Application of Enhanced Whale Adaptive Threshold Noise Reduction Method in Transformer Ultrasonic 3D Imaging Detection

Haoyang Du*, Yimu Li and Wanting Liu
Electric Power Research Institute of Jilin Electric Power Corporation SGCC, Changchun 130021, China

*Corresponding author email: snzhang@imr.ac.cn

Abstract. Most of the detection methods for transformer winding faults are off-line detection, which have to know the internal parameters of the transformer including the winding radius and the position of the winding center point. It is only suitable for radial deformation, which has great limitations. Therefore, based on the principle of the ultrasonic wave propagation character, this paper designs a vertical 3D imaging detection system, which can visually display the 3D pattern of the winding deformation. This system can quantitatively and qualitatively detect the transformer and is suitable for various shapes of transformer winding deformation. An improved whale adaptive threshold optimization noise reduction algorithm has been improved in this paper based on wavelet decomposition for the problem that echo is easily interfered by noise in ultrasonic detection. After testing, most of the interference noise can be filtered, so that the transformer can be more intuitive around the three-dimensional state diagram, which can better distinguish the fault location.

1. Introduction
Transformer failures will affect the safety and stability of power system. Transformer will be deformed when other faults, such as short-circuit faults occur during operation [1], researching the transformer winding deformation can be used to evaluate the transformer status. The traditional winding detection methods are low voltage pulse (LVI) method [2], short circuit impedance (SCR) method [3] and frequency response analysis (FRA) method [4]. Both the short-circuit and frequency response method have detection effects on relatively severe winding deformation [5]. Based on these two methods, the sweep impedance method [6] is formed. The sweep impedance curve and the short-circuit impedance value can be obtained by one test to judge the winding state, which has better test repeatability and anti-interference. However, the above conventional methods can only be detected in the off-line state of the transformer and have considerable limitations. To realize the electrification detection of the winding, the vibration signal analysis method [7] has been applied. A method of winding deformation diagnosis based on vibration information is proposed. This method can analyze the vibration signals of different windings under the condition of transformer operation by wavelet packet transform, and classify the different states of the windings [8]. However, this method can only indirectly infer the winding deformation through vibration signal analysis. In order to realize the intuitive charging detection, the 3D imaging detection method is proposed [9]. In the process of ultrasonic detection, the echo signal will be subjected to interference noise during the acquisition process, which will reduce the signal-to-noise ratio and affect the detection effect. Among them, wavelet analysis is widely applied in noise reduction ultrasonic [10-13].
In this paper, the vertical distance of the winding surface to the ultrasonic transducer is used to characterize the winding state. A quantitative qualitative detection method for winding deformation based on the vertical representation 3D imaging algorithm is proposed. Next, a vertical characterization ultrasonic 3D imaging detection system for transformer winding deformation is designed. For the problem of receiving interference noise, an improved whale adaptive threshold optimization algorithm is designed to reduce noise. The test shows that the algorithm can effectively remove most of the noise and improve the final winding 3D imaging state diagram visual effect.

2. Transformer Winding Ultrasonic Testing

2.1. Ultrasonic Testing
When the ultrasonic wave is emitted, it passes through the transformer casing and the transformer oil in turn, and will reflect after reaching the internal winding of the transformer. The reflected ultrasonic signal will be accepted by the ultrasonic transducer:

\[ l = vt \]  

(1)
t-ultrasonic propagation time; l-ultrasonic propagation path; v-ultrasonic wave in transformer oil. According to (1), intuitive quantitative detection of the transformer winding can be realized.

2.2. Vertical Characterization Ultrasonic 3D Imaging System Design

2.2.1. Vertical characterization ultrasonic 3D imaging system algorithm. The ultrasonic wave is emitted from point A perpendicular to the surface of the transformer tank wall to point D of the transformer winding and is received by the receiving converter at point B of the transformer tank wall after the launch. The distance AD is defined as the characterization of the state of the point D winding. Assume that the velocity, propagation time of the ultrasonic wave and the position of the ultrasonic transducer on the wall of the transformer are known.

(1) When the ultrasonic signal is transmitted and received on the same side of the transformer:

\[ AD = \frac{1}{2} \left( vt - \frac{AB^2}{vt} \right) \]  

(2)

(2) When the receiving transducer and the transmitting transducer are located on the side wall:

\[ AD = \frac{1}{2} \left( vt + OB - \frac{OA^2}{vt - OB} \right) \]  

(3)

2.2.2. Quantitative qualitative representation of transformer windings.

Figure 1. Convexly deformed  

Figure 2. Concave deformation
According to whether the position of the normal winding and the receiver are on the same side and whether the location of the transmitter and the receiver of the deformed winding are on the same side, it can be divided into four cases:

(1) When the transmitter and receiver of the normal and deformed winding are on the same side. The vertical characterization of the normal winding at this time is:

$$DD' = \frac{1}{2} \left( vt' - vt + \frac{AB^2}{vt'} + \frac{AB^2}{vt} \right)$$

(4)

(2) The normal winding transmitter and receiver are on the same side with the deformation on the opposite side.

$$DD' = \frac{1}{2} \left( vt' - vt + OB' - \frac{OA^2}{vt' - OB'} + \frac{AB^2}{vt} \right)$$

(5)

(3) The normal winding transmitter and receiver are on the opposite side with deformation on the same side.

$$DD' = \frac{1}{2} \left( vt' - vt - OB - \frac{AB^2}{vt} + \frac{OA^2}{vt - OB'} \right)$$

(6)

(4) The normal winding transmitter and receiver are on the opposite side, and the deformation is on the opposite side.

$$DD' = \frac{1}{2} \left( vt' - vt + OB' - OB - \frac{OA^2}{vt' - OB'} + \frac{OA^2}{vt - OB} \right)$$

(7)

For the above four cases, it can be judged whether the winding is concave or convex.

3. 3D Imaging System Design

3.1. Vertical Characterization of 3D Imaging System Design

When performing winding detection, the low-voltage high-frequency pulse is converted into a high-voltage pulse of several hundred volts by a pulse-boosting HV driving circuit. The HV pulse excites the 400k transducer to generate high-frequency ultrasonic waves, which penetrate the transformer tank wall and pass through the transformer oil to reach the winding surface for emission. The echo-conditioned signal is received by the micro-controller. The ultrasonic wave propagation time can be obtained by stopping the timer. At the same time, the temperature compensation module passes the temperature signal to the processor. Then, the winding distance data can be obtained from the propagation time and the real-time temperature. A 3D image of the winding state is generated.

3.2. De-noise of 3D Imaging System

For the problem that the 3D imaging system is susceptible to interference noise during use, the 3D imaging effect is weak. After multiple scales wavelet decomposition of the signal, the adaptive threshold method based on gradient value reduction is introduced to estimate different wavelet decomposition layers. The threshold is then improved by the whale algorithm, the adaptive threshold function gradient value is optimized, and the optimal noise reduction threshold is determined.

3.2.1. Adaptive algorithm based on gradient value descent. Assuming the observed value of the noisy ultrasonic signal as \( X = [X_0, X_1, \ldots, X_i, \ldots, X_{N-1}]^T \), the real signal can be expressed as \( e = [e_0, e_1, \ldots, e_i, \ldots, e_{N-1}]^T \), then the measured ultrasonic echo signal is as shown in equation(8).
In the equation, \( n_i \) is an independently distributed Gaussian white noise. The purpose of noise reduction is to obtain an estimated signal of the noisy ultrasonic echo signal \( X \) such that the mean square error with \( e \) and \( e' \) is as small as possible. The adaptive wavelet threshold estimation uses the gradient descent method, and the next moment threshold is equal to the threshold value minus the mean square error function gradient value, as shown in equation (9).

\[
\lambda(t+1) = \lambda(t) - \mu \Delta \lambda(t)
\]  

(9)

In the equation, \( \mu \) is the step size, as shown in equation (10).

\[
\Delta \lambda(t) = 2 \left( \sum_{j=0}^{N-1} g_j \frac{\partial \eta(d_{j,k}, \lambda)}{\partial \lambda} + \sum_{j=0}^{N-1} \frac{\partial^2 \eta(d_{j,k}, \lambda)}{\partial d_{j,k} \partial \lambda} \right)
\]  

(10)

In the equation, \( d_{j,k} \) is the wavelet coefficient on the j scale, \( \eta(d_{j,k}, \lambda) \) is the threshold function, \( g_j \) is the function estimation expression, as shown in equation (11).

\[
g_j = \frac{\partial}{\partial \lambda} \eta(d_{j,k}, \lambda) - x_i
\]  

(11)

In order to facilitate the adaptive iteration of the threshold function, the Sigmoid function is used as the threshold function [14].

3.3. Whale Algorithm

WOA algorithm is a new type of heuristic optimization that imitates the hunting behavior of humpback whales [15], which is characterized by simple operation and easy to jump out of local optimum. It includes three stages: random foraging, contraction and spiral predation.

1) Random foraging

The first thing a whale does when preying is to surround the prey. Assuming that the optimal position in current population is the prey, the whales are surrounded by the optimal position.

2) Shrinking envelope

After the whale searches for food, update the location again.

3) Spiral predation

After successfully surrounding the prey, the whale takes a spiral motion to capture food.

3.3.1. Improved whale optimization algorithm. WOA algorithm that the algorithm optimization process is straightforward to fall into the optimal local solution, resulting in distortion of the signal after noise reduction, loss of signal details, and incomplete signal noise reduction, which is not conducive to observing the deformation position of the winding and affecting the 3D imaging of the accuracy of the detection.

1) Variation operation of differential evolution.

For each target individual, randomly select 3 different individuals from the current G to mutate:

\[
V_{i,G+1} = X_{r1,G} + F \ast \left( X_{r2,G} - X_{r3,G} \right)
\]  

(12)

In the equation \( r_1, r_2, r_3 \in \{1,2,\ldots,N\} \) is a randomly generated integer and \( r1 \neq r2 \neq r3 \neq i \), \( F \) is the scaling factor between \([0,1]\), taking \( F =0.5\).

2) Cross-operation of differential evolution.

In order to evolve the target individual \( x_{i,G+1} \), it is necessary to first randomly select one of the test vectors \( U_{i,G+1}(U_{1,G+1}, U_{2,G+1}, \ldots, U_{N,G+1}) \) to be contributed by the target individual \( x_{i,G} \), otherwise the population will not be changed.
In the equation, \( u_{j,Gt} \) is a uniformly distributed random number; \( mb(i) \in [1,2,...,n] \) is a random integer; \( CR \in [0,1] \) is the crossover probability, and \( CR=0.1 \).

3) After the crossover operation, the individual is compared to the current individual, and the smaller fitness function value will enter the next generation population.

\[
x_{i,Gt} = \begin{cases} 
    U_{i,Gt}, & f(U_{i,Gt}) \leq f(x_{i,Gt}) \\
    X_{i,Gt}, & f(U_{i,Gt}) > f(x_{i,Gt}) 
\end{cases}
\]

\[(14)\]

4. Simulation Analysis and Example Verification

4.1. Simulation Analysis

Ultrasonic echo is a non-stationary time-varying signal with a distribution similar to a sinusoidal function, so the echo can be simulated and random noise with 0.005 dBW is added to the signal. In order to verify that the proposed noise reduction algorithm has better effect, the gradient descent based adaptive and law enforcement, example group optimization adaptive method, gray wolf optimization adaptive threshold method and the algorithm of this paper are introduced.

After ATE noise reduction, the integrity of the waveform is destroyed. After PSOTE and GWOTE noise reduction, the noise reduction effect is not good even the waveform distortion is reduced. After WOATE noise reduction, the noise reduction effect is better visually. Refers to table 1.

**Table 1. Signal noise reduction price index**

| Evaluation standard | ATE | PSOTE | GWOTE | WOATE |
|---------------------|-----|-------|-------|-------|
| SNR                 | 4.2402 | 5.2752 | 5.6879 | 5.9162 |
| STD                 | 0.0553 | 0.0523 | 0.0492 | 0.0475 |

4.2. Example Verification

In order to illustrate the effectiveness of the proposed algorithm further, the winding state of the winding is deliberately set on the laboratory transformer winding model, and then the ultrasonic winding 3D imaging system is used to detect the state of the transformer winding at this time. After ATE noise reduction, the ultrasonic signal is distorted; after PSOTE noise reduction, a lot of details are lost; after GWOTE noise reduction, although the noise reduction effect is good, the wave tail still has distortion; and after WOATE noise reduction After that, not only can the useful information in the original signal be preserved, but also the noise can be effectively removed, and the fault can be easily identified. Also, it can be seen from Table 2 that after noise reduction by this algorithm, the signal-to-noise ratio is the largest and the mean square error is the smallest, indicating that the algorithm has the most noise reduction effect.

**Table 2. Signal noise reduction price index**

| Evaluation standard | ATE | PSOTE | GWOTE | WOATE |
|---------------------|-----|-------|-------|-------|
| SNR                 | 1.0398 | 5.1530 | 5.4785 | 6.7315 |
| STD                 | 0.0642 | 0.0547 | 0.0514 | 0.0485 |

It can be seen that the 3D image fault location of the transformer winding after noise reduction by other three algorithms is not clear enough and difficult to identify. The transformer winding fault location is more prominent after noise reduction by the algorithm. The winding has a more concave and convex state. Moreover, the windings in the non-faulty position are smooth. In summary, this paper has a significant effect on the noise reduction algorithm of the transformer winding 3D imaging detection system.
5. Conclusions
In this paper, a 3D imaging system based on vertical characterization is designed. Then, the 3D imaging system for transformer winding ultrasonic detection is susceptible to noise during the field detection process, and the imaging effect is poor. The gradient threshold value adaptive threshold method is introduced. It is used to estimate the threshold of different wavelet decomposition layers, then improve the enhanced whale algorithm, optimize the adaptive threshold function gradient value, and determine the optimal noise reduction threshold. Through simulation and experimental verification, the algorithm is used to de-noise while retaining a large amount of effective detail information in the signal, which is more convenient for signal recognition, lower signal distortion and better noise reduction performance. The imaging system is optimized by this algorithm. The 3D view of the transformer winding is clearer, the fault location is more obvious, and the non-faulty area is smoother.

Acknowledgments
This paper is sponsored by Jilin Electric Power Co., Ltd., SGCC (Project number: 52234217000H).

References
[1] Wang Wei, et al. Design of 3D imaging detection device for winding deformation based on ultrasonic technology[J]. High Voltage Technology, 2017, 43(12):4054-4059.
[2] Redondo LM, et al. Pulse Shape Improvement in Core Type High-Voltage Pulse Transformers With Auxiliary Windings[J]. IEEE Transactions on Magnetics, 2007, 43(5):1973-1982.
[3] Liu Jun, Zhang Anhong. Detection and Identification of Winding Deformation of Power Transformer Windings[J]. Transformer, 2018, 55(11):62-67
[4] Zhang Zhongyuan, et al. Simulation & case study of frequency response method for diagnosing radial deformation of transformer windings[J]. Insulation Materials, 2018, 51(10):67-72.
[5] Huang Hua, et al. Diagnosis of power transformer winding distortion by impendence method and frequency response method[J]. High Voltage Technology, 1999, (02):70-73.
[6] Liu Yong, Zhai Shengchang, Yang Fan, et al. Research and application of sweep impedance method for detecting transformer faults[J]. High Voltage Technology, 2016, 42(10):3237-3245.
[7] Xu Zhichao, Li Kai, Zhao Zhengang, et al. Application of buried FBG vibration sensor in transformer [1] core-winding vibration detection [J]. Instrumentation technology and sensors, 2017(06):107-110.
[8] Zhang Bin, Xu Jianyuan, Chen Jiangbo, et al. Winding deformation diagnosis method based on vibration information of power transformers[J]. High Voltage Technology, 2015.
[9] LIU Wei-jia, WANG Xin, ZHENG Yihui, et al. The on-line monitoring of the winding deformation of transformer based on the improved ultrasonic ranging method [J]. Applied Mechanics & Materials, 2014, 672(10):1159-1162.
[10] Zhou Zhengqian, Sun Guangkai. Progress in Research and Application of Advanced Ultrasonic Testing Technology[J]. Journal of Mechanical Engineering, 2017, 53(22):1-10.
[11] Sun Lingfang, Wang Wei, Xu Manfei, et al. Noise reduction of thin layer fouling ultrasonic detection signal based on improved CEEMD[J]. Chinese Journal of Scientific Instrument, 2018, 39(12):2879-2887.
[12] XIE Z. J. et al. Application of an Improved Wavelet Threshold noise reduction Method for Vibration Signal Processing[J]. Advanced Materials Research, 2014, 889-890:799-806.
[13] HASHEMI M, BEHESHTI S. Adaptive Bayesian noise reduction for General Gaussian Distributed Signals[J]. IEEE Transactions on Signal Processing, 2014, 62(5):1147-1156.
[14] Zhou Jian, et al. Research on adaptive wavelet packet threshold function noise reduction algorithm based on Shannon entropy[J]. Journal of Vibration and Shock, 2018, 37(16):206-211.
[15] Mirjalili S, Lewis A. The whale optimization algorithm[J]. Advances in Engineering. Software, 2016. 95:51-67.