Investigation on the Placement Effect of UHF Sensor and Propagation Characteristics of PD-induced Electromagnetic Wave in GIS Based on FDTD Method

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ABSTRACT
Using ultra-high-frequency (UHF) method in practical partial discharge (PD) detection can be affected by the positioning and placement of the UHF sensor. This in turn can affect the PD diagnosis. To ensure optimal performance of the sensor and understand the propagation process of electromagnetic (EM) wave, there is a need to fully analyze how the sensor’s placement affects the output signal and the attenuation of EM wave in various positions and directions. As the previous researches are mainly concentrating on the radial component of the UHF signal, the propagation of the signal components in axial and radial directions and that perpendicular to the radial direction of the GIS tank are investigated in detail in this paper. Firstly, the attenuation of UHF signals at different radial positions of a GIS model is analyzed using the finite difference time domain (FDTD) method. Then, secondly, the coupled signals in the three directions are calculated respectively. By comparing the signal received for different directions and circumferential angles, the peak to peak value (Vpp) and cumulative energy of the coupled voltage in each case are considered both in the time and frequency domain. As well, the attenuation characteristics and rules are summarized, based on which a new method for circumferential and axial location is proposed. The investigation on the propagation and the detection mechanism of EM wave in GIS provides a significant understanding of the application of UHF sensor and actual PD detection.

Index Terms - Gas insulated switchgear (GIS), partial discharge (PD), UHF sensor, electromagnetic (EM) wave propagation, finite difference time domain (FDTD).

1 INTRODUCTION

Ultra High Frequency (UHF) method has gained broad acceptance and application in partial discharge (PD) diagnosis mainly for its high sensitivity and disturbances immunity. By detecting the electromagnetic (EM) signals radiated from PD in the UHF range, this method could achieve the identification of PD types and location, insulation condition assessment, etc [1-5]. Therefore, it is essential to undertake research to understand the propagation characteristics of EM wave in GIS for UHF detection.

Although the structure of GIS is similar to that of the coaxial waveguide, which makes the EM wave travel long distances, the UHF signal still experiences reflection and refraction many times as it propagates. Meanwhile, GIS has some complicated structures, such as L-section and T-branch part, the circuit breakers, isolators and other electrical equipment which can affect the continuity of coaxial structure or the transmission medium. These factors make EM field distribution more complicate, and will certainly have a great impact on the propagation and attenuation of EM wave. At present, many researchers have considered these factors [6-12]. In the perspective of EM wave mode, lots of works about propagation properties in such systems are conducted including a diagnostic algorithm [13-18]. And plenty of studies on the real-time monitoring and charge accumulation process of PD have been conducted [19-25]. Since the position and properties of a discharge signal can vary randomly in ways which are difficult to reproduce or predict experimentally, Green's functions is proposed for simulation of PD-induced UHF signal at the beginning [26, 27]. Then the Finite Difference Time Domain (FDTD) method is found to be useful for modeling electrical plant [28], propagation process of UHF signal in GIS [22] and simulating the sensor response characteristics to optimize the design [29].

Currently, a lot of research on propagation characteristics of electromagnetic waves in GIS have been made, but most of them concentrate on the radial direction component[6, 7, 22, 26, 27], while different components in different directions have rarely been considered. Practically, the complicated field
intensity distribution in GIS, different placements and installation locations of the sensor would all inevitably influence the signal component received by the sensor. As a result, the output signal will change, which will affect a series of PD analysis, such as the location and charge quantity estimation. And according to the study of propagation characteristics, constructive conclusions regarding the installation and placement of UHF sensor are few in number, too [30-33]. Therefore, based on the widely used FDTD method, the feasibility of adopting probe coupler to obtain the output voltage has been verified firstly in this paper. Secondly, the attenuation characteristics of the electromagnetic (EM) wave in different radial positions, directions and circumferential angles are obtained through simulation. The peak to peak value ($V_{pp}$) and the energy of the coupled PD signal are analyzed in both time and frequency domain. Then, based on the attenuation rules summarized according to the results, a new circumferential and axial location method is proposed.

2 MODELS AND ANALYSIS CONDITIONS IN FDTD SIMULATION

2.1 SETUP OF SIMULATION MODEL

The calculation model consisting of coaxial cylindrical conductors is made corresponding to a type of 252 kV GIS busbar with one phase in the tank. For a real GIS product, the straight GIS tank is the most common but fundamental unit, based on which other special structures are formed, such as L-shaped and T-shaped tank. And as [10] declares, the reason for the decreasing of UHF signal in straight GIS is not attributed to the attenuation of EM wave intensity by the passage of the spacer. Therefore, in order to investigate the effect of sensor’s placement on the output signal substantially, a basic straight GIS model without any spacers or other segments is adopted [6, 7, 34]. The diameters of the central conductor and the tank are 120 mm and 400 mm respectively, while the thickness of the tank wall is 10 mm and the tank length is 2.2 m. The model, together with the coordinate system is shown in Figure 1. The coordinate origin is set to the center of the high voltage conductor in the left end, while x and y axes are along with the radius direction and the axial direction is taken as z axis.

![Figure 1. Simulation model.](image)

A metal needle 30 mm in length is mounted on the high voltage conductor as the excitation source to imitate the insulation defect. A Gaussian pulse with broadband characteristics of -30 dB attenuation at 3 GHz is added on the needle as the PD current pulse. Because of the HV field which causes PD current to flow is predominantly radial [26], both the needle and the current are set vertical to the conductor surface along y direction so as to make them consistent with the actual situation.

Its peak value is 15 mA and the half value width is 0.35 ns as shown in Figure 2. The charge quantity of this pulse is 5 pC, which meets the sensitivity requirement of conventional PD detection.

![Figure 2. The excitation source waveform.](image)

2.2 SETTINGS OF RELATED PARAMETERS

7 layers of Perfect matched layers (PML) for both terminals are applied to match the impedance of the adjacent mediums, and then the reflection and refraction at the end of the GIS can be neglected. The boundaries out of the tank in the other two directions are also set in the same way. In addition, the HV conductor and the tank use perfect conductors to neglect the loss at the conductor wall. The relative permittivity of SF6 that filled in GIS tank takes 1.00205, while the density is set as 23.727 kg/m³ under the pressure of 0.4 MPa-abs. The relative permeability and conductivity takes 1 and $1.1015 \times 10^{-5} \text{ S/m}$ respectively. It has been tested that the results with and without SF6 only have tiny differences, but the former one is more consistent with the actual situation.

The relationship between the maximum cell size and the minimum wavelength in FDTD calculation may be determined by:

$$L_{\text{max}} = \frac{\lambda_{\text{min}}}{10}$$

The highest frequency calculated here is 3 GHz. So the cell size is determined as $10 \text{mm} \times 10 \text{mm} \times 10 \text{mm}$ [8]. The simulation time is 100 ns and time step is 19.2583 ps.

To ensure the calculation running accurately and fast, two procedures are taken as below.

1) The metal needle is placed 200 mm away from the left end of the tank, which makes the distance between the excitation and the boundary more than 10 mesh cells. This will guarantee the stability of the calculation.

2) To ensure the accuracy and stability of the calculations at external boundary, 10 cells of free space in x and y directions are added outside the GIS. This method can significantly improve the convergence speed by testing.

2.3 SIGNAL ACQUISITION

Ten sensing points are placed on the axial direction distant from the excitation source at 200 mm intervals. And three
sensing points with 90-degrees intervals in the circle are used at identical cross sections, as in Figure 1.

From the algorithm of FDTD approach, it is known that the electric and magnetic fields are divided into discrete segments both spatially and temporally. The time-dependent curl equation is transformed into the finite difference expression to get the solution to the Maxwell’s equations directly in time domain. Thus, it is easy to get the field quantity in each position. But the output of the sensor in actual detection is voltage value. If that is expected to be obtained in the simulation, a probe coupler with certain impedance is considered to be used as the carrier of the voltage [27, 28], which can induce the EM waves like a sensor. Then the coupling voltage across the probe would be sequentially achieved. Moreover, as most of the attention has been paid to the radial direction signal in previous research, the probe coupler is applicable to investigate the signal in every direction since it will only respond to the electric field component in its own direction. Then the understanding about the propagation mechanism of UHF signal will be completed and improved.

So in this paper, a probe coupler is applied at each sensing point, which is set in the form of a load in certain length shown in Figure 3. Taking account of impedance matching to the coaxial cable, the input impedance of UHF sensor in actual use is usually designed close to 50 Ω as much as possible. Therefore, the impedance of probe coupler is set as Z = 50 Ω, and its length within the scope of the entire computing domain should satisfy:

\[ 2l < \lambda_{\text{man}} \]  \hspace{2cm} (2)

Referring to M. D. Judd’s analysis about the effective length of the probe in [27] and considering the cell size in this research, \( l = 10 \text{ mm} \) is taken to meet the requirement above. The electric field strength at the sensing point is also extracted for analysis.

From the response to the electric field, it can be seen that the probe coupler here works similarly as a monopole antenna to receive the EM wave. Essentially, this kind of treatment is a numerical method to define a resistor value so as to evaluate the potential from electric field, which avoids the bandwidth and impedance matching requirement for using a concrete sensor [35] and achieves the acquisition of the entire frequency component in the calculation. Since the voltage signal is accessible to be obtained conveniently, this means is suitable for the simulation research of the propagation characteristics. What should be noticed is that if the monopole is expected to be represented in detail, some other parts like the metal connected to it are also needed, and it would be more complicated to execute.

3 PREPARATORY WORK AND ANALYSIS

3.1 THE RELATIONSHIP BETWEEN THE PROBE’S VOLTAGE AND ELECTRIC FIELD STRENGTH

At each detecting point, the relationship between the electric field strength and the output voltage of probe coupler which are placed along y direction near the tank wall is analyzed firstly. The component of electric field intensity \( E_y \) when no probe is added and the coupled voltage of probe \( U_y \) are put together to have a comparison. And the place is chosen randomly at the sensing point 6 at \( \theta = 0^\circ \), near the middle of the tank. The result is shown in Figure 4.

![Figure 4](image)

**Figure 4.** Comparison of the waveform between EM wave strength and original electric field strength on y direction at point 6 and \( \theta = 0^\circ \).

It can be seen from Figure 4a that the black curve of voltage and the red one of the original are consistent on the overall trend. And in Figure 4b, each peak of voltage is accompanied by one of E field at the same frequency, which shows the relationship between the amplitude-frequency characteristics of them. It can be seen that the voltage and electric field are in consistency. This is because when the probe is placed in a certain direction in the coordinate system, it will inevitably be perpendicular to the plane formed by the other two. Then the electric field component in this plane cannot be coupled but
only the one in the place direction can. In other words, the output voltage of the probe is an indirect reflection of the original field component in the probe direction. Similar results can be seen in the other sensing points, and they are not repeated here. It also verifies the feasibility and rationality of using probe voltage to imitate the sensor’s output.

Nevertheless, Figure 4 also shows that there is not a strictly proportional relationship between the voltage waveform and that of original electric field intensity. The error existing in some position is caused due to the influence of the added probe in GIS tank over the original electric field distribution. Practically, the installation of the internal sensors will unavoidably influence the original electric field more or less. Thus, in the actual installation process this effect should be minimized as much as possible to make the output of sensor reflect the real propagation feature of PD signal.

3.2 THE SIGNAL ATTENUATION CHARACTERISTICS IN DIFFERENT RADIAL POSITION

Although it needs to make installation design for the application of internal sensor at the beginning of GIS design, which causes the failure to the installation on GIS in the field, it still has advantages of high sensitivity and is less vulnerable to outside interference. However, the output signal can be affected due to the difference of radial installation positions of the sensor. So to study the attenuation in different locations, four radial positions at \( \theta = 0^\circ \) are chosen for the probe, and the \( y \) coordinates of them are (190,200), (170,180), (150,160) and (130,140) respectively. The peak to peak value \( V_{pp} \) and cumulative energy of UHF signal which is calculated by equation (3) are adopted in the analysis.

\[
E = \frac{1}{Z_L} \int U(t)^2dt
\]

where \( U(t) \) denotes the UHF voltage signal, \( Z_L = 50\Omega \) is the input impedance of UHF sensor, \( E \) denotes the received energy during simulation time of 100 ns. The result is shown in Figure 5.

Figure 5a shows the \( V_{pp} \) attenuation of 10 sampling points, which demonstrates that the radial position of detection point has a significant impact on the results. Basically, the further away from the tank wall, the smaller the \( V_{pp} \) value will be, and it doesn’t continue to decay. A slight increasing process starts from the point 6, which does not exist in (130,140), instead of a continue decrease. Besides, as the probe getting close to the central conductor, the \( V_{pp} \) of the first point shows a transition from decrease to increase, and the value reaches the maximum in (130,140). This variation, which is quite different from the other points, is determined by the field distribution in the cross section of excitation. In Figure 5b, the energy decay situation calculated by using equation (3) has a very similar trend to that in Figure 5a, while in the last three cases the energy attenuation is more stable overall after point 5.

In fact, what Figure 5 reflects is a field distribution in different radial positions within the GIS coaxial structure, which leads to the propagation of electromagnetic wave and is determined by the constitution of the EM wave modes. In different radial positions, the modes of the EM wave are superimposed together to form the electric field of the location in space. Due to the velocity dispersion effect, the electric field components of the modes and their contribution in that point are distinct, which also results in the variation of the electric field strength in different locations. Consequently, when the detection point is located in a different radial location, both the results of \( V_{pp} \) and energy vary. In the case of (190,200) where near the tank wall, the mandatory zero point of the electric field distribution is formed as it’s close to metal conductor. Thus, the change of the electric field near the wall is greater and then results in a higher \( V_{pp} \).

![Figure 5](image)

**Figure 5.** \( V_{pp} \) and energy attenuation of different radial positions at \( \theta = 0^\circ \).

Besides, it is found that the maximum \( V_{pp} \) is generated in detection point 1 which is right above the defect. This is mainly because that, after the EM wave being reflected by the tank, the superimposition situation of the reflection and incidence wave in different positions becomes diverse. And \( V_{pp} \) and energy value of each location are larger in (190,200), which makes it easier to detect in practice. But in (130,140), the difference between the value of point 1 and those of the others is the largest. That is obviously more conducive to the accurate locating of defects in actual detection. Considering that the internal sensors are installed in the hand hole or reserved interface of GIS in general, and sensors’ surfaces are required to be parallel to the inner surface of the tank in order
to protect the electrical field inside GIS from being influenced, the radial position (190,200) closer to the tank wall is used in the subsequent simulation.

4 THE EFFECT OF CIRCUMFERENTIAL ANGLE AND PLACEMENT DIRECTION TO THE SIGNAL ATTENUATION

Now the attenuation of the propagated EM wave signal at three circumferential angles is analyzed, while the probe couplers are placed along the x, y and z directions respectively.

4.1 THE SIGNAL ATTENUATION CHARACTERISTICS IN DIFFERENT DIRECTIONS AT $\theta = 0^\circ$

When the probe is placed along the three directions respectively, the coordinate of the probe’s midpoint on y-axis are all 195 mm. The Vpp attenuation of 10 sensing points is shown in Figure 6. Specially, the value of Vpp_y is divided by 10 to be shown together with the other two.

![Figure 6. Coupled voltage waveform of sensors in different directions at $\theta = 0^\circ$.](image)

According to Figure 6, Vpp values in the three directions differ significantly from each other. The Vpp in x and z are about one order of magnitude smaller than that in y. And there is a similar trend of continuously reducing for the Vpp both in x and y. Ostensibly, it is the excitation of the insulation defect which is set along y axis that makes the component of the electric field in y become the largest. Indeed this is reasonable because PD current in GIS are caused by the electric field which is predominantly radial. As the reflection from the upper tank wall of the insulation defect is the strongest, certain frustration occurs to the coupling voltage, but in the whole, it still shows a downward trend. While the component of electric field in x takes the smallest part and the reflection is less than the declining trend, so it only displays the attenuation rule overall. From reference [6, 7], it is known that among the three modes that EM wave produced in PD, only the TM mode contains the component of electric field in z, so the voltage value in z is smaller as well. Besides, the propagation velocity in different modes differs from one another. Namely, TEM mode has the fastest velocity approaching to the light speed, while the velocity of high order modes like TE and TM is slower, which also depends on dielectrics and frequency. With the frequency increasing, the velocity becomes even lower and it leads to the separation of each mode. So the detection points far beyond the PD source receive the TEM and lower order modes first but the high-order mode later. Then it causes difference of superimposing of the reflection wave and forward traveling wave in locations differently distant from the PD source, and finally leads to the attenuation of Vpp.

As for the increasing phenomena at the first two points along z direction, it may be caused by the establishment of axial electric field which needs a process in both time and space to conduct the EM wave. Reference [15] indicated that, the direction in which the electric field vectors of emitted EM waves are excited is parallel to the charged electric fields, because the PD is the electric charge movement in the electric field direction in very minute areas. For the inside electric field of GIS is mainly perpendicular to the metallic surfaces of tank wall and central conductor, the moving direction of the electric charges is basically along the radial direction. Therefore, just above the excitation, the output of the probe coupling of axial electric field is very small, which makes the maximum value of Vpp not appear on the top of the defects. Further analysis will be made about this in the following.

In Figure 7, the Vpp and energy of the coupled EM signal in each direction are plotted together separately. The waveforms of them in three directions are consistent well. Among them, the ones in x and y almost coincide with each other, whereas those curves in z have a larger deviation in the latter part and still associate with an obvious increase at the first two points. This result, which is similar with that in Figure 5, testifies that the attenuation of Vpp could represent the variation of coupled energy. In addition, since the excitation along the y direction, the component $E_y$ of the electric field takes the largest part. So when the polarization direction of the sensor keeps parallel with the y direction, the coupled signals can be the strongest and the output of the sensor is the largest. It can also explain why Vpp can reach the maximum when the sensor and the defect are at an angle of $0^\circ$ in the cross section of the tank, as mentioned in literature [34].

![Figure 7. Comparison of waveform between the coupled voltage and energy of sensors in different directions at $\theta = 0^\circ$.](image)
4.2 THE SIGNAL ATTENUATION CHARACTERISTICS IN DIFFERENT DIRECTIONS AT $\theta = 90^\circ$

When the probe is placed along the three directions respectively, the coordinate of the probe’s midpoint on x-axis are all 195 mm. The $V_{pp}$ and energy attenuation in each direction are separately shown in Figure 8.

![Figure 8](image)

Figure 8. Comparison of waveform between the coupled voltage and energy of sensors in different directions at $\theta = 90^\circ$.

As Figure 8 shows, the $V_{pp}$ values in three directions also have significant distinction. What different from Figure 6 is, the $V_{pp}$ values in x are greater than those in y and z, with the difference not reaching an order of magnitude. And the attenuation curve of $V_{pp}$ in x exhibits bimodal shape which is distinct from that in y of Figure 7. Before point 3, the $V_{pp}$ in y keeps decreasing while that in z increasing oppositely. After that the $V_{pp}$ in y is relatively stable, meanwhile the $V_{pp}$ in z begins to decline gradually. So it’s easy to see that the largest components of both $V_{pp}$ and energy are still in the radial, however, in which the offset effect from the refraction and reflection of EM waves is more significant, and it weakens the gap between the radial and the other components of electric field. This causes that the $V_{pp}$ and energy in x, the maximum of three cases at $\theta = 90^\circ$, are all less than the corresponding value in y at $\theta = 0^\circ$ in Figure 7.

In Figure 8, similarly to the previous statement, the attenuation of $V_{pp}$ in each direction keeps the same trend with their energy respectively. Only the rise and fall speeds of energy in x are different from those of $V_{pp}$. While the energy decline in z is gentler than $V_{pp}$, which results in some difference of the two in the middle and posterior segments. At the same time, comparing with Figure 7, it can be found that the variation tendency of $V_{pp}$ and energy along the radial direction has changed at $\theta = 90^\circ$ whereas those in the other two directions are basically consistent.

4.3 THE SIGNAL ATTENUATION CHARACTERISTICS IN DIFFERENT DIRECTIONS AT $\theta = 180^\circ$

When the probe is placed along the three directions respectively, the coordinate of the probe’s midpoint on y-axis are all -195 mm. The $V_{pp}$ and energy attenuation in each direction are separately shown in Figure 9.

![Figure 9](image)

Figure 9. Comparison of waveform between the coupled voltage and energy of sensors in different directions at $\theta = 180^\circ$.

As Figure 9 illustrates, the difference of $V_{pp}$ and energy in three directions is still evident. And analogously to Figure 6, $V_{pp}$ and energy in the radial direction are maximal, as the differences from those in the other directions reach an order of magnitude again. But there is an obvious difference that the decay curve shows a unimodal-like shape. The $V_{pp}$ and energy remains a decreasing trend in x, and the variation in z rises first and drops then. The rule that the $V_{pp}$ and energy take the maximum value in radial direction is still valid at $\theta = 180^\circ$.

Another finding is that, compared with Figure 7, the value range of both $V_{pp}$ and energy in x and z are all essentially unchanged, meanwhile that in y is reduced by half. It indicates the offset by the superposition of EM waves here in radial direction is great, too.

Similarly as the rule before, both $V_{pp}$ and energy in the same direction have the same tendency of attenuation. The distinction is that the variation is more mitigate in y and z, especially the rising trend of the front 4 points in z becomes much more evident and gentle, as well a little fluctuation is found in x direction. Combined with the previous results, it is found that only the variation tendency of $V_{pp}$ and energy along the radial has changed at $\theta = 180^\circ$ while those in the other directions are hold without changes yet.

4.4 COMPARATIVE ANALYSIS AND THE LOCATION METHOD

By summarizing all the preceding results and comparing the values of $V_{pp}$ and energy, it can be concluded that, when the probe is placed along the radial direction, the $V_{pp}$ and energy are all the largest in three circumferential positions. And in this case the value range has the relationship as $0^\circ > 180^\circ > 90^\circ$ with different attenuation characteristics in each angular position, from which it can be inferred that the best position for detecting the radial component is certainly $\theta = 0^\circ$. By utilizing this variation rule of $V_{pp}$ along the radial direction, the judgment of circumferential angular for the defect can be
made then. And it provides great help in circumferential location for the protrusion defect on high voltage conductor.

At any circumferential angle except 90°, the Vpp and energy in different directions also meet such relationship as: radial > axial > perpendicular to the radial. And the attenuation characteristics in the latter two cases remain basically unchanged in the three angular positions. However, the signal in the last direction is relatively weak and hard to detect. From the feature of the Vpp and energy in axial direction, it is noticed that using the variation rule of the axial signal, which means to search the position with the lowest Vpp, could achieve the longitudinal location of the defect without any influence of the detection angle on the cross section.

In addition, when the probe is set perpendicularly to the radial direction, it is the location 90° on which the value ranges of both Vpp and energy are found to be the maximum. When the probe is set in axial direction, the value ranges are higher at θ=0° and 180°, which is different from other cases. But in Figure 9, the axial Vpp of the defect location is more recognizable than others. Therefore, when conducting the longitudinal location by detecting the axial Vpp whose attenuation rule does not change with the detection angle, if the circumferential location could be made firstly and then the detection performed at 180°, the received signal would be stronger and the judgment of location will be done more easily.

By studying the propagation characteristics of PD radiated EM wave components in different directions and combining the above analysis, a new PD location method is proposed in this paper, the circumferential location and longitudinal location which respectively take advantage of the attenuation characteristics of the EM waves in radial direction and axial direction included. Figure 10 shows the flow, and the specific procedure is listed as follows.

1) Build the curve database which reflects the Vpps (or cumulative energy, the same below) attenuation characteristics of PD signal in radial direction on different circumferential angles.

2) According to the characteristics of Vpp attenuation curve in radial direction, compare it to the curve database in 1), then find the most similar type and consequently determine the circumferential angle position of PD defect on GIS cross section.

3) In the best angular position for longitudinal location analysis obtained from 2) (for example, the position with 180° to the insulation defect), search the position with the lowest Vpp, could achieve the longitudinal location of the defect in the axial direction of GIS tank.

This location method can avoid the difficulty in determining the correct arrival time of EM wave and the high requirement towards hardware equipments like the oscilloscope in the time-of-flight measurement method [36, 37].

5 PROPERTIES CHARACTERISTICS ANALYSIS OF EM WAVE MODE IN FREQUENCY DOMAIN

In this section, the FFT transformation for the output signal of the probe is carried out to analyze the propagation characteristics of different modes in frequency domain. First, the cutoff frequency of each mode is calculated. For the TE and TM mode, it can be obtained by the equations as below [14-16].

\[ f_{c,TE_{m}} = \frac{cm}{\pi(b+a)} \quad m = 1,2,3,... \]  
\[ f_{c,TM_{n}} = \frac{cn}{2(b-a)} \quad n = 1,2,3,... \]

where \( a \) and \( b \) are the radius of high voltage conductor and the tank respectively, and \( c \) is light velocity. From the previous content, it’s known that \( a=60 \text{ mm}, b=200 \text{ mm} \). Then the results of cutoff frequency are obtained shown in Table 1 and 2.

<table>
<thead>
<tr>
<th>Table 1. The cutoff frequencies of TE_{m} modes in GHz.</th>
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<td>( m )</td>
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<tr>
<th>Table 2. The cutoff frequencies of TM_{n} modes in GHz.</th>
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<td>( n )</td>
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<td>( f_{c} )</td>
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Next, the voltage waveforms of sensing point 1 and 6 are extracted to conduct FFT transformation. From the perspective of EM wave mode, the propagation characteristics of EM wave in each direction and detecting position are analyzed in frequency domain.

5.1 THE SITUATION OF \( \theta = 0^\circ \)

As Figure 11a shows, the amplitude of \( U_y \) is apparently higher than the other two, and peaks appear at each cutoff frequency of TE mode, which confirms the existence of each corresponding TE mode and also the validity of the results. Amplitude of \( U_x \) basically maintains in the range close to that of \( U_z \), and also has peaks at each cutoff frequency of TE mode. This spectrum’s characteristics are determined by the field distribution in the cross section [16, 17]. With regard to \( U_z \), peaks merely appear at the cutoff frequency of TM mode. As mentioned before, among the three kinds of mode included in the PD signal, only the TM mode contains the axial electric
field component. So when the probe is placed along the longitudinal axis, the coupled signal comprises just the TM mode without TEM and TE mode. In other words, this kind of placement is an approach to solely extract the TM mode. It may also be seen that after the peak appears at the cutoff frequency of TM11, several more peaks emerge in the following, as the broken line in blue shows. This is due to the generation of other TM mode, such as TM12, TM13, etc, whose cutoff frequencies are not listed here. The similar phenomenon happens for TM21 and TM31 with the same principle. From this fact, it is inferred that the TM mode usually appears in groups. Furthermore, from Figure 11, whenever the TM modes are generated, there will be some fluctuation around the corresponding frequency in the other two spectrum curves. It is obviously caused by the introduction of the transverse electric field component of TM modes.

![Spectrum intensity (dBm) vs Frequency (GHz) for TM modes](image)

**Figure 11.** Frequency spectrums of propagated EM waves in different directions (θ = 0°).

From Figure 11b, when the EM wave propagates to the point 6, the amplitude of U_y decreases greatly. This is because the signal is strongest and the amount of mode components is the largest in the same direction with excitation, in which the velocity dispersion effect is reflected more apparently, too. The mode separation caused by this effect, with the refraction and reflection in the transmission, leads to the disorder of the spectrum in the sensing position away from the source. On the contrary, the amplitude of U_z begins to uplift after 1 GHz. As mentioned before, the electric field at the excitation position is mainly along the radial direction. So the TEM and TE modes are easily excited, while the TM mode that has larger elements of electric field in longitudinal direction is more prone to be generated in location away from the source. When the TM mode could be excited in somewhere more distant, then there will be an increment of new high frequency components after the corresponding cutoff frequencies of TM, which induces the former phenomenon.

5.2 THE SITUATION OF θ = 90°

In Figure 12, the signal frequency spectrum at θ = 90° shows quite different characteristics from that at θ = 0°. The amplitude of U_x that along the radial at point 1 is still the highest, but lower than that of U_y in Figure 11 about 20 dBm. The amplitude of U_z reduces nearly 30 dBm than that in Figure 11 and becomes the lowest one, which makes the spectrum lines of U_z and U_y no longer close but instead, a certain gap appears. And compared to Figure 11, the difference of U_x and U_y shrinks a lot. More specifically, since the TE odd-number-order modes have nodal points of electric field strength, it can be seen that U_x only contains even-number-order modes which are consistent with the results of [15, 16], while the TE odd-number-order modes in U_y display more significantly. In Figure 12b, similarly as before, even-number-order modes of TE are significant in U_y. But besides odd-number-order modes of TE, small peaks of TE21 and TE41 also appear in U_y with the propagation distance increasing.

![Spectrum intensity (dBm) vs Frequency (GHz) for TM modes](image)

**Figure 12.** Frequency spectrums of propagated EM waves in different directions (θ = 90°).
What also can be seen in Figure 12 is that, the low frequency component of $U_z$ at $\theta=90^\circ$ is very small. Furthermore, for the amplitude of $U_z$, there is a very remarkable mutation at the cutoff frequency of TM11, at both points 1 and 6. However, the spectrum line of $U_z$ is still the lowest among the three.

5.3 The Situation of $\theta=180^\circ$

In Figure 13a, $U_x$ and $U_y$ have returned a similar feature in Figure 11. It contains all of the TE modes with the peaks that become more apparent, but the amplitude is decreased. The higher amplitude of $U_z$ doesn’t appear until the frequency reaches the cutoff frequency of TM11, and each TM mode is accompanied by a number of peaks.

When the signal propagates to point 6, as in Figure 13b, the amplitude of $U_z$ reaches the degree only second to $U_y$, and the group of TM modes is relatively obvious, too. The amplitude range of axial signal goes back to that similar range of Figure 11b. This is the maximum intensity of $U_z$ in the frequency domain analysis, which is also consistent with the previous conclusion. Therefore, when the signal of $U_z$ is detected to be strong, it indicates that the PD source is still far away. Besides, similarly to the situation of $\theta=0^\circ$, the spectrum gets to be a little disordered in some distance away from PD source, and some TE modes are no longer clear to be identified easily.

![Figure 13](image)

Especially, combining with the results above, it is found that only the axial signal in Figure 11a contains certain low frequency component which does not exist under any other circumstances. This is because that in the location of sensing point 1 at $\theta=0^\circ$ where the source of outward-spread EM wave is, the strongest reflection occurs and leads to the born of a small amount of axial signals with low frequency.

7 Conclusion

From the viewpoint of propagation and receiving mechanism, the propagation characteristics of UHF signal are studied in both time and frequency domain. The results, based on which a new location method is proposed, can be used as a comparison reference to clarify the propagation mechanism and impact of the special structures. Simultaneously, this research work provides reference value for practical application of the UHF sensor and actual PD detection, and the findings can be summarized as follows.

1) The voltage waveform obtained from the probe coupler well reflects the original field strength’s component in the direction that the probe is placed, and it can be used in the research about propagation characteristics of PD signal. Moreover, the variation of both $Vpp$ and energy curves in the same directions is found to be very consistent, which illustrates that the tendency of $Vpp$ can reflect that of energy in some extent.

2) The closer to the tank wall where the $Vpp$ gets a continuously declining trend it is, the larger the $Vpp$ and energy in the radial position will be, which will benefit the PD detection. But in a certain depth inside the tank, the $Vpp$ disparity between the location of the defect and that of somewhere distant is the most obvious. Considering from the perspective of location for protrusion defect on central conductor, if the sensor which achieves the placement at a certain depth in the tank were invented, the location accuracy would be improved then.

3) Through comparison, the $Vpp$ and energy are both found to be the highest when the probe is along the radial direction regardless of the circumferential angle, while the radial $Vpp$ attenuation in different circumferential positions show unique characteristics of their own. In addition to $90^\circ$ position, the $Vpp$ and energy in axial direction are only second to those in radial direction, the attenuation characteristics of which do not change with the circumferential angle basically. Moreover, the axial signal component of the defect location is more recognizable at $180^\circ$ than the other circumferential positions. According to these, a new circumferential and axial location method is proposed.

4) It is found that TM modes usually appear in groups through the analysis in frequency domain. A method for individual extraction of the TM mode by placing the probe along the axis is proposed. The variation rule of axial voltage signal is also analyzed.

In the future, a further validation and application for the conclusion in this paper would be done. And for GIS with more complex structure, the signal characteristics in different directions and locations would be analyzed.
REFERENCES


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