Detection method of inner lead wires of transformer bushing based on parameter estimation of ultrasonic echo model

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Abstract. In order to solve the problem of low accuracy of the ultrasonic detecting method for the lead wires of the transformer bushing, this paper used the method of parameter estimation of the ultrasonic echo model to improve the accuracy of the ultrasonic flight time. First, this paper proposed an ultrasonic Gaussian model that suitable for detecting inner lead wires of transformer bushings, constructs a least-squares objective function, and then uses a particle swarm optimization algorithm to search for the optimal solution of the objective function globally, and proposes an algorithm for parameter estimation of the echo model. Finally, it is proved that the detection method proposed in this paper has the advantage of anti-noise interference through experiment, and the detection accuracy is improved. So, this method can detect the state of the lead wires in the transformer bushing.

1. Introduction

As people’s demand for electricity is getting higher and higher, the power system is facing the challenge of providing larger capacity and higher quality power, Transformers that the most important power equipment in the power system undertake this arduous task. In recent years, there have been more and more power accidents caused by fault of transformer bushing. In transformer faults above 220kV, the number of transformer bushing faults accounted for four percent of the total number of faults, and as the voltage level increases, the proportion of transformer bushing faults are getting higher. As one of the main insulation parts of the transformer, the main purpose of the transformer bushing is to lead the lead wires inside the transformer to the outside. The bushing plays a role in isolating and stabilizing the lead wires. If the insulation performance of the bushing is affected, which may threaten the operation about transformers, or cause a large-scale power cut.

During the long-term operation of oil-immersed transformers, lead wires are easily removed from the original fixed position, because of external force, electric power, etc., resulting in deformation faults. Deformation of lead wires will cause uneven electric field distributed in the bushing, and spark discharge will cause cracks in casing wall or casing explosion fault. In summary, in order to ensure the safe operation of transformer, the state of the lead wires inside the transformer bushing must be detected in time.

The existing methods for detecting the state of lead wires inside the transformer bushing are regular maintenance and infrared detection. The shortcomings of regular maintenance are: 1. The transformer needs to be powered of during detecting, it will cause unnecessary economic losses; 2.
The staff judges and tests lead wires based on experience, testing results are subjective. The disadvantages of infrared detection are: 1. It can only detect temperature of the casing ceramic wall; 2. It can’t effectively present the state of the inner lead wires of the casing. Therefore, there is an urgent need for a method that can detect the state of the lead wires in the transformer bushing online.

Considering that the ultrasonic Non-destructive testing technology can detect the inner lead wires without affecting the internal structure of the transformer and not being affected by electrical factors, the research on the ultrasonic method of detecting the lead wires of the transformer had been launched in China. Literature [8] proposed an algorithm about enhance grey wolf adaptive threshold denoising, which enhances the signal-to-noise ratio and improves the accuracy of detecting. Since the lead wires is fixed in the transformer bushing, when using ultrasonic technology to detect the lead state, the ultrasonic signal will penetrate twice in the bushing, resulting in serious attenuation of signal received by the ultrasonic probe, and it also result deviation of the echo signal's directivity or phase deviation [9,10], when detecting large transformers, traditional ultrasonic testing methods may fail. The key to detection is ultrasonic time of flight (TOF). The methods to obtain ultrasonic transit time include threshold method [11], cross-correlation method, model parameter estimation method.

In order to solve the problems raised above, this paper proposes a method that estimate the parameters of the ultrasonic echo model to improve the accuracy of the detection of the state of the lead wires in the transformer bushing. This paper first analyses the traditional ultrasonic method for detecting the inner lead wires of the transformer bushing, and then uses the Gaussian model envelope to fit the ultrasonic echo signal. According to the proposed model, the least square function is constructed to use the particle swarm optimization algorithm to calculate the parameters. Finally, we carried out experiments in combination with the actual transformer bushing model, which verified that method proposed in this paper was precise.

2. Principle of Ultrasonic Testing Method for Lead wear in Transformer Bushing

The ultrasonic detection method of the lead wires in the transformer bushing is based on the ultrasonic distance measurement technology to detect the distance between the lead wires and the inner wall of the bushing porcelain wall, so it can be applied to the online detection of the lead wires status. The principle of this method is shown in Figure 1.

![Figure 1. Principle of Ultrasonic Testing Method for Lead wires in Transformer Bushing](image)

The ultrasonic probe is closely attached to the porcelain wall of the transformer bushing through the coupland, and continuously emits high-energy ultrasonic signals into the bushing; after the ultrasonic signal penetrates the bushing, it propagates in the transformer oil toward the lead, because the transformer oil and the lead There is a big difference in acoustic impedance between the materials. When the ultrasonic signal encounters the lead wires, it will explode and reflect. The signal returns along the original path of the transmission path, penetrates the ceramic wall of the casing again and is received by the probe; the echo signal received by the ultrasonic probe is converted After the electrical signal is collected and stored, the echo signal is processed, and finally the time of flight (TOF) of the ultrasonic signal in the transformer bushing is obtained. The transit time consists of two parts:
In the formula, $t$ is the time for the ultrasonic signal to propagate in the porcelain wall of the transformer bushing, and is the time for the ultrasonic signal to propagate in the transformer oil. After the transit time is compensated for the ceramic wall time, the propagation time of the ultrasonic signal in the transformer oil can be calculated, and the distance between the lead wires and the bushing ceramic wall can be calculated through the distance conversion algorithm, so as to judge the state of the lead wires in the bushing.

According to the above analysis, the acquisition of the transit time is a key issue in the ultrasonic inspection of the lead wires in the transformer bushing. The accuracy of the transit time directly determines the accuracy of the inspection. There have some problems affecting the detection accuracy in the actual operation:

(1) The thickness of large transformer bushings is wide, the ultrasonic attenuation in the bushing is very serious, and the complete echo waveform cannot be collected, and the echo waveform needs to be fitted;

(2) The noise during the operation of the transformer cannot be ignored. Noise will cause measurement difficulties and errors. It is necessary to denoise the echo waveform to improve the signal-to-noise ratio.

In order to solve the above problems and improve the accuracy of the ultrasonic detection method, this paper proposes to use the ultrasonic echo model parameter estimation method to fit the ultrasonic echo, use the least square algorithm to estimate the parameters of the echo model, and fit the ultrasonic echo wave signal, calculate the ultrasonic transit time more accurately.

3. Mathematical model of ultrasonic signal

3.1. Ultrasonic echo signal waveform

After the transducer receives the ultrasonic echo signal, the resonator vibrates, and the mechanical energy of the vibration is converted into the electric potential energy of the piezoelectric chip. At this time, the electric potential energy obtained by the piezoelectric chip per unit time is greater than the loss; At this moment, as the vibration amplitude of the resonator becomes smaller, the potential energy obtained by the piezoelectric wafer per unit time is less than the loss. Therefore, when the pulse voltage is used to excite the transducer to emit an ultrasonic signal, the transducer receives the actual return reflected by the winding. The wave signal waveform is shown in Figure 2.

![Figure2. Waveform of actual echo signal](image)

3.2. Mathematical model of ultrasonic echo signal

The mathematical models of ultrasonic echo signals include linear models and nonlinear models. The linear model takes the ultrasonic echo signal as the output response of the linear system, and the output response is the convolution of the ultrasonic emission signal response and the signal path transmission response. Since the path transmission response of the ultrasonic signal is affected by the porcelain wall of the transformer bushing and noise, it cannot be directly calculated, and the signal envelope can describe the trend of the waveform with certain anti-noise interference ability, so this paper uses a nonlinear model to fit the actual return wave envelope signal.
The commonly used ultrasonic Gaussian model in oil medium is shown in the following formula:

\[ f(\theta, t) = f_0 e^{-\alpha(t-\tau)} \cos(2\pi f_c(t - \tau) + \varphi) \]  

(2)

In the formula, \( \theta = [f_0, \alpha, \tau, T, \alpha, \varphi] \) are characteristic parameters of echo model, \( f_0 \) is initial amplitude, \( \tau \) is delay time, \( \alpha \) is generally taken as a positive integer between 1-3, \( f_c \) is the frequency of the ultrasonic transducer, the value of \( T \) is equal to the time at the crest divided by \( \alpha \), \( \varphi \) is the initial phase.

The envelope of the ultrasonic Gaussian model is shown in Figure 3. It is an ultrasonic signal with a fast-rising edge and a slower falling edge attenuation. Similar to the waveform trend in Figure 3, this model can be better applied to detect the lead wire of the transformer bushing.

\[ \text{Figure 3. Ultrasonic Gaussian model envelope diagram} \]

In the process of testing the transformer, the noise generated by the operation of the transformer has a great influence on the ultrasonic wave, so the actual ultrasonic echo signal \( x(t) \) is expressed by the following formula:

\[ x(t) = f(\theta, t) + n(t) \]  

(3)

In the formula, \( n(t) \) is the noise signal during the operation of the transformer.

4. **Parameter Estimation Algorithm of Ultrasonic Testing Model for Leads in Transformer Bushings**

According to the model proposed in Chapter 2, it is necessary to estimate the parameters of the model of equation (3) to accurately obtain the ultrasonic transit time. This chapter uses the least square method to estimate the parameters of the ultrasonic echo model proposed in equation (3). Construct the objective function as follows:

\[ \min f(\theta^k) = \sum_{i=1}^{N} \left[ s(\theta^k, t) - x(t) \right]^2 \]  

(4)

In the formula, \( x(t) \) is the ultrasonic echo signal, and \( s(\theta^k, t) \) is the ultrasonic echo function value corresponding to the characteristic parameter after \( k \) times iterative calculation. According to formula (4), only need to calculate the characteristic parameter \( \theta \) when the objective function reaches the minimum value, then the delay time \( \tau \) can be obtained.

This chapter uses the particle swarm optimization algorithm to perform a global search for the optimal solution to equation (4). The principle of the particle swarm optimization algorithm is as follows: A moving particle is distributed in a space, the dimension of the space is \( D \), the sequence of the \( i \)th particle is defined as \( X_i = (x_{i1}, x_{i2}, \ldots, x_{iD}) \), the speed of each particle is \( V_i = (v_{i1}, v_{i2}, \ldots, v_{iD}) \), and then the fitness \( f_{fitness} \) is designed according to formula (4), the pros and cons of the particles moving to different positions Judged by calculations \( f_{fitness} \). The particle starts to move at the position \( X_i \) with the speed \( V_i \), and the optimal position experienced by the particle in the whole
movement process is defined as \[ P_{\text{best},i} = (P_{i1}, P_{i2}, \cdots, P_{im}) \], for \( i \) th particle at \( t \) time, the speed and position of the \( j \) th particle at \( t+1 \) time are calculated by the following formula:

\[
\begin{align*}
    v_j(t+1) &= wv_j(t) + r_1c_1(p_{ij} - x_j(t)) + r_2c_2(g_j - x_j(t)) \quad (5) \\
    x_j(t+1) &= x_j(t) + v_j(t+1) \quad (6)
\end{align*}
\]

In the formula, \( i = 1, 2, \cdots, m \) and \( r_1, r_2 \) are randomly selected from 0 to 1, \( w \) is the weight coefficient, and \( c_1, c_2 \) are the acceleration weight coefficient.

The algorithm of the parameter estimation algorithm of the ultrasonic inspection model of the lead wire inside the transformer bushing proposed in this chapter is shown in Figure 4.

![Figure 4. Echo model parameter estimation algorithm](image)

5. Experiment and analysis

The experiment used a casing with a model of BJ-35/800, the voltage level is 35kV, and the experimental lead wires was made by copper. The deformed lead is shown in Figure 5.

![Figure 5. Casing and lead wires in experiment](image)
The thickness of the ceramic wall of the 35kV casing is 2.15 cm. At room temperature, the ultrasonic signal propagates in the ceramic wall at a speed of about 5850 m/s. The propagation time of the ultrasonic signal in the ceramic wall of the casing is calculated as \(7.35 \times 10^{-4}\) seconds. This result is porcelain wall compensation time mentioned in chapter 1. Then set the particle swarm optimization parameters: the population size of the particle swarm was \(m = 50\), set the maximum number of iterations \(k_{\text{max}} = 200\), set the range of the characteristic parameters \(f_0\) to (0.5V, 8V), the range of \(T\) was (80us, 150us), and the range of \(\alpha\) was (1,5).

In order to reduce the signal attenuation in the ceramic wall of the bushing, the experiment used a 1MHz piezoelectric ultrasonic transducer. The ultrasonic transducer was attached to the surface of the transformer bushing through a Coupland. The main control circuit transmitted a high-voltage signal to drive the transducer transmitting ultrasonic signals inside the casing, a data acquisition card with a sampling frequency of 5MHz was used to perform AD conversion of the echo signal. The sampled waveform data was amplified, denoised, and envelope analysed. The waveform transformation of the signal processing process is shown in Figure 6.

![Sampled waveform](image1)

**Figure6 (a) Sampled waveform**

![Denoising waveform](image2)

**Figure6 (b) Denoising waveform**

![Envelope waveform](image3)

**Figure6 (c) Envelope waveform**

Figure 6 Signal processing waveform transformation

In the figure6(a), the first waveform is reflected by the lead wire, and the second waveform is the reflected signal when the ultrasonic signal encounters the ceramic wall of the casing on the opposite side.

In order to verify that the measurement method proposed in this article can obtain a more accurate ultrasonic transit time, carry out a comparative test with the threshold method and the cross-correlation
method. Bend the lead wire leads to deformation failure, make the distance between the lead wire and the inner ceramic wall of transformer bushing become 4.1, 4.2, 4.8 cm, so we can do 8 experiments to compare, the experimental results are shown in figure 7.

![Figure 7. The comparison of absolute error](image1.png)

![Figure 8. The comparison of standard deviation](image2.png)

It can be seen from Figure 7 and Figure 8 that the measurement error of the threshold method is more obvious, because the ultrasonic transducer has a vibration time. The cross-correlation method also has a large error, which is caused by the attenuation of the echo in the casing, and the cross-correlation method needs to match a large amount of waveform data, so the actual operation is complicated. The absolute error range of the method proposed in this paper is 0.729–3.857us, and the standard deviation range is 0.122–0.948us. Therefore, the echo model parameter estimation method proposed in this paper can accurately detect the state of the lead wire in the transformer bushing.

Through the method of increasing the noise, in the case of different signal-to-noise ratios (20dB, 10dB, 5dB, 0dB in the experiment), the effectiveness of the method of estimating Gaussian model parameters based on particle swarm optimization is verified. The parameter estimation results are shown in Table 2.

| Parameters/units | β | (α / MHz)^2 | τ / us | f_0 / MHz | φ / rad |
|------------------|---|-------------|--------|-----------|--------|
| Actual value     | 1 | 25          | 1      | 5         | 1      |
| Initial value    | 0.9–1.1 | 22.5–27.5 | 0.9–1.1 | 4.5–5.5   | 0.9–1.1 |
| SNR=20dB         | 0.99 | 25.18       | 0.99   | 5.01      | 0.99   |
| SNR=10dB         | 1.02 | 24.70       | 1.00   | 4.97      | 1.01   |
It can be seen from Table 2 that when the signal-to-noise ratio changes, the particle swarm optimization algorithm can accurately estimate the parameters of the Gaussian echo model. The ultrasonic echo parameter estimation method proposed in this paper has a certain anti-noise ability and can accurately detect the state of the leads in the transformer bushing.

6. Conclusions
(1) This paper proposed a method for parameter estimation of ultrasonic echo model to solve the problem of low accuracy of ultrasonic testing method for transformer bushing lead wires.
(2) This paper constructed the least square objective function, used the particle swarm optimization algorithm to search for the optimal solution of the wooden plaque function globally, and proposed a transformer bushing lead detection algorithm based on the parameter estimation of the ultrasonic echo model.
(3) This paper had designed a detection hardware device. Through the method of increasing the noise, in the case of different signal-to-noise ratios (20dB, 10dB, 5dB, 0dB in the experiment), the effectiveness of the method of estimating Gaussian model parameters based on particle swarm optimization is verified.

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