Propagation and localisation of partial discharge in transformer bushing based on ultra-high frequency technique

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Abstract

As an essential component of power transformers, the detection and diagnosis of incipient partial discharge (PD) activities of bushings are of great significance. A 35-kV oil-impregnated paper (OIP) bushing is investigated. The bushing is modelled by coaxial theory and electromagnetic (EM) simulation. As the paths of PD-induced ultra-high frequency (UHF) signal propagating in the bushing are OIPs and oil gap, small attenuation during signal propagation is seen. Since OIP is composed of heterogeneous media compared with pure oil, there will be relatively less UHF signal leakage from OIPs, whereas more leakage from the oil gap. This leakage provides the possibility of non-contact detection outside the bushing by UHF method. PD measurements with UHF method are carried out on the bushing. Then, the minimum energy method is used to extract time-difference-of-arrival (TDOA), and Chan algorithm is adopted to locate points of UHF signal radiation. High accuracy locating with a small error of 15 cm has been achieved. The contactless UHF method-based tests have demonstrated the effectiveness of online monitoring and locating of bushing PD.

1 | INTRODUCTION

The transformer bushings are one of the most important components in a power transformer, whose role is to conduct and electrically insulate. However, bushing-related defects contribute a lot to the failures of power transformer irrespective of application or manufacturing period [1–3]. Especially, failures originating in the bushings are prone to severe consequences such as fires or even explosions [4,5]. Therefore, it is significant to evaluate the status of bushings and detect incipient defect to improve the reliability for long-term operation.

Capacitance and loss tangent (tanδ) for bushings are permanent and regular parameters until a disturbance occurs, making them very favourable for condition monitoring [6,7]. Nevertheless, even the advanced method such as frequency domain spectroscopy (FDS) [8,9] based on these parameters is insufficient to provide the information of incipient bushing defect.

In fact, the electric field strength in the condenser body of bushing, which is a multi-layer structure, is quite high, vulnerable to excite partial discharge (PD) activities. When it comes to the PD detection of bushings, there are several methods that provide relatively preliminary results. With regard to PD on the surface of bushing, optical radiation induced by PD phenomenon provides easy but limited access to evaluate the occurrence through photographic technique [10]. With regard to internal PD, both fibre optic-based sensor wound

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around the bushing and pressure sensor mounted through oil-valve help to get the signal of discharge from bushing inside \[11,12]. However, the installation needs to be checked with the long-term reliability.

The mainstream methods are realised by refitting the construction of tap such as coupling the discharge pulse with high-frequency current transducer (HFCT) or capacitors/inductors with the similar principles \[13–15\]. It could indeed monitor PD signals transmitted from bushing tap to grounding wire effectively through wide-band frequency detection, even ultra-high-frequency band. However, it brings in potential safety risks since this scheme and sensors change the original grounding circuit loop. Therefore, it is of great significance to offer a non-contact and safe on-site solution specially for PD detection in high voltage bushing.

The ultra-high frequency (UHF) technique is used in bushings \[16\], which has been investigated as a successful approach for PD measurement in power transformers \[17\] and gas insulated switchgear (GIS) \[18,19\]. It has been one of reliable choice for device monitoring due to non-contact and online detection. As the number of bushings can be higher than 10 for one transformer, a failure of any of them leads to transformer failure as a consequence \[2\]. Hence, the confirmation of the faulty bushing and the PD location is necessary for practical application.

The PD sources can be localised by extracting waveform features such as amplitude, energy and arrival time of acquired signals. The time-difference equations are solved by extracting time difference of arrival (TDOA) \[20–25\] and numerical solution algorithms such as Newton–Raphson approach is widely adopted for localisation \[26\]. However, there are few reports based on the PD localisation in bushings due to the complex and particular structure while PD location of bushing is forward-looking to evaluate the state of bushing insulation system. Therefore, research on the feasibility of UHF for PD detection and localisation is extremely challenging but necessary for practical application.

To reveal the propagation of PD-induced electromagnetic (EM) signals from bushing body, a three-dimensional oil-impregnated paper (OIP) bushing model is established in this paper. Based on the contactless UHF array, a remote live technique of measuring and locating PD in bushing was verified on the basis of real 35 kV OIP bushing test platform. At last, PD localisation in bushing was carried out by TDOA and Chan algorithm to achieve effective measurement.

This study provides a method to extract bushing outline, then the fault region, and further fault diagnosis parameters regarding to the field application of bushing infrared images, as shown in Figure 1. It does not rely on the conversion relationship between infrared images and temperature but directly diagnoses faults based on the infrared images. This kind of diagnosis method can help diagnose in the infrared images collected by different equipment, which reduces the limitation caused by the inconsistent conversion relationship between infrared images and temperature. The remainder of this paper is organised as follows. Chapter 2 briefly introduces the considerations of bushing region detection and segmentation.

Due to the compact mechanical design and closed structure of the bushings, it is necessary to identify the path and process of EM signal leaking from bushing inside to outside.

The condenser body is composed of multiple aluminum foils such as multiple layers of effective coaxial waveguide structure for EM signals, as shown in Figure 1. In the coaxial waveguide, there are three modes defined to analyze EM signals propagation processes: transverse electromagnetic (TEM) mode, transverse magnetic (TM) mode and transverse electric (TE) mode \[27\]. For TM and TE modes, signals attenuate exponentially, and the frequency is lower than its cut-off frequency \(f_0\). Non-existence of \(f_0\) in TEM mode, it is necessary to calculate \(f_0\) of TM and TE modes to analyse the propagation processed by solving Maxwell’s equations.

In the cylindrical coordinate system, the cut-off frequency \(f_0\) under each mode is follows:

\[
\begin{align*}
\frac{f_0}{(TM_{mn})} & \approx \frac{\psi \cdot n}{2(a - b)} \quad m, n = 1, 2, \ldots \\
\frac{f_0}{(TE_{m1})} & \approx \frac{\psi \cdot m}{\pi(a + b)} \quad m = 1, 2, \ldots
\end{align*}
\]

where \(a\) and \(b\) are the outer and inner diameters of the coaxial waveguide, respectively. \(\psi\) is speed of EM signals in the waveguide. The meaning of subscripts \(m\) and \(n\) is corresponding to the modes of TM or TE, for example, TE21 means the mode of TE is 11. In each waveguide of the actual condenser body, \((a - b)\) is about 2 mm and \((a + b)\) could reach more than 10 cm, which shows the \(f_0\) of TM mode is high, and of TE mode is relatively low, as calculated in the Table 1. Therefore, the \(f_0\) of TM mode is beyond of the band of UHF \((0.30–3.00\ GHz)\), and the modes propagating in the waveguide are TEM and TE theoretically.

Moreover, there are non-negligible losses caused by the materials of waveguide wall (aluminum) and medium (OIP) between waveguide wall. To calculate losses precisely, so that electrical conductivity, \(\sigma \neq 0\) and permittivity, \(\varepsilon\) is modified
TABLE 1 Cut-off frequency of different modes in different layers of OIP

| Mode   | 1st Layer of OIP | 2nd Layer of OIP | 3rd Layer of OIP | 4th Layer of OIP |
|--------|------------------|------------------|------------------|------------------|
| TM_{m1}| 39.53 GHz        | 39.53 GHz        | 39.53 GHz        | 39.53 GHz        |
| TE_{m1}| 0.55 GHz         | 0.48 GHz         | 0.43 GHz         | 0.39 GHz         |
| TE_{m2}| 1.10 GHz         | 0.97 GHz         | 0.87 GHz         | 0.79 GHz         |

Abbreviation: OIP, oil-impregnated paper.

as complex permittivity $\varepsilon$, and then the $\mu$ is the magnetic permeability of OIP in waveguide, $\omega$ is the angular frequency and let $\omega^2 = k^2 + j\beta$ ($\alpha$ is the attenuation constant and $\beta$ is the phase constant). There exists induced current on the surface of waveguide wall during the EM signals propagation, also known as skin effect [27]. The induced current density is the highest near the surface of waveguide wall and decreases exponentially with greater depths. The skin depth of EM signals in the metal is obtained as follows:

$$\delta = \frac{1}{\omega} \left( \frac{2}{\mu \varepsilon} \left( 1 + \frac{\sigma^2}{\mu \varepsilon^2} \right)^{\frac{1}{2}} - 1 \right)^{-\frac{1}{2}}$$  \hspace{1cm} (2)

The waveguide wall is constructed by aluminum, with $\sigma = 3.4 \times 10^7 \text{S/m}$ and $\mu = \mu_0 = 4\pi \times 10^{-7} \text{H/m}$. When $f = 0.30$ and 3.00 GHz (the lower and upper limits of UHF band), the skin depths are calculated as 4.97 and 1.58 μm. The actual thickness of waveguide wall is about 7.00 μm, so that signals in the UHF band cannot penetrate the structure. Moreover, the energy loss due to the skin effect is calculated as follows:

$$\alpha_c = \sqrt{\frac{\omega \varepsilon}{\sigma}} \left( \frac{\beta + \frac{\sigma^2}{\mu \varepsilon^2}}{\ln \frac{\beta}{\sigma}} \right)$$  \hspace{1cm} (3)

The loss increases with the increase in frequency, and the attenuation constant is 0.27 dB/m at 3.00 GHz.

On the other hand, there is a polarisation phenomenon that causes dielectric loss because signals transmit through the OIP. The dielectric loss constant in the coaxial waveguide can be calculated as follows:

$$\alpha_m = \frac{\pi}{\lambda_0} \sqrt{\varepsilon_r} \frac{\sigma}{\omega \varepsilon}$$  \hspace{1cm} (4)

where $\lambda_0$ is the wavelength of UHF signals in the air and for OIP, $\sigma = 10^{-15} \text{S/m}$ and $\varepsilon_r$ is the relative permittivity. The dielectric loss is small (less than $10^{-6} \text{dB/m}$) because of the low electrical conductivity and good insulation properties of the OIP.

Based on above analysis, UHF EM signals cannot penetrate the aluminum in the condenser body resulting in some loss due to skin effect. OIP and the oil gap between the condenser body and flange are effective paths for transmission leading to polarisation.

3 35 kV BUSHING PARTIAL DISCHARGES SIMULATION ANALYSIS

To verify the above analyses, a 3D mechanical software is used to model a BRW-36/400-3 35 kV bushing (manufactured by Jiangsu Zhida Electric Company, China), including the external upper and lower porcelain envelopes, condenser body, central tube, electrostatic shield, and a cylindrical oil tank set under the bushing. The parameters of oil are the same as Nytro Gemini X. The bushing is placed in the oil tank to simulate the actual operating conditions. The lengths of upper and lower porcelain envelopes are 485 and 225 mm, respectively; the width of oil gap between condenser body and flange is 7 mm. To simplify the model, it should be noted that the condenser body of the bushing is simplified to four layers of foils, and the thickness of OIP is set as 1 mm in accordance with the physical size as shown in Figure 2.

As EM signals cannot penetrate foil of aluminum, it does not affect the characteristic of signal propagation to increase the thickness of foil from 7 μm to 3 mm. Then, the simplified model is imported into the EM simulation software to evaluate the propagation process. The finite difference time domain (FDTD) method is used in it to analyse the propagation process of UHF EM signal. The central difference quotient is used to replace the EM field’s derivation of time and space, and then recursive calculation in the time domain is simulated to obtain the field distribution during the propagation process.

In the simulation, electrostatic shield, foils, flange, and central tube are set as perfect electric conductor (PEC), which has a conductivity of infinity. The relative permittivity of porcelain, OIP, and oil is 5.8, 3.6 and 2.2, respectively. There are seven layers of perfect matched layer (PML) set at the area boundary to ensure no reflection by the boundary.

In order to make the electric field uniform, the length of foils decreases with the increasing diameter as shown in Figure 3. Probes are arranged at head (1ProbeOIPn) and end (2ProbeOIPn) in each layer of OIP and oil gap to receive the E component of EM signals.

A current source and a 10 Ω resistor in series construct the PD circuit, and it is set on the surface of the lower porcelain envelope. The PD occurs if the voltage increases when the surface of the lower porcelain envelope is dirty or rough. Current waveform is set as Gaussian and actual pulses for comparison, as shown in Figure 4.
propagating in the four layers of OIP. Moreover, signals leak much earlier from the side closed to the PD source, and the attenuation is less. The paths of PD signal propagating from inside to outside are shown in Figure 6.

According to the definition of TEM, TM and TE modes, TE mode has magnetic field component along the propagation direction, TM mode has electric field component along the propagation direction and the TEM mode has neither. It is difficult and non-essential to calculate the specific proportions of each mode in the actual/field detection. As E component of radial direction in the coaxial waveguide structure like GIS is relatively higher, UHF sensors adopted receive EM signals by inducing electric field components [28,29]; it is proper to study the changes of the E components in radial direction. For bushing structure, which is a coaxial waveguide essentially, the relative conclusion should be also applied theoretically. Therefore, the proportions of the electric field energy in the three directions are analysed. The results of probes in OIP1 and oil gap as examples are shown in Tables 2 and 3.

According to the results, there is a similar conclusion in bushing that the changes in energy in all three directions are almost the same. Although there are multiple waveguide structures, the energies in the normal and axial directions are very small, and more than 99% is concentrated in the radial direction. Therefore, it is proper to take the signal of the radial electric field of each probe for analysis, and the accumulated energy in each 0.1 GHz frequency band is calculated, shown in Figure 7.

There are attenuations of energy in each frequency band, and the energy of actual waveform distributes mainly before 1.5 GHz. Due to the energy of actual waveform covers a relatively wider frequency band according to the PD waveform, there is also an obvious changing process of energy after 1.5 GHz. Moreover, the total energy entering each layer of OIP and oil gap are compared as shown in Table 4.

The energy attenuation is small in the UHF band as it is from -2.57 dB to -7.01 dB, because there is a part of high-order mode in the signal, and its frequency is lower than corresponding $f_c$. In fact, OIP is uneven medium, which leads to reflections, causing more losses. Therefore, compared with the theoretical and simulation results, there should be relatively less EM signals leakage from OIPs and more leakage from the oil gap.

4 | PARTIAL DISCHARGE DETECTION AND FAULT LOCALISATION

In this section, a PD test platform is set to verify the position of UHF signals leaking from the bushing in the above analysis. UHF sensors are set outside at different positions without contact to bushing. To calculate the coordinate of the signal leaking position, algorithms of TDOA extraction and localisation are introduced and adopted.
4.1 | Experimental setup

A 35 kV OIP bushing with no defects is taken as the model and placed in the oil tank to simulate the actual operating conditions. The oil of Nytro Gemini X is adopted. The diameter of the oil tank is 300 mm, and its height is 400 mm. As shown in Figure 8, the PD fault was set along the surface of lower porcelain envelope. PD occurs if the voltage increases when the surface of the lower porcelain envelope is dirty or rough. A hard copper wire is adhered to the surface of the lower porcelain envelope, and its end is connected to the electrostatic shield, which is under HV applied. The wire head is wrapped with insulating tapes to prevent tip discharge.

The test layout is shown in Figure 9. The output of the step-up transformer (YDTW-10/100, rated capacity is 10 kVA) is connected to the top of the bushing, and four UHF sensors (ZCCGQ-U-PZ-01) are set around the bushing to receive PD-induced EM signals. The bandwidth of sensors is 300 MHz–2 GHz, and the matching impedance is 50 Ω. The four UHF sensors are connected to the signal amplifier module (HD-iPD) with its gain of 40 dB. The amplifier module outputs are connected to four channels of an oscilloscope (LeCroy 610Zi) working as a high-speed data acquisition unit. The whole circuit is connected by a radio-frequency (RF) cable with the matching impedance of 50 Ω. The sampling rate is 10 GS/s while collecting the UHF signals, and the period of sampling is 500 ns every time.

In the space coordinate system, the horizontal plane is set as the xOy plane, the point of signal leaking from oil gap to outside is at (-0.40 m, 0.40 m, 0.60 m), the PD position is (-0.35 m, 0.35 m, 0.45 m). The positions of the four UHF sensors are set as S1 (-0.40 m, -0.90 m, 1.20 m), S2 (0.00 m, 0.00 m, 0.25 m), S3 (1.80 m, 3.00 m, 0.50 m), S4 (3.00 m, 1.80 m, 1.50 m). The sensors are arranged towards the bushing, and the distances between the four sensors and the bushing gradually increases by about 1 m to reduce the error of TDOA calculation.

4.2 | Fault localisation of partial discharge detection

Locating calculation can be divided into two steps: (a) TDOAs calculation and (b) solution of locating equations.
From Figure 10, $t_1$–$t_4$ represent the PD-induced signals propagation time from the leaking point to UHF sensors relatively. It is obvious that TDOA could be calculated by extracting the first point of the arrived signals at UHF sensor.

The cumulative energy function method (CEF) is used to integrate the signal to obtain its energy accumulation over time, and TDOA is calculated by ensuring the inflection point of its integration curve. The accumulated energy before the PD signal arrive is small and it rises slowly, and the accumulated energy, after the PD signal arrive, is enormous and it rises rapidly. It is feasible to calculate the propagation time. The CEF is:

$$W_1(t) = \int_{t_0}^{T} u^2(t) dt$$

where $u(t)$ is the amplitude of sampling point, $t_0$ is the start time of signal acquisition, and $T$ is the end time of signal acquisition. There is an obvious inflection point in $W_1$, and it is corresponding to the time of signal arriving; then, the TDOAs are $t_{12}$, $t_{13}$ and $t_{14}$ as shown in Figure 11.

Nevertheless, the inflection point extraction is not ideal in practice because the curve is obtained by integration; energy is delayed compared to the original signals, and it is difficult to be judged artificially. To facilitate the calculation, the mathematical derivation shows that the inflection point can be converted to the minimum point. The minimum energy curve is expressed as:

$$W(t) = W_1(t) - \frac{t}{T-t_0} W_1(t)$$

| Probe   | Radial (%) | Normal (%) | Axial (%) |
|---------|------------|------------|-----------|
| 1ProbeOIP1 | 98.95      | 0.10       | 0.95      |
| 2ProbeOIP1 | 99.88      | 0.12       | 0.00      |
| 1Probeog  | 97.62      | 0.00       | 2.37      |
| 2Probeog  | 100.00     | 0.00       | 0.00      |

Abbreviation: PD, partial discharge.

| Probe   | Radial (%) | Normal (%) | Axial (%) |
|---------|------------|------------|-----------|
| 1ProbeOIP1 | 99.07      | 0.10       | 0.83      |
| 2ProbeOIP1 | 99.87      | 0.13       | 0.00      |
| 1Probeog  | 97.90      | 0.00       | 3.09      |
| 2Probeog  | 100.00     | 0.00       | 0.00      |

Abbreviation: PD, partial discharge.

Figure 7 Partial discharge (PD) detection results of various sensor devices. (a) PD waveform is Gaussian pulse. (b) PD waveform is actual pulse.
### Table 4

| PD Waveform      | OIP1 | OIP2 | OIP3 | OIP4 |
|------------------|------|------|------|------|
| Gaussian pulse   | -3.60| -3.16| -2.49| -7.01|
| Actual pulse     | -3.36| -3.31| -2.57| -6.31|

Abbreviations: OIP, oil-impregnated paper; PD, partial discharge.

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**Figure 8** Partial discharge (PD) along the surface of lower porcelain envelope

**Figure 9** Experimental setup and wiring in HV laboratory

\[
W'(t) = u^2(t) - \frac{u^2(t)}{T-t_0} = 0 \tag{7}
\]

The instant of the signal arriving is solved by Equation (7) \[29\]. As the TDOA results are obtained, it is necessary to establish the spatial coordinate system and calculate the coordinates of each sensor to solve the localisation equations and realise the location of the PD.

Chan algorithm is adopted for localisation. It is a non-recursive hyperbolic equation system with analytical expression \[30\]. Therefore, the coordinates of PD are calculated directly as the solving matrix is positive definite (it means the number of sensors are four in the spatial coordinate system).

According to the foregoing analysis, the coordinates of each sensor and three TDOA values are obtained. \((x, y, z)\) is set as the coordinates of point of UHF signal leaking, \((x_i, y_i, z_i)\) is the coordinates of the sensors, and \(r_i\) is the distance between UHF sensor \(S_i\) and \((x, y, z)\), and the equation is:

\[
\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = r_i, i = 1, 2, 3, 4 \tag{8}
\]

The Equation (8) is transformed into a linear equation by separating the variables. It is:

\[
(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = K_i - 2x_i x - 2y_i y - 2z_i z + x^2 + y^2 + z^2 \tag{9}
\]

\(K_i = x_i^2 + y_i^2 + z_i^2\) and \(r_{i,j}\) is the difference between \(r_i\) and \(r_j\), which is equal to the product of TDOA value and the speed of the EM signal. \(r_j\) is assumed as known, and the point of UHF signal radiation is solved as follows:

\[
\begin{bmatrix}
  x \\
  y \\
  z \\
\end{bmatrix} = -\begin{bmatrix}
  x_{2,1,2,1,3,2,1,3} \\
  x_{3,1,3,2,1,3,3,1,2,4,1,4,1,3,4,1} \\
\end{bmatrix}^{-1} \begin{bmatrix}
  r_{2,1} \\
  r_{3,1} \\
  r_{4,1} \\
\end{bmatrix} + \begin{bmatrix}
  \frac{1}{2} (r_{2,1}^2 - K_2 + K_1) \\
  \frac{1}{2} (r_{3,1}^2 - K_3 + K_1) \\
  \frac{1}{2} (r_{4,1}^2 - K_4 + K_1) \\
\end{bmatrix} \tag{10}
\]

Equation (10) is substituted into Equation (8) to calculate \(r_j\), and then, the point of UHF signal generation that is PD source is obtained.

**4.3 Test results**

One thousand sets of effective UHF pulses are acquired under the stable condition of PD. TDOAs of the signals
are calculated by the minimum energy method. Then, the TDOAs and coordinates of sensors are provided as input to the Chan algorithm for solution. The results are shown in Figure 12 and Table 5. 781 sets of effective localisation coordinates were obtained, which shows the data utilisation rate reaching to 78.1%. According to the results, the points of UHF signal radiation are concentrated on the lower part of the upper porcelain envelope (near end of the oil gaps), and a part of is located about \( z = 1 \) m (near the end of foils). The standard deviation value of each coordinate is small, which shows the consistency of results. It proves that the correctness of the aforementioned theoretical and simulation analysis that UHF signals do not directly propagate from the actual point to the sensor. The leaking points contain the end of foils and oil gaps.

The combination of the three factors leads to error in the localisation results: (1) There is a part of the UHF signals that reaches the sensor after reflection. It means that the localisation result is not the actual point but the reflection point. (2) The parameters of each sensor are not totally the same such as workmanship that causes signals received not as ideal as theoretical analysis, and it could be considered as measurement error. (3) There are also inevitable calculation errors in the TDOA data processing. It should be noted that the error in \( z \) affects a lot because there is a small part of UHF signal leaking from the end of OIP along the \( z \) direction, so the localisation results are more scattered. The error of 0.15 m is qualified to distinguish the faulty bushing on a power transformer in the field.

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**Figure 11** Time-difference-of-arrival (TDOA) extraction in the cumulative energy curve

**Figure 12** Results of locating of partial discharge (PD) along the surface of lower porcelain envelope. (a) Results of locating in the \( xy \) plane. (b) Results of locating in the \( yz \) plane
TABLE 5  Statistical results of locating of PD

| Coordinate | Average | Standard deviation | Actual value | Error value |
|------------|---------|--------------------|--------------|-------------|
| x/m        | -0.42   | 0.24               | -0.40        | -0.02       |
| y/m        | 0.37    | 0.10               | 0.40         | -0.03       |
| z/m        | 0.75    | 0.15               | 0.60         | 0.15        |

Abbreviation: PD, partial discharge.

5 | CONCLUSION

This article focuses on the PD failure detection and localisation of OIP bushing. A 35-kV bushing is set as the object for analysing the propagation process of PD signals in UHF in the bushings by establishing simulation model. Then, PD test of bushing is conducted for locating and verifying the results of simulation. The following conclusions are drawn:

1. The paths of PD-induced UHF signal propagation in the bushing are OIPs and oil gap, and there is a small attenuation during signal propagation. Considering the inhomogeneity of OIP, which causes more losses actually, there will be relatively less UHF signal leakage from OIPs, and oil gap is the main path that transmits signals due to it is shorter and wider.

2. External UHF sensors at different positions receive UHF signals, which facilitate PD source location. The extracted and located algorithms of TDOA are adopted to calculate the position of signal leaking. The error value of locating is 0.15 m, and it shows that the locating results has a high accuracy.

3. Different voltage levels of OIP bushings are similar in the structure (all are coaxial waveguides); it is possible to realise the online monitoring of the bushing and locating through UHF method without contact ensures the safety and stability of the insulation system.

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