Partial discharge detection method for lower porcelain shell of oil paper insulation bushing based on spatial UHF signals

Jiansheng Li*, Shengquan Wang
State Grid Jiangsu Electric Power CO.,LTD. Research Institute
*Corresponding author’s e-mail: lijsdky@js.sgcc.com.cn

Abstract. The partial discharge in lower porcelain shell of oil paper insulation bushing is one of the important reasons for transformer failures. Based on the analysis of the oil paper insulation bushing structure characteristics, the finite difference time domain simulation model of the partial discharge in lower porcelain shell is established. And the path of UHF signal of partial discharge is obtained that the signal spreads through the insulation between capacitor screens and oil passage to the outer space. Then the lower porcelain shell partial discharge detection method based on the space UHF signal is proposed and verified.

1. Introduction
The oil paper insulation bushing is one of the key components of transformers. Its failure directly affects the safe operation of transformers, and may lead to transformer fire accidents in serious cases. According to the fault cases of oil paper insulation bushings in recent years, the ratio of partial discharge faults accounts for 60%. It is very important to diagnose the internal discharge of bushing timely and accurately.

To detect the oil paper insulation bushing faults, many experts and scholars have carried out a lot of research works[1-9]. (1) The methods of retrofitting the bushing end screen lead wires with high-frequency current sensors are proposed, which use the online monitoring high-frequency current to realize internal discharge diagnosis. But there is a risk of poor contact of the end screen grounding wire, which may harm the safe operation of bushings. (2) The detection and diagnosis methods are studied, which use discharge ultrasonic signal by sticking ultrasonic sensor on the hoist seat of the bushing. However, the sensor layout is limited by the position of the hoist seat of the bushing, and the vibration and rain have great interference on the detection. (3) Referring to GIS partial discharge detection method, the inner discharge defection methods of bushing diagnosed by detecting UHF signal outside the bushing are discussed. This technology is still in the research stage, and the propagation path and attenuation characteristics of discharge signal inside the bushing are not yet mastered.

Aiming at the UHF detection method of internal discharge in bushing, taking the partial discharge in lower porcelain shell as the object, the finite difference time domain simulation model of bushing is established, and the propagation path of UHF signal generated by the discharge of porcelain bushing is obtained, and the experimental platform is built in the laboratory for verification.

2. Structure analysis of oil paper insulation bushings
The oil paper insulation bushing is mainly composed of porcelain shell, capacitor core, central copper tube, oil conservator, mounting flange and equalizing ball. According to the core structure, the bushings can be divided into two types. One type is the bushing whose capacitor screens are used of complete
aluminum foil. The other type is the bushing that the metal aluminum foil of some capacitor screens is set at the upper and lower ends.

(a) main components of oil paper bushings (b) two different types of capacitor screens

Figure 1. Structure of oil paper insulation bushings

3. Simulation analysis of oil paper insulation bushings

3.1. Theory of electromagnetic wave propagation in oil paper insulation bushings

The key to the analysis of oil paper insulation bushings is the modeling of capacitance core. The capacitance core is made by applying pressure on the oil paper and aluminum foil and winding them on the central copper tube alternately. The aluminum foil forms a concentric cylinder capacitance screen parallel to the central copper tube, which essentially constitutes an effective coaxial wave-guide structure.

Oil impregnated paper between the capacitor screens is the main medium of electromagnetic wave propagation in the bushings. There is polarization phenomenon when the alternating electromagnetic wave propagates, and the capacitor screen itself also has impedance, which leads to the propagation loss of electromagnetic wave. In order to simplify the analysis, the oil impregnated paper is assumed to be uniform, linear and isotropic. The Maxwell equations shown in (1) are used to analyze.

\[
\begin{align*}
\nabla \times \mathbf{E} &= -j \omega \mu \mathbf{H} \\
\nabla \times \mathbf{H} &= j \omega \varepsilon \mathbf{E} \\
\n\nabla \cdot \mathbf{E} &= 0 \\
\n\nabla \cdot \mathbf{H} &= 0
\end{align*}
\]

(1)

Where, \(E\) and \(H\) are electric field intensity and magnetic field intensity respectively, \(\omega\) is the angular frequency of electromagnetic wave, \(\mu\) and \(\varepsilon\) are the permeability and dielectric coefficient of oil impregnated paper respectively. Because of the loss, the permittivity is changed to complex permittivity. \(\sigma\) is the conductivity of oil impregnated paper.

\[
\tilde{\varepsilon} = \varepsilon - j \frac{\sigma}{\omega}
\]

(2)

Substitute the complex permittivity into Maxwell's equations and the corresponding Helmholtz equation can be obtained.

\[
\begin{align*}
\nabla^2 \mathbf{E} + \omega^2 \mu \tilde{\varepsilon} \mathbf{E} &= 0 \\
\nabla^2 \mathbf{H} + \omega^2 \mu \tilde{\varepsilon} \mathbf{H} &= 0
\end{align*}
\]

(3)

In order to further solve the loss in the process of electromagnetic wave propagation, the loss can be equivalent to the impedance of the medium itself. Set \(\tilde{n} = \sqrt{\mu / \tilde{\varepsilon}}\) as the intrinsic impedance of
electromagnetic wave propagation in the medium, which represents the phase difference between the electric field intensity and the magnetic field intensity in the propagation process. Let \( \omega^2 \mu \varepsilon = k^2 \), \( \beta = \alpha + j \beta \), and substitute into equation (3) to obtain the attenuation constant \( \alpha \) and phase constant \( \beta \).

\[
\begin{align*}
\alpha &= \frac{\omega \mu \varepsilon}{2} (1 + \frac{\sigma^2}{\mu \varepsilon^2})^{-\frac{1}{2}} \\
\beta &= \frac{\omega \mu \varepsilon}{2} (1 + \frac{\sigma^2}{\mu \varepsilon^2})^{\frac{1}{2}}
\end{align*}
\]

(4)

Let us suppose that the positive direction of the \( z \)-axis is the direction along the guide rod from the bottom to the top, and the electric field intensity and magnetic field intensity can be calculated.

\[
\begin{align*}
E &= E_0 e^{-j \beta z} e^{-\alpha z} \cdot e_x \\
H &= \frac{E_0}{\eta} e^{-j \beta z} e^{-\alpha z} \cdot e_y
\end{align*}
\]

(5)

Where, \( e_x \) and \( e_y \) represent the unit normal vector along the \( x \) and \( y \) axes respectively, and \( E_0 \) is the amplitude of the initial electric field intensity. Due to the existence of propagation loss, the amplitude of electromagnetic wave is attenuated in the process of propagation. Therefore, electromagnetic waves with different frequencies have corresponding penetration depth \( \delta \) in different media.

\[
\delta = \frac{\omega \mu \varepsilon}{\omega \mu \varepsilon^2} \left( 1 + \frac{\sigma^2}{\mu \varepsilon^2} \right)^{-\frac{1}{2}}
\]

(6)

The capacitor screen is generally made of metal aluminum. In formula (6), the aluminum conductivity \( \sigma = 3.4 \times 10^7 \) S/m and the permeability \( \mu = \mu_0 = 4\pi \times 10^{-7} \). The maximum depth of electromagnetic wave penetrating aluminum capacitor screen can be obtained. When the frequency is 0.3 GHz, the depth is 4.97\( \mu m \). And the depth is 1.58\( \mu m \) when the frequency is 3GHz. Because the depth of the aluminum screen is 7\( \mu m \), the UHF electromagnetic wave cannot penetrate the capacitor screen.

\[
\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \approx 4.97 \ \mu m
\]

(7)

![Figure 2. Schematic diagram of equivalent coaxial wave-guide for capacitor core](image)
3.2. The FDTD model of oil paper insulation bushings

The finite difference time domain (FDTD) method is based on Maxwell's equations to simulate and analyze electromagnetic problems on computer platform. In this paper, a bushing whose rated voltage is 35 kV is used to model.

In the 35 kV bushing model, the structure and probe arrangement are shown in Figure 3. The actual capacitor core contains multi-layer aluminum capacitor screens, and the thickness of aluminum foil is 7μm. It is very difficult and time-consuming to set the mesh size close to the actual foil thickness. Considering the aim of the research mainly focuses on the propagation characteristics of electromagnetic wave, and it is clear that the electromagnetic wave signal in UHF band cannot penetrate the capacitor screen, the model is simplified in this study. Specifically, the oil paper thickness is 1 mm, the depth of capacitor screen is 3mm, and the number of oil paper layers is set to be 4.

3.3. Simulation results of the lower porcelain shell partial discharge

In the simulation, the partial discharge source is set on the surface of the lower porcelain shell, and the partial discharge equivalent circuit is set as the current source series resistance. In the model, the current amplitude is 1 A, the resistance value is 10Ω and the partial discharge waveform is set as ideal Gaussian pulse that it covers the UHF band completely.
In the simulation, the propagation process of electromagnetic wave is represented by the change of Poynting vector, as shown in Figure 5. In the bushing with complete aluminum foil, at about 1.5 ns, the electromagnetic wave propagates through the oil passage to the outer space. And in the bushing with aluminum foil at the upper and lower ends, the results are similar. That is to say, the propagation is different only in some local area, and the structure of capacitor screens doesn’t cause significant effects to the electromagnetic wave propagation.

![Distribution of Poynting vector of electromagnetic wave in simulation](image)

(a) in the bushing with complete aluminum foil

(b) in the bushing with aluminum foil at the upper and lower ends

Figure 5. distribution of Poynting vector of electromagnetic wave in simulation

When the electromagnetic wave propagates, it is reflected in the oil tank for many times and then fills the whole oil tank. The electromagnetic wave first leaks from the end of the oil passage near the partial discharge source to the outside. With the increase of time, the electromagnetic wave leaks from the end of the whole oil passage and the capacitor screen. Compared with the oil passage, the time of signal leakage from the oil impregnated paper to the outside space is relatively delayed, which is about 2 ns later. Therefore, the propagation path of electromagnetic wave is shown in Fig. 6.
According to the simulation results shown in Table 1, the intensity of radial electric field component is relatively high.

| 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% |

It can be concluded that the total energy of propagation is basically concentrated in the radial direction. When the UHF signal enters the oil impregnated paper and oil passage, there is a small part of energy in the normal and axial direction, but it is completely attenuated eventually, resulting in the energy concentration in the radial direction. Take the radial electric field signal of each probe for analysis, calculate the cumulative energy proportion in every 0.1 GHz frequency band, and the results are shown in Figure 7.

![Figure 6. electromagnetic wave propagation path](image)

Figure 6. electromagnetic wave propagation path

According to the simulation results shown in Table 1, the intensity of radial electric field component is relatively high.

It can be concluded that the total energy of propagation is basically concentrated in the radial direction. When the UHF signal enters the oil impregnated paper and oil passage, there is a small part of energy in the normal and axial direction, but it is completely attenuated eventually, resulting in the energy concentration in the radial direction. Take the radial electric field signal of each probe for analysis, calculate the cumulative energy proportion in every 0.1 GHz frequency band, and the results are shown in Figure 7.

![Figure 7. Proportion of energy](image)

(a) in the first layer  
(b) in the second layer
According to the above results, it can be seen that the attenuation of electric field energy is different in each frequency band. When the partial discharge waveform is Gaussian pulse, the corresponding results show that the main energy is concentrated before 1.4 GHz.

Comparing the total energy in each layer of oil paper and oil passage, the results are shown in Table II. The maximum attenuation is in the fourth layer of oil paper, followed by the oil passage, and the minimum attenuation is in the third layer of oil paper. The reason may be related to the multiple refraction caused by the structure of oil tank, the position of partial discharge source and the number of layers of capacitor screen. But in general, the attenuation of the whole propagation process is very small. In fact, the increase of oil paper's inhomogeneity will lead to the increase of loss.

Table 2. Electromagnetic wave attenuation in each layer of oil paper and oil passage (dB)

| Wave type | OIP1 | OIP2 | OIP3 | OIP4 | og |
|-----------|------|------|------|------|----|
| Gaussian pulse | -3.60 | -3.16 | -2.49 | -7.01 | -4.79 |

4. Partial discharge test of 35 kV bushing

The partial discharge test platform of 35kV bushing is built, and four UHF signal sensors are set outside. The output of the sensor is connected with Lecroy-610zi oscilloscope through UHF signal conditioner and signals are collected. RF coaxial cable is used for signal transmission, and the matching impedance is 50 Ω.

In the partial discharge test, the bushing is vertically placed in the oil tank, the oil tank is filled with transformer oil, and the oil tank is well grounded with the bushing end shield and flange. Four UHF sensors are placed near the bushing through the bracket, keeping a certain distance from the bushing to avoid suspension discharge. HFCT (high frequency current transformer) is set on the bushing ground wire to measure the partial discharge. The test platform is shown in Figure 16. The discharge is caused a section of thick wire attached to the surface of porcelain bushing.

According to the above-mentioned test and sampling settings, the step-by-step boost method is used to pressurize the bushing. Record the initial partial discharge voltage and the corresponding discharge quantity when the partial discharge is stable, and then collect the UHF detection signal corresponding to the four sensors.

Adjust the gain of the signal amplifier to be 40 dB and the gain band to be 0.3 GHz-2 GHz. When collecting statistical data, the sampling rate is 5 MS/s, and the partial discharge signal in one power frequency cycle (20 ms) is collected.
The initial voltage of the discharge is about 15 kV. When the voltage is raised continuously, it can be observed that the number of partial discharges in a single cycle increases significantly, and the amplitude also increases slightly. When the voltage is raised to 30 kV, it is mainly distributed in $0^\circ$-$110^\circ$, $150^\circ$-$270^\circ$ and $340^\circ$-$360^\circ$. In the process, the stable partial discharge charge is about 100 pC, and the maximum is 120 pC.

In the test, the external UHF sensors can receive effective UHF signals. In order to study the differences of the signals, set the distances between sensors and bushing be different. And the signals received by four sensors are shown in Figure 10. From the figure, we can see that the signals are similar in shape, because of the same discharge source. The time that is detected by sensors is different because of the propagation distance, which is the base to diagnose bushings with discharge.
5. CONCLUSION
In this paper, the propagation progress of UHF electromagnetic wave caused by the discharge in the lower porcelain shell of oil paper insulation bushings is obtained, and the discharge in bushings can be detected by analyzing the space UHF signals.

(1) The propagation path of UHF signal in bushings is obtained that the signal caused by discharge spreads through the insulation between capacitance screens and oil passage to the outer space.

(2) By the simulation and test results, the attenuation of the UHF signal is got. And in general, the attenuation of the whole propagation process is very small.

(3) The time that the UHF signal is received by the sensors are different, which is helpful to determine the fault bushings.

Acknowledgment
The authors acknowledge the financial support of State Grid Jiangsu Electric Power CO., LTD. (Research on the explosion performance improvement of oil immersed transformers). NO. J2020037

References
[1] Zhang X, Xu Y, Wang Y, et al. (2016) UHF Sensing of Partial Discharge in Condenser Type Bushing from End Shield Grounding Tap. High Voltage Apparatus, 52(02): 62-67+73.
[2] Liu Y, Lv F, Li C, et al. (2004) On-line Monitoring Transformer’s Bushing Insulation Based on Its Tap Capacitive Divider, 02:121-123.
[3] M. P. G. Botelho, T. B. Gomes, F. V. B. de Nazaré, et al. (2013) A novel monitoring method for condensive bushings, 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Minneapolis, MN, pp. 1266-1271.
[4] Yin H. (2016) Research on Partial Discharge Location for Bushings using UHF Method[D]. North China Electric Power University(Beijing).
[5] Yin H, Zhu X, Li C, et al. (2016) Analysis of TDOA for Locating PDs in Bushing Based on UHF Signal Features. High Voltage Apparatus,52(04):180-187.
[6] Zhang Q, Li C, Liu Q, et al. (2017) Research on Propagation of UHF Signals by Partial Discharges in Ascending Flanged Base, Power System Technology,41(04):1332-1337.
[7] Zheng S, Zhang Q, Ying H, et al. (2016) Feasibility of detection partial discharges in bushings using UHF method[C]/ IEEE International Conference on High Voltage Engineering & Application. IEEE.
[8] Liu Q, Zheng S S, Zhang Q, et al. (2016) Experimental study on UHF pattern of partial discharges in transformer bushings. IEEE International Conference on High Voltage Engineering & Application. IEEE.

[9] H. Wang, J. Cheng, D. Ding, et al. (2018) A feasibility study on bushing tap UHF sensing method for partial discharge in transformer. 2018 Condition Monitoring and Diagnosis (CMD), Perth, WA, pp. 1-4.