Scholar Publishing Group
International Journal of Engineering Technology and Construction
https://doi.org/10.38007/IJETC.2025.060103
ISSN 2789-7176 Vol. 6, Issue 1: 28-35

Study on the Local Discharge Detection Technology of Ultrasonic Transformer

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Keywords: Transformer; Partial Discharge; Ultrasonic Positioning

Abstract: Partial discharge of the transformer is a key factor affecting its safe and stable operation. As a non-destructive testing method, ultrasonic positioning technology plays an important role in transformer partial discharge detection. This technology analyzes and processes ultrasonic signals to achieve accurate positioning of the internal partial discharge position of the transformer. Its advantages are non-contact measurement, strong anti-electromagnetic interference ability, high positioning accuracy, and the ability to detect without affecting the normal operation of the transformer. This helps engineers accurately determine the severity and cause of partial discharge and provides a scientific basis for the maintenance and management of transformers. Therefore, transformer partial discharge ultrasonic positioning technology is of great significance to ensure the safe and stable operation of the power system. The purpose of this paper is to explore the application and technical characteristics of the ultrasonic method in the field detection of transformer partial discharge. The ultrasonic method realizes real-time monitoring and evaluation of the insulation status of the transformer by capturing the ultrasonic signal generated by partial discharge. This method provides a strong guarantee for the safe operation of the transformer. However, there are some limitations in the practical application of ultrasonic methods, such as signal attenuation, the influence of propagation speed by media, and the difficulty of energy calibration, which may affect the accuracy and reliability of detection.

1. Introduction

Partial discharge is a phenomenon in which only a localized area of the insulator occurs, and it does not penetrate between the conductors to which the voltage is applied. This phenomenon can occur near conductors or elsewhere[1]. Partial discharge mainly refers to the phenomenon that occurs in high-voltage electrical equipment, which is an important cause of insulation breakdown of high-voltage electrical equipment and an important indicator of insulation deterioration[2]. Causes of partial discharge may include uneven distribution of the electric field, such as when the electric field on or inside the insulator is particularly concentrated. In addition, partial discharge can also occur when there are bubbles, impurities, and cracks at the interface and inside the medium, or when there are uneven edges or tips on the surface of the conductor in the electric field, such as burrs. Partial discharge detection has a wide range of applications in the power system, including the detection of power transformers, switchgear, cables and other power equipment. Through the regular inspection of this equipment, possible partial discharge problems can be found in time, and corresponding maintenance and replacement measures can be taken to prevent the occurrence of equipment failure. In addition, partial discharge detection can also be used to evaluate the insulation performance and aging degree of equipment, providing a basis for equipment life prediction.

Partial discharge is a physical phenomenon, which is a discharge phenomenon of the bridging of the insulation guard part between conductors, which will produce a series of physical phenomena and chemical changes such as photoacoustic, electrical, and mechanical vibration in and around the power equipment, which provides a detection signal for detecting the internal insulation state of power equipment[3]. There are a variety of detection methods for partial discharge, such as the traditional pulse current method and the high-frequency pulse current method for live detection[4], the ultra-high frequency method and the ground wave method for electromagnetic wave emission phenomenon, and the ultrasonic detection method for the acoustic emission phenomenon caused by the burst wave generated by partial discharge[5]. Given the luminescence and heating phenomenon caused by partial discharge, we have developed photometric and temperature measurement methods, that is, ultraviolet imaging and infrared imaging detection methods in live detection. Finally, for the chemical decomposition products produced by the chemical reaction of the insulating medium caused by partial discharge, we have developed a chemical analysis method, that is, the analysis of dissolved gas in transformer oil and the analysis of SF6 sulfur gas components.

Partial discharge has some characteristics under AC voltage, and partial discharge is pulsed, because each discharge time is extremely short, about 10~100 nanoseconds, which is pulsive. Partial discharge has obvious phase characteristics under AC voltage, and its initial discharge phase is 45 degrees ~ 90 degrees, 225 degrees to 270 degrees. The amplitude of the discharge pulse for a single cycle is not uniform, but it is symmetrical in a statistical and probabilistic sense, which is symmetry. For ellipse plots and PRP plots (waterfall plots), there is a certain degree of repeatability in the phases of typical local pulses and the spectra for each fair period. Ultrasonic testing is for oil-immersed power transformers[6]. You may be familiar with the ultrasonic detection method used in the switch cabinet and have had a lot of operations. However, for equipment such as transformers, the ultrasonic method is used to detect and generally have less contact in the work.

2. Ultrasonic detection transformer partial discharge phenomenon detection technology

The an important part of the power system, the stability and safety of the transformer are crucial to the stable operation of the entire system[7]. However, during the operation of the transformer, due to the aging of the insulation material, design defects improper operation, it may lead to the occurrence of partial discharge. Partial discharge not only damages the insulation properties of transformers but can also cause serious failures and even paralysis of the entire power system[8]. Therefore, it is of great significance to accurately and reliably detect transformer partial discharge. Ultrasonic detection of transformer partial discharge phenomena is an important non-destructive testing method used to evaluate the insulation performance of transformers and detect potential faults.

At present, there are various detection methods for transformer partial discharge, among which the ultrasonic method has attracted extensive attention due to its unique advantages. The ultrasonic method uses the ultrasonic signal generated by partial discharge for detection, which has the characteristics of strong anti-electromagnetic interference ability, convenient discharge positioning, and wide adaptability[9]. Through ultrasonic testing, the fault of the transformer can be found in time, its health status can be determined, and its life can be predicted, to improve the reliability and safety of the transformer.

Ultrasonic testing uses the reflected signals generated by different interfaces when ultrasonic waves propagate inside the transformer to detect partial discharge. When a partial discharge occurs inside a transformer, ultrasonic signals are generated, which can be captured by ultrasonic sensors mounted outside the transformer. By analyzing the ultrasonic signals received by the sensor, the location, magnitude, and severity of the partial discharge can be inferred.

The principle of the ultrasonic testing method is to fix the ultrasonic sensor at a specific position of the transformer (such as the oil pillow wall) and feel the ultrasonic signal generated by the partial discharge inside the transformer through the sensor. These ultrasonic signals can reflect the intensity and location of partial discharges. In practice, ultrasonic sensors are often attached to the housing of electrical equipment for in vitro testing.

In practical applications, ultrasonic detection of transformer partial discharge is usually carried out by continuous monitoring or regular inspection. Continuous monitoring can obtain the partial discharge of the transformer in real-time and detect potential faults in time, and regular inspection can be carried out during equipment outages or maintenance to comprehensively evaluate the insulation performance of the transformer.

During the inspection process, attention needs to be paid to selecting the right ultrasonic sensor and the appropriate detection frequency. The choice of sensor should be determined based on the structure, size, and installation location of the transformer to ensure that the ultrasonic signal generated by partial discharge can be accurately captured. The selection of detection frequency should be determined according to the frequency of the sound wave generated by partial discharge, and high-frequency sensors are generally selected to improve the detection sensitivity.

3. The significance of transformer partial discharge ultrasonic positioning

The the improvement of the voltage level of the power system and the compactness of the structure of voltage electrical equipment, the test of the insulation structure of the power transformer is becoming increasingly severe. For example, more than 20 years ago, transformers with very small capacities were relatively large. 500,000 transformers will be relatively compact and compact. For grid companies, the compact design reduces floor space and transportation costs. The compact design reduces manufacturing costs compared to manufacturing plants. However, the compact design will not allow the insulation density to be as high as before. In the case of a failure of one point in the insulation structure, it is easy to cause a chain reaction. Therefore, the requirements for manufacturing materials, processes and operation and maintenance have increased, which requires strict assessment of the insulation performance of the equipment and timely grasp of insulation status of the equipment. It is an effective method for measuring and verifying the insulation characteristics of partial discharge in power transformers.

Measuring the partial discharge amount, can help engineers and technicians grasp the process of changing the insulation level of the equipment. In the process of on-site measurement, the location of the partial discharge point is determined, which is conducive to the correct judgment of some special partial discharge problems. The oil color of the transformer is not abnormal, and the analysis of whether there is a defect in the partial discharge is on the main insulation, and if it is on the main insulation, it needs to be treated with a power outage in time. If it is not on the main insulation, it can be persist until the planned power outage is overhauled. Offline partial discharge experiments and traditional pulsed current methods can be used to electrically locate defects using multi-terminal measurement comparison, but only the ultrasonic method can be used for geometric location. Discharge positioning is of great help to the maintenance of internal power loss in the transformer, and can also help to improve the design of the transformer. PD ultrasonic testing can be performed while the transformer is in operation. This is an important role of ultrasonic positioning and detection of partial discharge, and this detection method can locate partial discharge defects for operating transformers with partial discharge defects. Partial discharge defects in many transformers are not fatal. Only fatal defects require an immediate power outage. Many non-fatal defects can be delayed until the planned power outage for maintenance, which is of great significance for the safe and stable operation of the power grid.

3.1 Sonic characteristics

When we use ultrasound for partial discharge detection, we first need to understand the characteristics of sound waves. A sound wave is a type of mechanical vibration wave. The acoustic signal produced by partial discharge is very small. The ratio of the energy of the sound wave generated by the discharge to the total discharge energy is generally less than 1%, and the conversion rate of this sound energy is different in different media and different discharge states.

The sound waves that propagate in gases and liquids are longitudinal waves, i.e., the direction in which the particle vibrates is parallel to the direction of propagation of the wave. Sound waves propagating in solids, in addition to longitudinal waves, have transverse waves, i.e., the direction of motion of the particle is perpendicular to the direction of propagation of the wave. In gases and liquids, longitudinal waves are measured, and in solids, they are mainly transverse waves. When a longitudinal wave propagating through a liquid reaches the metal shell, the transverse wave will appear in the metal body and continue to propagate. This means that the sound wave is transmitted from the transformer to the shell, and will be converted from longitudinal wave to transverse wave, of course, this conversion has a certain energy loss.

The characteristics of the transformer partial discharge ultrasonic signal received by the ultrasonic sensor, the transformer partial discharge ultrasonic waveform has the following characteristics that can be used as a basis for discrimination: the received signal waveform generally shows a large initial and then continues to attenuate the oscillation triangle shape, and the center frequency range of this signal is 70 kHz~140 kHz. The waveform length of an acoustic signal is generally about 0.6 ms, and if the waveform is short, it is generally considered to be an effect of electromagnetic interference. Ultrasonic testing is strictly less affected by electromagnetic interference, but ultrasonic sensors are composed of piezoelectric ceramics as sensing elements and stainless steel as metal housings. When the sensor is attached to the metal housing of the transformer, the metal housing of the sensor and the metal housing of the transformer form a capacitance. The metal housing of the transformer itself is coupled to external electromagnetic interference. When there is an internal discharge, it is also coupled to the electromagnetic interference generated by the internal discharge. In this case, the electromagnetic interference coupled to the transformer housing is coupled to the ultrasonic sensor via a capacitive effect. This kind of groundwave detection, which is similar to partial discharge, is the principle of TV detection.

The signals received by the acoustic sensors at different locations have a certain time difference. According to the actual size of the high-voltage appliance and the speed of sound wave propagation in the high-voltage appliance, the range of time difference should be within 0~2 ms. This refers to the size of a 500,000-level unidirectional autotransformer. If the size of the transformer is relatively large, the range of time difference should be relaxed accordingly. It's the time it takes for sound to travel from one end of the transformer to the other, and if it takes more than that, then obviously not both of these two sound signals are coming from the transformer. The ultrasonic waveform of partial discharge is repeatable. Because the pulse signal of partial discharge has a certain degree of repetitiveness, then the mechanical wave it excites, that is, the ultrasonic wave, is transmitted through the same path, and the signal waveform received and converted by the same sensor should also be repeatable.

An important concept of sound waves is the critical angle of ultrasonic partial discharge of transformers. The concept of critical angle relates to ultrasonic sensors.

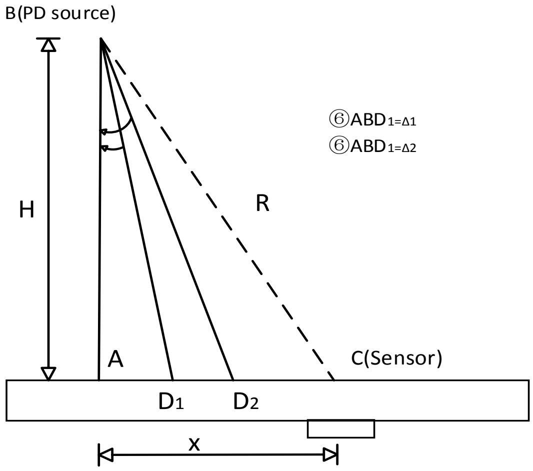

Figure 1. Example diagram of propagation path in oil

For the partial discharge source at point B, the sound wave emitted by it is transmitted to the shell, and the fastest transmission path is directly perpendicular. If the probe is placed exactly at point A, in this case, all the probe receives is a direct wave. If you go at a small angle, it will be less than 14.6 degrees. Since the indirect wave reaches point A of the steel plate at this time, the distance that travels to the first point is shorter. It is not enough to lead the direct wave that goes directly from this B, so the amplitude attenuation of the indirect wave is relatively large. Submerged in the direct wave that came first. As a result, the probe can still only receive a direct wave signal. However, if you take a larger angle from the partial discharge source at point B, for example, take the indirect path of this BAC or BDC. Due to the large angle, the path in the steel plate in the indirect path is longer. Plus the speed of sound in the steel plate is faster. Therefore the indirect does not precede the direct wave. The greater the angle to reach this probe, the more indirect waves lead over direct waves.

3.2 Ultrasonic positioning method

There are three methods of ultrasonic positioning method, transformer partial discharge ultrasonic positioning method. They are the vertical positioning method, acoustic electro-localization method and acoustic positioning method. At present, the comprehensive positioning method is rarely used in the field, mainly in the transformer factory experiment and when the partial discharge defects are investigated. Its principle is to use two ultrasonic probes to do the detection, when the two probes receive the same signal start time, then it means that the distance between the PD source and the two probes is equal. Make a vertical plane on the line of the two probes, and the local discharge source must be located on this vertical plane. Through multi-directional measurement, three or more vertical surfaces can be obtained, and the intersection point of these vertical surfaces is the location of the partial discharge source, which will encounter great difficulties in field detection. The internal structure of the transformer is too complex, resulting in the presence of ultrasonic signal blind spots on the surface of the transformer tank. That is to say, in the process of moving the ultrasonic probe so that the signal it receives is consistent at all times, the probe will suddenly fail to receive the signal, and it will not be able to achieve the same signal at all times, which leads to low positioning success rate and poor positioning accuracy. At present, this method is no longer used in the field, but it can be used to determine the possible location of the partial discharge source.

It is used to guide the placement of probes and capture better ultrasound signals. With the advancement and upgrading of technical methods and equipment, the commonly used methods are electroacoustic localization and acoustic localization methods. The acoustic and electric positioning method is mainly used in the factory experiment of the transformer factory, which is easier to use in this environment. When the transformer is partially discharged, live detected or tested offline, it can receive ultra-high frequency signals or pulse current signals. These are all electrical signals. The signal propagation speed is 300,000 km/s. For a device of the size of a transformer, the transmission time of the PD signal is only in the nanosecond range, and compared with the speed of the ultrasonic signal of 1400 meters per second, it can be considered that the time when the electrical signal is received is the time when the PD occurs. The distance between the partial discharge source and the probe can be obtained by calculating the time difference between the electrical signal and the ultrasonic signal and multiplying it by the speed of sound in the transformer oil.

The positioning of acoustic and electrical signals is expressed by the formula, that is, if the number of sensors adsorbed on the transformer housing is m, and the propagation speed of sound waves in the transformer is from the discharge point to the i-th sensor time, Then, you can pass the product of V_e and t_i , $V_e \bullet t_i$ converts the propagation time of a sound wave into a propagation distance. Based on the measured time delay, spherical equations for the distance and time of the acoustic sensing can be established. As(1):

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=(V_e \bullet t_i)^2 \tag{1}$$

Wherein, i=1,2,3,.....,m. (x, y, z) corresponds to the position of the discharge point (x_i, y_i, z_i). The three-dimensional coordinates correspond to the position of the i th sensor, and its physical meaning is: the discharge point is located on the sphere centered on the ith sensor and thought to $Ve \bullet t_i$ be the radius, so that the multiple spheres intersect at one point, and this point is the discharge point. For partial discharge positioning with spherical technology, the number of acoustic transducers is at least three (m⩾3), as shown in Figure 2.

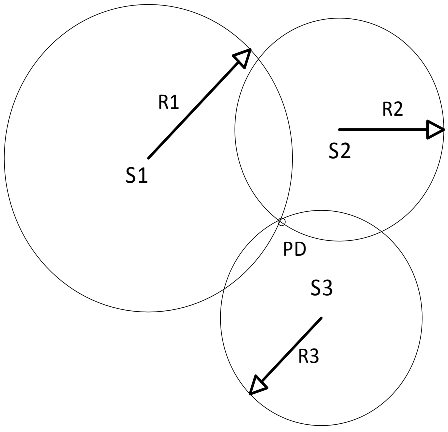

Figure 2. Schematic diagram of physical significance

If the sensor that receives the first acoustic signal is taken as the reference point, the sound wave propagation time difference of the ith sensor relative to the reference sensor can be measured, and the relative sound wave propagation time of each sensor can satisfy the hyperboloid equation, as shown in equation (2):

$$\frac{\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}}{V_e}-\frac{\sqrt{(x_0-x)^2+(y_0-y)^2+(z_0-z)^2}}{V_e}=t_{i-0} \tag{2}$$

Finding the solution of the above nonlinear equation gives us the position coordinates of the discharge point, which is the intersection point of the (m-1) hyperboloid. The solution of such a single equation in coordinate space is a set of hyperboloids, as shown in Figure 3, so it is also called a hyperboloid equation.

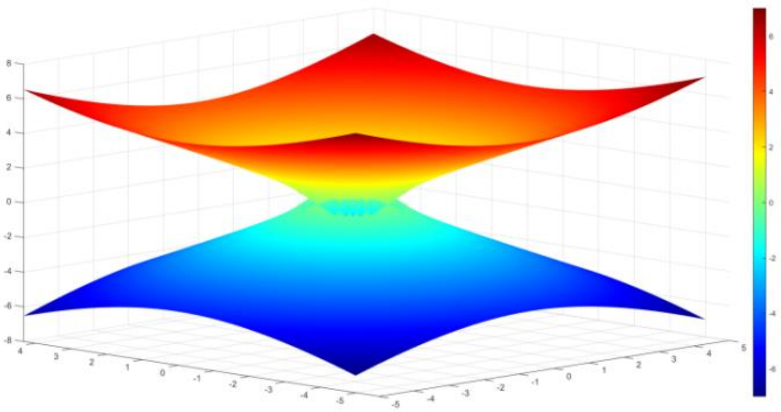

Figure 3. An example diagram of a solution (hyperboloid) for coordinate space

4. Limitations of the ultrasound method

The ultrasonic method has a wide range of applications in transformer partial discharge detection, but there are also some limitations, which mainly come from the characteristics of the ultrasonic signal and the complexity of the actual detection environment. Ultrasonic waves are refracted and reflected many times during the propagation of complex equipment inside. As a result, the ultrasonic signal reaching the sensor is the signal after a series of attenuation losses, so partial discharges occurring deep in the insulation may not be detected. The propagation speed of ultrasonic waves varies from medium to medium, which makes precise positioning difficult. The ultrasonic method cannot directly determine the magnitude of the discharge energy, so it cannot quantitatively reflect the severity of the partial discharge. The ultrasonic signals produced by different types of partial discharges do not differ much, which makes it difficult to determine the type of partial discharge signal and the cause of the discharge based on the ultrasonic signal.

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