Research on Denoising of Transformer Bushing Leads Based on IITD-WTD

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Abstract. When conducting ultrasonic testing of transformer bushing leads, the detection accuracy is susceptible to noise, and it is difficult to accurately determine the state of the leads in the bushing. Aiming at the common noise pollution problem of casing ultrasonic echo signal, we propose an improved inherent time scale decomposition (IITD) and wavelet denoising (WTD) joint denoising algorithm. First, the ultrasonic echo signal is decomposed by improving the time scale; then, the wavelet denoising algorithm is used to remove the noise of each decomposed component; finally, simulation examples and experimental verification show that the signal-to-noise ratio is higher after denoising using the algorithm in the article, the average error is smaller, and the effective vibration information in the ultrasonic echo can be effectively retained. Therefore, the algorithm has certain practical value in engineering applications.

1. Introduction

With the rapid increase in my country's electricity demand and the rapid development of the power industry, the issue of power supply reliability has attracted more and more attention[1-2]. As transformers are indispensable electrical equipment in all aspects of power generation, transmission, distribution and power consumption, it is necessary to study the stable operation of transformers. Although the transformer bushing is only an inconspicuous insulation device outside the transformer, it is also an indispensable part to ensure the stable operation of the transformer. Because the transformer bushing needs to be affected by factors such as electricity and heat for a long time during operation, the end of the lead under the bushing is easily deformed under the influence of electromotive force or external force, which will cause the lead to break. Therefore, if the bushing lead failure is not eliminated in time, the transformer will not operate normally and even affect the power supply stability of the power system. At this stage, the detection methods of transformer bushings mainly include partial discharge detection, high-voltage dielectric loss detection, infrared detection[3]. However, because the above method can only perform structural inspection on the outer insulting ceramic of the transformer bushing, it is difficult to judge the actual working state of the lead inside the bushing. Ultrasonic testing technology is a newly developed non-destructive testing technology, because the ultrasound used in it has strong penetrating, no electromagnetic interference, non-contact and other characteristics, so the testing technology is gradually and deeply applied to industrial non-destructive testing.

In ultrasonic testing, the echo will carry structural information inside the casing, so the detection of the casing lead defect can be realized by analyzing the transmitted wave and echo signal. But because
the emitted ultrasonic waves will undergo multiple reflections, refractions and even diffraction, the ultrasonic echo signals will inevitably contain noise signals, and the acquisition card will also introduce noise interference when collecting the echo signals, so effectively removing the noise signal in the ultrasonic echo is the beginning of echo signal processing, and it is also the guarantee for correct extraction of ultrasonic echo characteristic components. In recent years, SURE threshold wavelet denoising method and adaptive threshold wavelet denoising method have been widely used in the field of denoising [4]. However, because the ultrasonic signal is generally a non-stationary signal, when the frequency of the echo signal overlaps the frequency of the noise signal, the wavelet denoising algorithm performs poorly and the calculation efficiency is low. In addition, the wavelet transform is not adaptive, and there is a problem of choosing a suitable wavelet base. In order to improve the analysis results of non-stationary signals, Frei et al. proposed a new method for non-linear and non-stationary signals in 2006-Intrinsic Time Scale Decomposition (ITD) [5]. This method is more suitable for analyzing non-linear, non-stationary signals with time-varying spectra, and does not require spline interpolation and screening processes, so there is almost no edge effect, the calculation speed is fast, and a large amount of data can be processed in real time. However, with the deepening of ITD algorithm research, the end effect and rotation aliasing phenomenon of ITD gradually attracted the attention of researchers [6]. In order to solve this problem, some scholars have proposed an improved ITD algorithm.

Aiming at the common noise pollution problem of casing ultrasonic echo signal, we propose a joint ITTD-WTD de-noising algorithm. First, the ultrasonic echo signal is decomposed by improving the time scale; then, the wavelet denoising algorithm is used to remove the noise of each decomposed component; finally, simulation examples and experimental verification show that the signal-to-noise ratio is higher after denoising using the algorithm in the article, the average error is smaller, and the effective vibration information in the ultrasonic echo can be effectively retained. Therefore, the algorithm has certain practical value in engineering applications.

2. Ultrasonic testing

2.1 Principles of Ultrasonic Testing

The tube wall of the transformer bushing to be tested is made of ceramic, and the bushing is filled with transformer oil, and the conductive copper rod is passed through the center of the bushing, and the copper rod is wrapped with insulating paper [7]. The ultrasonic probe is selected as a transmitter-receiver integrated probe. When testing, the probes are evenly dispersed and vertically placed at three positions on the outer wall of the transformer bushing end, and the couplant is applied to the contact between the probe and the outer wall of the bushing end.

Since the three sets of ultrasonic echo signals all need to be insulated by the ceramic bushing, they have the same attenuation effect on signal transmission. Therefore, the influence of ultrasonic propagation in the transformer bushing ceramics on the results is not considered in the test. During data processing, by measuring the transit time of the ultrasonic signal, and then according to the propagation speed of the ultrasonic wave in the insulating oil, the distance between the lead and the transformer bushing can be calculated, so as to achieve the purpose of judging the state of the bushing lead. In the test, if the deviation of the three sets of ranging results is less than a certain range, the reliability of the ranging results can be considered high; if the three sets of ranging results differ greatly in the test, it is considered that the casing lead may be faulty and the position of the probe needs to be adjusted to confirm state of bushing leads.

2.2 Signal analysis

As a kind of non-stationary time-varying signal, ultrasonic waves propagate in different media, due to the different acoustic impedances between different media, reflected echoes will be generated at the interface between the media [8]. The excitation signal sent by the ultrasonic probe needs to pass through the outer wall of the transformer bushing and the transformer oil twice. When the ultrasonic echo signal encounters different types of oil molecules in the transmission process, it will produce more complicated
scattering attenuation, and the signal energy loss will be greater. In addition, the presence of bubbles in the transformer oil will also have a certain attenuation effect on the ultrasonic signal. When the material inside the transformer attenuates the ultrasonic wave greatly, the received echo signal will be relatively weak, and the signal must be collected by a high-sensitivity sensor. However, in the process of collecting weak echo signals, the influence of factors such as device operating noise and environmental noise has a greater impact on the actual results of the echo signals, so the echo signals obtained are often not satisfactory.

In order to make the echo signal easy to measure the moment of its onset, it is necessary to reduce the interference of noise to the signal. Signal filtering includes hardware filtering and software filtering. Hardware filtering can filter out more obvious noise signals, but it has limited capability for noises that are similar to the echo signal waveform or have small amplitude changes. Therefore, this article mainly considers the way of software filtering.

3. IITD-WTD algorithm

3.1 Introduction to ITD algorithm and IITD algorithm

In the ITD method, it is assumed that $X_t$ (t represents time t) is the signal to be analyzed, and L is the baseline extraction operator. After applying L to the original signal $X_t$, the signal remaining after the calculation is defined as the inherent rotation component. Let H be the inherent rotation extraction operator, then $H=1-L$. Then we get the first decomposition of $X_t$ as:

$$X_t = LX_t + (1-L)X_t = L_t + H_t$$ (1)

Where $L_t$ represents the baseline signal, and $H_t$ represents the inherent rotation component.

Let \{τ_k, k=1,2,...\} be the local extreme point of $X_t$, and assume that the extreme point is the extreme point. When the value of $X_t$ in a certain time interval is constant, the extreme value $τ_k$ is selected as the right end point of the time interval. For simplicity, $X(τ_k)$ and $L(τ_k)$ are expressed as $X_t$ and $L_t$.

Let the domain of $L_t$ and $H_t$ be $[0,τ_t]$, and the domain of $X_t$ is $[0,τ_t+2]$. Within the range of continuous extreme points $[τ_t,τ_{t+1}]$, baseline extraction operator L is defined as

$$LX_t = L_t = L_k + \frac{k+1-k}{x_{k+1}-x_k}(X_t-X_k)$$ (2)

In the formula, the calculation expression of $L_{k+1}$ is

$$L_{k+1} = \alpha \left[ X_k + \frac{τ_{k+1}-τ_k}{τ_{k+2}-τ_k}(X_{τ_{k+2}}-X_k) \right] + (1-α)X_{k+1}$$ (3)

In the formula, the value range of α is 0<α<1, and α generally takes 0.5.

In order to initialize the decomposition on $[0,τ_1]$, the first point of the signal can be defined as the extreme point, and $L_0$ is defined as $L_0 = X(τ_0) + X(τ_1) = X_0 + X_1$. Then the expression of $X_t$ can be obtained as

$$X_t = HX_t + LX_t = HX_t + (H + L)LX_t = [H(1 + L) + L^2]X_t = (H\sum_{k=0}^{n-1}L_k + L^p)X_t$$ (4)

In the formula, $H^LX_t$ represents the inherent rotation component (PRC) obtained during the (k+1)th decomposition, and $L^pX_t$ represents the monotonic trend term (residues) after the decomposition.

The ITD algorithm has rotation aliasing and end point effect. In order to solve this problem, the ITD algorithm can be improved. The reason why ITD has rotational aliasing is mainly when determining the extreme point of the signal, because the position of the interference extreme point of noise is random. In other words, when calculating $L_{k+1}$ according to equation (3), the influence of the span of the extreme point on the calculation result is not considered, so the calculated PRC component has uncertain frequency components. Therefore, to solve the rotation aliasing effect, the time distance scale $D_n$ can be introduced in the n-th decomposition process of ITD to realize the limitation on the extreme point span. The calculation formulas of $L_{k+1}$ and $D_n$ are shown in formula (5) and formula (6).

$$L_{k+1} = \left\{ \begin{array}{l}
X_t, \quad d_{k+1} > D_n \quad \text{and} \quad d_{k+2} > D_n \\
\alpha \left[ X_k + \frac{τ_{k+1}-τ_k}{τ_{k+2}-τ_k}(X_{τ_{k+2}}-X_k) \right] + (1-α)X_{k+1}, \quad \text{the other}
\end{array} \right.$$ (5)
\[ D_n = \begin{cases} 2, & n = 1 \\ \frac{1000}{4D_{n-1}}, & n \geq 2 \end{cases} \] (6)

An effective way to solve the ITD end effect is to extend the signal, such as mirroring the two ends of the signal.

### 3.2 WTD algorithm

Wavelet transform has the characteristics of low entropy, de-correlation and flexible base selection. It can effectively extract low-frequency and high-frequency useful information and eliminate noisy information, so it is widely used in the field of data denoising [9].

The steps of the wavelet threshold denoising (WTD) method are as follows:

1. Discrete wavelet transform is performed on the original noisy detection signal to obtain the decomposed wavelet coefficients: useful signal wavelet coefficient and noise wavelet coefficient. After discrete wavelet transform, the energy of useful signals is mainly distributed on the few wavelet coefficients with larger amplitude, while the energy of useless noise signals is mainly distributed on the wavelet coefficients with smaller amplitude. After the discrete wavelet transform, the heuristic threshold form criterion is used for division.

2. Reconstruct the signal through wavelet inverse transform to get the signal after wavelet threshold denoising.

### 3.3 Steps of IITD-WTD algorithm

1. Extend the original signal, and use the extended signal as the input signal.
2. Determine the decomposition times \( m \) of IITD based on experiments.
3. Determine whether the current decomposition times are less than \( m \), if yes, go to (4), otherwise go to (7).
4. Find the extreme points of the input signal, and then calculate the values of \( L_{k+1} \), \( L_t \) and \( H_t \).
5. Intercept the value of \( H_t \) and the original signal at the same position to obtain an inherent rotation component.
6. Take \( L_t \) as the input signal and turn to (3).
7. The wavelet base is selected as sym8, the number of decomposition layers is 5, and the threshold denoising method is heuristic denoising. Use the constructed wavelet function to sequentially denoise the obtained inherent rotation components.
8. Linearly superimpose the inherent rotation component after denoising to obtain the denoised input signal.

### 4. Instance verification

In order to verify the effectiveness of the IITD-WTD algorithm, we selected a 35kVA/10kV/400V transformer to test. In the test, the ultrasonic probe uses a transceiver integrated probe, and the probe is evenly dispersed and vertically placed on the outer wall of the transformer bushing end during the test, and the couplant is applied to the contact between the probe and the outer wall of the bushing end.

Using the acquisition card to collect the probe transmitting and receiving signals, we get the original signal as shown in Figure (1).
Figure (1) Original transmitted wave and echo signal

Figure (1) The content of noise in the signal is less, in order to compare the denoising effects of different algorithms more clearly. We add a certain amount of noise to the original signal to obtain a noisy input signal with a signal-to-noise ratio of 30dB, as shown in Figure (2).

Figure (2) The transmitted wave and echo signal with a signal-to-noise ratio of 30db

4.1 Denoising effect

The denoising results of WTD and IITD-WTD are shown in Figure (3) and Figure (4) respectively. Comparing the two figures shows that figure (4) contains less noise, and this figure also well records the starting point of the transducer's emission wave and receiving wave, which is beneficial to the subsequent calculation of the ultrasonic crossing time.
Figure (3) WTD denoising results

Figure (4) IITD-WTD denoising results

Figure (5) shows the signal components of the noisy ultrasonic signal after four times of IITD decomposition. It can be seen from Figure (5) that the first two inherent rotation component has more noise content, while the remaining components contain almost no noise. Therefore, in order to increase the speed of denoising and even realize real-time denoising, we only denoise the first two PRC components, and the remaining components remain unchanged.
In order to further verify the accuracy of the observation conclusion, we introduced the signal-to-noise ratio (SNR), root mean square error (RMSE) and correlation coefficient (R) to evaluate the denoising effects of different algorithms. The larger the SNR, the smaller the RMSE, and the larger the R, the better the denoising effect of the algorithm. The final results are shown in Table (1).

| algorithm   | SNR    | RMSE  | R      |
|-------------|--------|-------|--------|
| WTD         | 25.4597| 0.0108| 0.9958 |
| IITD-WTD    | 27.1527| 0.0083| 0.9991 |

5. Conclusion
Aiming at the deficiencies of ultrasonic signal wavelet denoising and ITD decomposition and reconstruction denoising, this paper proposes a wavelet threshold denoising method based on improved inherent time scale decomposition. By decomposing noisy ultrasonic detection signals, several inherent rotation components are obtained. After reconstructing it, the Sym8 wavelet base is used for 5-layer wavelet decomposition, and the maximum signal-to-noise ratio and the minimum root mean square error can be obtained after denoising. Finally, we use the measured ultrasonic emission wave and echo signal to verify. The verification result shows that the wavelet threshold denoising method based on IITD proposed in this paper is effective and has certain practical value.

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