figure 1.

![Figure 1. The relationship chart of the partition and regroup in space according to the wavelet packet transform.](image)

In the wavelet decomposition of the signal, the wavelet basis function has only two parameters of discrete scale \( j \) and discrete translation \( k \). The wavelet basis function is characterized by these two parameters:
\[ \psi_{j,k}(t) = 2^{j/2} \phi(2^j t - k) \]  \( (2.7) \)

In addition to the two discrete parameters, the wavelet packet basis function also adds a frequency parameter (or the number of zero crossings) \( n = 2k + m \). The parameter \( n \) represents the number of zero crossings of the wavelet packet basis function, that is, the number of oscillations of the waveform. It is the function of this frequency parameter that makes the wavelet packet overcome the disadvantage of low frequency resolution when the wavelet time resolution is high. The wavelet packet basis is generally expressed as:
\[ \psi_{j,k,n}(t) = 2^{(j-k)/2} W_{2^k+m}(2^{j-k} t - 1) \]  \( (2.8) \)

It should be noted that the frequency bandwidth \( \Delta f \) and the number of decomposition layers \( N \) and the sampling frequency of the wavelet packet decomposition \( f_s \) satisfies the following relationship \([6]\):
\[ \Delta f = f_s / (2 \times 2^N) \]  \( (2.9) \)

According to the above equation, we can choose the appropriate number of decomposition layers and sampling frequency to obtain the required frequency band width and the start and stop frequency of each frequency band, so the frequency segment containing characteristic parameters in the signal can be separated.

2.3. Wavelet packet-energy spectrum

The decomposition results of wavelet packets are expressed in terms of energy as wavelet packet-energy spectrum \([7]\).

Let the original signal be \( f(x) \). In the wavelet transform, the squared sum signal of the Euclidean norm of the signal is equivalent to the energy in the time domain, so the energy of the original signal and the energy of the wavelet transform have the following relationship:
\[ \int_R |f(x)|^2 \, dx = \| f \|_2^2 = \int_R \int_R W_f(a,b)^2 \, da \, db \]  \( (2.10) \)

In the wavelet packet energy spectrum, the sum of squares of signals in each frequency band is used as a feature of energy. After \( j \)-layer wavelet packet decomposition of the original signal, the
energy of each frequency band (or subspace $W_{2j}$) is the sum of the squares of the wavelet coefficients of the segment:

$$G_m = \sum_{k=1}^{2^j} |W_m(k)|^2$$

(2.11)

In equation (2.11), $m=1,2,\cdots, 2^j$.
This infers the expression of total energy as:

$$G_u = \sum_m \sum_{k=1}^{2^j} |W_m(k)|^2 = \sum_m G_m$$

(2.12)

Since the width of the frequency band after wavelet packet decomposition is the same, taking the decomposition results in each frequency band as the input of the energy spectrum, a series of energy proportion ratio histograms can be made according to the proportion of the energy in each frequency band to the total energy. The sum of height of the histogram is equal to 1. The height of each histogram reflects the proportion of the energy of each frequency band in the total energy, so the characteristic frequency band of the signal can be intuitively identified as the theoretical basis for fault diagnosis.

3. Circuit breaker vibration test system in arctic area

In order to study the time-frequency switching vibration signal of SF6 high voltage circuit breaker in the arctic area, the SF6 high voltage circuit breaker at the 220kV Jibuhu switching station in the eastern part of Inner Mongolia was taken as a research object to carry out the arctic area SF6 circuit breaker vibration monitoring. Table 1 shows the main parameters of outdoor high voltage AC SF6 tank circuit breaker.

| Model                | Rated voltage | Rated voltage | Rated breaking current | Gas pressure rating |
|----------------------|---------------|---------------|------------------------|---------------------|
| LW30-252(T)/T4000-50 | 252kV         | 4000A         | 50kA                   | 0.6MPa              |

The SF6 circuit breaker vibration signal monitoring system is mainly composed of piezoelectric acceleration sensor, signal processing unit, acquisition card and LabVIEW PC monitoring system. The system has the advantages of simple operation, high reliability and stable operation. It can be stable to collect and store the switching vibration signal of SF6 high voltage circuit breaker. The field monitoring is shown in figure2.

4. The analysis of Vibration Test of SF6 Circuit Breaker

The operating mechanism of the circuit breaker is selected as the vibration measurement point, and the acceleration sensor is installed in the horizontal direction of the circuit breaker static contact to obtain the vibration signal of the circuit breaker opening and closing. Figure 3 represents the time-frequency diagram of the vibration signal generated by one closing of A-phase of the SF6 high voltage breaker under normal conditions. Among them, figure a shows the time domain vibration signal, figure b shows the frequency domain vibration signal.
In this paper, the wavelet packet decomposition is performed on the basis of the Fourier transform of A-phase switching vibration signal. The Daubechies6 wavelet was chosen as the wavelet basis function when implementing the wavelet packet analysis program. The number of layers of wavelet packet decomposition is closely related to the precision of time domain analysis of vibration signals. If the number of decomposition layers selected is small, the analysis speed is fast, which is especially obvious for high-band signals, but the band resolution is low; if the number of decomposition layers selected is large, the analysis speed is slow, but the band resolution is high [3]. Based on the actual situation and taking into account the time-varying and frequency-varying characteristics of the vibration signal, a 9-layer wavelet packet decomposition is applied to the normal phase breaker A-phase closing vibration signal. The characteristic curve of 512 frequency bands is obtained, and the first 8 are intercepted according to the actual situation. The characteristic curve of the frequency band is shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** The result of the wavelet packet decomposition of A-phase closing.

To intuitively analyse the percentage of total energy in each frequency band, the energy of each frequency band after wavelet packet decomposition under normal condition is calculated by using equation 2.11, and the wavelet packet-energy spectrum histogram of the A-phase circuit breaker closing vibration signal, as shown in Figure 5, is drawn.

![Figure 5](image_url)

**Figure 5.** Wavelet packet energy spectrum of A-phase closing vibration signal.

As shown in Figure 5, the change of the mechanical state of the circuit breaker can be reflected in the energy variation of each band of the wavelet packet, and the frequency band reflecting the most intense state change is concentrated in the high frequency part. The energy of the switching vibration signal of the A-phase circuit breaker is mainly distributed in the 2000Hz~2500Hz, which accounts for about 42% of the total energy of the wavelet transform; another part is concentrated in 1500Hz~2000Hz, accounting for about 20%, which is consistent with the frequency range established in the frequency domain diagram of the vibration signal, and is more able to refine the vibration’s distribution of signals in the frequency domain. According to the band division rule of wavelet packet combined with frequency domain diagram of vibration signal, the characteristic frequency parameters of the vibration signal should be decomposed into two bands - (9, 2), (9, 3), and the two frequency bands respectively correspond to the frequency range is (1.24 kHz to 1.86 kHz) and (1.86 kHz to 2.48 kHz).
kHz). According to the results of the A-phase closing wavelet packet decomposition in Figure 4, we can see that this deduction is correct. These two frequency bands can truly reflect the vibration process of the circuit breaker and can be used as the characteristic parameters of the circuit breaker vibration signal in extremely cold conditions.

For any kind of unknown fault vibration signal, the wavelet packet energy spectrum analysis is carried out and compared with the normal frequency spectrum, it can be known that the frequency segment which has obvious change has the classification of the fault of the high voltage circuit breaker, so as to achieve the purpose of fault prediction and diagnosis. Therefore, using wavelet packet-energy spectrum analysis can intuitively identify the characteristic frequency of the fault and quantify the frequency as the feature fingerprint of the vibration signal.

5. Conclusions

The vibration analysis method based on wavelet packet-energy spectrum can give the frequency distribution of the vibration signal at different time periods, and can intuitively identify the changes of each frequency band, then judging the failure symptoms of the circuit breaker and providing a theoretical basis for condition based maintenance and fault diagnosis of circuit breaker.

In this paper, the wavelet packet energy-spectrum method is used to analyze the vibration signals of the SF6 circuit breaker in arctic area, which can directly identify the changes in the frequency bands, and the experimental results show that the wavelet packet-energy spectrum and FFT Spectral analysis results are consistent. The vibration signal of the SF6 circuit breaker consists of low frequency and high frequency and the frequency band of the most intense mechanical state change is concentrated in the high frequency part.

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