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The study of phased-ultrasonic receiving-planar array transducer for PD location in power transformer

***Abstract**. Partial discharge (PD) is the main cause of electric equipment degradation. PD location can provide the scientific direction and analysis for equipment condition monitoring. The phased-ultrasonic receiving-planar array transducer for PD location in transformer is studied in this paper. The operation environment and material properties of transducer are analyzed. The center frequency of transducer is 150 kHz and its bandwidth is 100 kHz. The piezoelectric source and oil interstitial defect are used to detect the transducer's performance in lab. Experimental results show the transducer has perfect ultrasonic receiving characteristics. The successful developments of this sensor provide a good foundation for PD location in transformer using phased-ultrasonic receiving-planar array transducer.*

***Streszczenie.** Wyładowania niezupełne są częstą przyczyną uszkodzeń urządzeń elektrycznych. W artykule przedstawiono ultradźwiękowy przetwornik o czestotliwości 150 kHz zaprojektowany do lokalizacji wyładowań niezupełnych. Preprowadzne eksperymenty dowiodły przydatności takiego przetwornika. **(Badania odbiornika ultradżwiękowego w zastosowaniu do lokalizacji wyładowań niezupełnych w transformatorach**)*

Keywords: partial discharge, ultrasonic, array transducer, PD location.
Słowa kluczowe: wyładowania niezupełne, przetwornik ultgradźwiękowy.

1. Introduction

Partial discharge (PD) is the main cause of insulation degradation in power transformers and is an important item of insulation detection. By locating PD inside the transformer, appropriate guides and suggestions can be made to eliminate failures and to carry out maintenance.

Partial discharge produces electrical pulse, electromagnetic radiation, ultrasonic, light, some new products, partial overheating, etc. Theoretically the above phenomena, if detectable, can be used as incitements of PD defects [1]. Promising developments have been made in PD location, including electro pneumatic location, ultrasonic location, electromagnetic location, light location, heat location and DGA location, etc. PD location method can be categorized in many ways [2]. Except applied voltage, PD can also be affected by external incentives such as X or γ irradiation which forms another PD location type [3,4,5]. Despite the different working status of the equipments where PD occurs, all the current PD detection and location treatments work as passive receivers, they work according to the radiation or change of PD signals. Thus the electric, ultrasonic, electric-ultrasonic method is still essential among the various forms of detection methods.

Ultrasonic phased array technology was firstly used in military field and then was widely used in radar, sonar and medical ultrasonic fields as the technology advances. Compared with traditional single transducer, the phased-ultrasonic receiving-planar array transducer stands out with flexible beam control, higher signal gain, strong interference rejection and spatial resolving capacity. Phased array technology can be used for PD location within the transformer with satisfactory accuracy and is capable of locating multiple PD sources. The transducer, more specifically the phased-ultrasonic receiving-planar array transducer, is the key technology of phased array technology used in PD location. The performance of the transformer has a direct impact on signal extraction, thereby affects the accuracy of PD location. This paper analyzes the transducer property based on both the phased array theory and laboratory measurements, which provide basis for the application of ultrasonic phased array in PD location.

2. Transducer structure analysis

The piezoelectric transducers for regular ultrasonic PD location system are placed on the outside wall of the tank. But the phased-ultrasonic receiving-planar array transducer has to be placed on the inner side of the tank wall. This is because the phased-ultrasonic receiving-planar array transducer has strict requirement to the transmission of signals before the array and the tank wall usually contains various wave patterns like the longitudinal wave, shear wave, Rayleigh wave and Lamb wave. Also, uneven thickness of the wall makes the location more complex. With transducers placed on the inner side of the wall, direct waves can be detected firstly, which avoids the inference of signals from other non-direct routes. Also, the impact of tank wall as the waveguide can be eliminated. However, the oil temperature of operating transformer is too high for the normal piezoelectric materials to work. For example, the oil temperature reaches as high as 120^0C for E-class insulation. Therefore the piezoelectric materials for ultrasonic transducer which works inside the oil should be specially designed to withstand high temperature and to maintain good piezoelectric properties under high temperature.

Former research shows that the ultrasonic signals from PD with frequency band of 60-300 kHz and amplitude between 0-80dB are receivable. Also the low frequency band signals are more abundant and have larger amplitude. However, the frequency band of ultrasonic sensors should be chosen appropriately to avoid the motion-induced noise and mechanic vibration. Besides, other studies show that the spectrum of PD acoustic signal concentrates around 150 kHz [6,7]. So, 70-150 kHz has been chosen as the frequency band for many transformer PD detections. Also, IEEE has recommended 120-160 kHz to be operating frequency band of ultrasonic PD detection. As to the phased array transducer, higher working frequency means smaller the transducer size. Considering all the above mentioned factors, the center working frequency of the transducer is set at 150 kHz with the bandwidth of 100 kHz.

The phased-ultrasonic receiving-planar array transducer has two basic forms. One is line array with all the array elements rowing in a straight line; the other is plane array with all the array elements arranged in a flat plane. The line array cannot work in the perpendicular direction to the array line, which means that spatial location cannot be achieved, while the plane array can scan both the directional and elevation angles. Thus, the plane array is applied in this paper to achieve spatial location.

The basic structure of ultrasonic plane array transducer contains:

(1) Piezoelectric crystal plane array;
(2) Acoustic backing;

(3) Acoustic matching layer;
(4) Electrode wire, shell, etc.

The above four parts form an organic whole by playing respective role. Fig 1 shows the structure of the ultrasonic phased- array transducer.

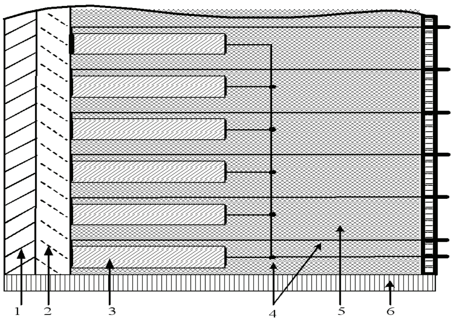


Fig.1. The structure of phased-ultrasonic receiving-planar array transducer (1, 2: Acoustic matching layer; 3: piezoelectric element; 4: down-leads; 5: backing; 6: encapsulation)

The main component of the transducer is the piezoelectric crystal. It is an acoustic-power conversion device which is made from piezoelectric materials like piezoelectric ceramic, piezoelectric thin film or composite piezoelectric materials. In order to obtain the expected performance indicators, the vibration mode, geometry shape and the arrangement should be considered during the design of piezoelectric crystal [8,9,10].

The acoustic backing works to increase the bandwidth of transducer probe. The pulse wave of sound radiation from PD has wide frequency range. In order to get undistorted pulse sound wave, the probe is required to have infinite bandwidth in theory, but it is impossible and unnecessary to realize. However, broader bandwidth is still wanted to suppress the distortion as much as possible. That's why the sound-absorbing backing is placed behind the piezoelectric crystal. The acoustic backing is intended to prevent the sound wave from being reflected to the piezoelectric crystal array and to undermine the acoustic coupling between array elements. However, this will make the receiving sensitivity of the probe greatly reduced. Therefore, the bandwidth and sensitivity is a contradiction to be appropriately solved based on the overall consideration of specific situations. But only by one best backing composition is not sufficient to solve this contradiction, the acoustic matching layer is further required.

The acoustic matching layer can improve the receiving sensitivity as well as broaden the bandwidth. Its substantive role is to greatly improve the sound transmission between probe and transformer oil. The material for acoustic matching layer is required to have low sound attenuation, appropriate acoustic impedance and thickness. The acoustic matching layer could be either a single layer or a multi-layer one.

Although acoustic lens are usually equipped in normal phased array ultrasonic transducers, the transducer in this paper has no acoustic lens due to the long distance between PD source and transducer. With acoustic lens, the location computing would be much more complex. Also, the acoustic lens cannot guarantee consistent focus.

According to the phased array theory, larger transducer size means more array elements, higher angular resolution and furthers the higher PD location accuracy even without going through super-resolution data processing [10-16]. But to control the influence of transducer to the internal structure of transformers, the transducer size should be the smaller the better. Also, the greater the array element spacing, the larger the cross-sectional area of the element could be, which leads to greater equivalent capacitance and higher receiving sensitivity of ultrasonic signals. The resulting grating lobe will then cause wrong location.

Therefore, there's a contradiction between location sensitivity and the possible transducer size and array element number. Based on overall consideration, the transducer array is designed as a 16×16 matrix. The numbers of line arrays in both directions are the same to ensure consistent performance parameters in both directions. Fig 2 shows the scheme of phased ultrasonic receiving-planar array transducer coordinate graph.

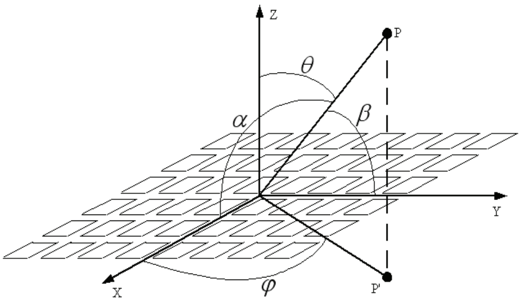


Fig.2. Schema of phased-ultrasonic receiving-planar array transducer coordinate graph

The directive accuracy of *xoz* plane with no deflection is:

$$\Delta\theta = 14^0 \cdot \frac{1}{N-1} \cdot \frac{N}{\sqrt{N^2-1}}$$

when N = 16, the $\Delta\theta = 0.93°$ can be computed through this formula and the location error caused by sensitivity is $\mathrm{tg}\Delta\theta = 1.6\%$, which means that if PD happens 5m away, there will be a 8cm distance between location result and actual PD position. This is acceptable in engineering. Besides, when N=20, $\Delta\theta = 0.7°$ $\Delta\theta = 0.7^0$ which is similar to that when N=16.

Due to the fact that the transducer is placed inside the oil tank, the relative elevation angle of PD position to the transducer plane approximately reaches 90^0. To ensure no grating lobe appears when the beam is within the scanning range, the center distance of the array should meet the following equation:

$$\frac{d}{\lambda} \le \frac{N-1}{2N}$$

Where d is the center distance of adjacent array element spacing and λ is the wavelength, thus the value of d equals to 0.5λ. 1500m/s is taken as the value of speed at which the 150 kHz ultrasonic wave propagates in the oil ($\varepsilon_r = 2.2$). The value of array element spacing 0.5λ is 5mm. So the side length of the piezoelectric array is 8cm and the side length of the whole transducer is no more than 10cm with the thickness of shell package taken account. Transducers in this size would cause no impact to the transformer operation when placed inside the transformers.

3. Transducer design

3.1 Structure design

Based on the above analysis, the Phased-Ultrasonic Receiving-Planar Array is composed by 256 (16×16) array elements. Each element functions as an independent ultrasonic transducer. The size of the element and the piezoelectric material are rationally selected.

The length and width of the array elements takes the same value in order to keep signals consistent in both length direction and width direction of the transducer. The choice of array length *L* is based on the following considerations:

1. *L*<*d*, array length should be less than the center distance of array spacing.
2. The smaller L is, the lower the acoustic coupling would be.
3. In order to obtain good modulation effect, the larger *L* is better.
4. Considering the sensitivity, larger *L* means larger equivalent capacity and further means higher sensitivity.
5. Larger *L* indicates much easier production processes.
6. Taking all the above factors, the array length *L* is set as *L*=4mm

The frequency of ultrasonic transducer is determined by the thickness of piezoelectric crystal. Under voltage application, the piezoelectric crystal vibrates and radiates energy to adjacent medium. The amount of energy radiation is relative to the boundary characteristics. Unless the characteristic impedance is the same, there is always part of the energy being reflected by the piezoelectric crystal and propagate toward the opposite direction of the piezoelectric crystal. If a vibration is being sent from the front surface of piezoelectric crystal and propagates to the back surface after reflection, the vibrations from front surface and back surface will stack up. According to the superposition principle of sound, only when the two sub-vibrations are at the same phase the total amplitude could be the largest and strong ultrasonic wave could be obtained.

When the crystal thickness is equal to exactly half the wavelength, resonance is generated which means that the two vibrations are at the same phase on the surface and the force is mutually reinforced to get the maximum vibration amplitude. The frequency corresponding to the half wavelength thickness is called the fundamental resonance frequency. If v is the velocity of wave in certain piezoelectric material and h is the material thickness, then $f_0h=v/2$. That is to say the product of wave velocity and material thickness is a constant, known as the frequency constant. If a hard material with much higher sound impedance is stuck onto the back surface of transducer, the back surface of transducer can be considered as clamped immobile. While the front surface of transducer is in contact with the mineral oil which has much lower sound impedance than the transducer, the front surface can therefore vibrate freely. This case is called the single surface radiation and the resonance occurs when $f_0h=v/4$.

Ultrasonic transducer use lead zirconate titanate (PbTio3) as the piezoelectric ceramic. Its frequency constant is 2.1MHz·mm in theory. The Curie temperature of lead zirconate titanate ceramic can reach up to above 400℃. Moreover, because the electromechanical coupling coefficient k_1 and k_{33} is very small, the vibrator made from lead zirconate titanate ceramic could easily get the approximate net model. The lead zirconate titanate ceramic is also suitable for receiving transducer material due to the large value of piezoelectric constant g_{33}.

With lead zirconate titanate as the transducer material, the transducer thickness should be selected as 14mm when both surfaces vibrate freely with the fundamental frequency of 150 kHz, while the thickness should be 7mm when only one surface could vibrate freely.

Under the actual condition, acoustic backing with moderate acoustic impedance is added to the transducer to increase the bandwidth of probe. With various factors considered, the thickness of transducer is selected as 12mm.

3.2 Backing design

The receiving sensitivity and bandwidth should be considered together when designing the acoustic backing because larger acoustic impedance of the backing indicates broader bandwidth but lower sensitivity. The frequency characteristics of the transfer function could be theoretically calculated to further analyze the influence of acoustic backing impedance on the receiving performance of piezoelectric transducer. The backing is intended to prevent sound wave being reflected to the array and to suppress sound coupling between array elements, which will greatly reduce the emission efficiency and receiving sensitivity. Thus, the bandwidth and sensitivity is a contradiction to be solved by exploring suitable acoustic backing structure for the probe.

At present, the common choice of backing material is a composite material made from tungsten powder and epoxy resin, with its advantages in the following aspects:

1)Moderate acoustic impedance: taken into account both the bandwidth of transducer probe and the sensitivity.

2) Satisfactory sound attenuation.

3)Suppressing sound coupling between array elements.

Therefore, this paper applies this composite material too but additional research on the composition and mixing ratio is still required.

The relationship between the tungsten powder/epoxy resin ratio and sound impedance

The density of composite material is expressed as:

$$\rho = \frac{\rho_1\rho_2}{\rho_2 - (\rho_2 - \rho_1)G}$$

where ρ_1 is the density of epoxy resin, ρ_1=1.1g/cm^3; ρ_2 is the density of the tungsten powder, ρ_1=18.7 g/cm^3. δ is the volume percentage of tungsten powder in the composite material. The percentage of tungsten powder in composite material is $G = \rho_2/\rho$.

When $G < 80\%$, the sound velocity gradually decrease with the increase of *G* while the sound velocity increase rapidly with the increase of G when G>80% .

Research and experiments of the ultrasonic propagation characteristics in composite material show that the sound attenuation of composite material is due to the scatting effect of the metal particles in it [17].

Based on the theoretical and experimental curves, sound attenuation constant α increases with the increase of frequency and decreases after it reaches the maximum. While with the increase of volume percentage δ, α increases firstly, then changes slowly to reach the maximum and tends to decrease finally.

Take $k_1 = 2\pi f/v_1$ as the beam of sound wave in epoxy resin, a as the radius of metal particle. The maximum sound attenuation of tungsten powder/epoxy resin composition is within k_1a = [0.3,0.5] when δ = 5% or δ = 15%. Also, the sound attenuation significantly changes when δ increases to 15% from 5%.

According to the above conclusion, take $k_1a = 0.3$, thus the radius of tungsten powder particle can be expressed as:

$$a = \frac{k_1 a}{k_1} = 0.3 \times \frac{\upsilon_1}{2\pi f}$$

If v_1 = 2150 m/s, f = 150 kHz, then a = 680 μm.

Parameters as acoustic impedance of backing, sound velocity and sound attenuation could be adjusted by changing the ratio of epoxy resin and tungsten powder. However, too high ratio of epoxy resin/tungsten powder would cause epoxy resin surplus during production, which forms a layer of epoxy resin without tungsten powder. Thus the lead titanate piezoelectric ceramic $PbTiO_3$ is introduced to solve this problem. The tungsten/piezoelectric ceramic/epoxy resin ratio of the finished backing is 9:7:1, acoustic impedance is 17.3×10^6 kg·m^{-2}·s^{-1} and the sound attenuation coefficient is 17 dB/cm.

3.3 Matching layer design

The increase of backing sound impedance could broaden the transducer bandwidth but at the same time reduce the receiving sensitivity. Matching layer is applied to solve this problem [18-21].

Suppose the incoming wave is a plane one. For single matching layer to obtain the maximum transmission coefficient, the following expression should be satisfied:

$$Z_1 = Z_0 Z_L$$

Where Z_0 is the acoustic impedance of lead zirconate titanate ceramic and takes the value of 33.4×10^6kg.m^{-2}.s^{-1}, Z_L is the acoustic impedance of transformer oil and takes the value of 1.1×10^6kg.m^{-2}.s^{-1}, Z_1 is the acoustic impedance of matching layer 1.

For double matching layers to obtain the maximum transmission coefficient, the following expression should be satisfied:

$$\left.\begin{aligned} Z_1 &= Z_0^{3/4} Z_L^{1/4} \\ Z_2 &= Z_0^{1/4} Z_L^{3/4} \end{aligned}\right\}$$

where Z_2 is the acoustic impedance of matching layer 2.

More layers of acoustic matching which are made from ideal non-attenuation material means better matching effect. But considering the attenuation of actual acoustic matching layer material, it's difficult to obtain the best matching of acoustic impedance. Besides, more layers make the production process more complex. The system requires the center frequency to be 150 kHz and with two layers of acoustic matching, the bandwidth could cover 100~200 kHz. The thickness of each layer is $d=0.25\lambda_s$.

Silicon rubber is the choice for first matching layer material with its 2.5×10^6 kg·m^{-2}·s^{-1} acoustic impedance and above 250℃ Curie temperature. Quartz crystal is the choice for second matching layer material with its 13.8×10^6 kg·m^{-2}·s^{-1} acoustic impedance and 576℃ Curie temperature.

Photographs of the designed Phased-Ultrasonic Receiving-Planar Array Transducer are shown in Fig 3.

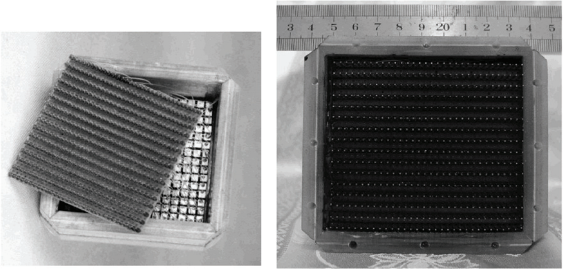
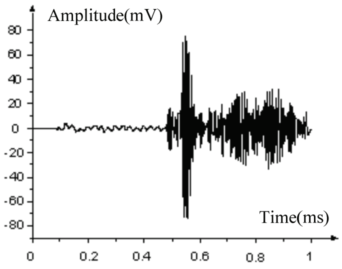


Fig.3. Photographs of the designed phased-ultrasonic receiving-planar array transducer

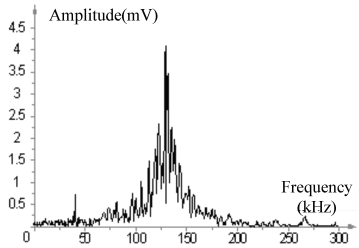
4. Performance test

Two kinds of discharge source were applied to test the performance of Phased-Ultrasonic Receiving-Planar Array Transducer. One is the piezoelectric emitter. High voltage pulse with the amplitude of 4.5kV and bandwidth of 3μs was generated by self-made pulse generator to drive piezoelectric probe to radiate ultrasonic signal. The other is the common oil gap model in oil-paper insulation system. Voltage was applied to the model to produce PD and then generate ultrasonic signals.

Array element (1, 1) of the phased array was chose to be the receiving transducer. The piezoelectric ultrasonic signal and its frequency spectrum received by one element are shown in Fig 4.



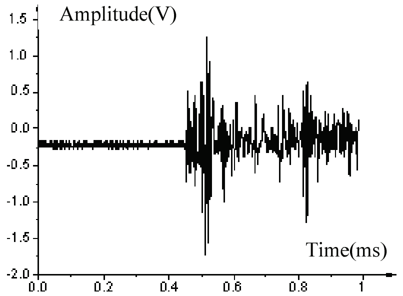
（a）Time domain signal



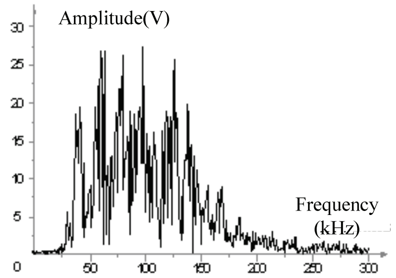
（b）Frequency spectrum

Fig.4 the piezoelectric ultrasonic signal and its frequency spectrum received by one element

Fig 4 shows low amplitude of the ultrasonic signals. Ultrasonic signals from a single application of voltage are unitary with clear delay. Time domain signals were transformed into frequency domain ones through fast Fourier analysis. The frequency of ultrasonic signals concentrates at 30-140 kHz. The frequency of the signal with the highest amplitude is 97 kHz.



（a）Time domain signal



（b）Frequency spectrum

Fig.5 The oil interstitial defect ultrasonic signal and its frequency spectrum received by one element

Fig 5 shows the oil interstitial defect ultrasonic signal and its frequency spectrum received by one array element. As can be seen from Fig 5, PD in oil gap has large primary discharge energy, single ultrasonic signal and clear delay. The frequency domain map shows that PD frequency concentrates at 30-140 kHz. The frequency of the signal with the highest amplitude is 97 kHz. The ultrasonic frequency concentrates in 30-140 kHz. The frequency of the ultrasonic signal with the highest amplitude is 97 kHz.

Therefore, the transducer is proved to be reasonable with the frequency band of 100-200 kHz and the center frequency of 150 kHz.

5. Conclusions

(1) In order to apply phased ultrasonic receiving theory to PD location, a 16×16 array of Phased Ultrasonic Receiving-Planar Transducer was designed based on the phased ultrasonic array theory. The structure and material of the transducer was discussed according to actual operating condition and ultrasonic characteristics of PD. The transducer is successfully developed with the center frequency of 150 kHz and the bandwidth of 100 kHz.

(2) Measurements and analysis of PD signals using this transducer were carried out in the laboratory. Results show that the transducer is capable of receiving ultrasonic signals generated from PD with satisfactory sensitivity and appropriate bandwidth.

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