Effect of disconnector and high-voltage conductor on propagation characteristics of PD-induced UHF signals

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Abstract: UHF (ultra high frequency) method has been widely used in PD (partial discharge) detection for its high sensitivity. The resonance, distortion, and attenuation appearing in the propagation process of UHF signals in GIS (gas insulated switchgear) will influence the real situation of PD detection. Therefore, it is necessary to investigate the effect of GIS components such as disconnectors or high voltage conductors on the propagation characteristics of PD-induced UHF signals in various voltage classes GIS. The factors of PD signals propagation characteristics in axial and radial directions are both analysed to avoid the effect caused by placement of sensor in this paper. First, the simulation models of GIS are built based on FDTD (finite difference time domain) method. Then the propagation characteristics of PD-induced UHF signals are studied in the GIS with different disconnector gap lengths and different high voltage conductor radii. Finally, the reliability of the simulation results is verified by compared with laboratory tests. The disconnector gap and the change of conductor radii can both result in the signals attenuation which rises highest in the direction of 180°. The lower the GIS class voltage is, the larger the attenuation of signals after passing through disconnector gap is.

1 Introduction

Ultra-high-frequency (UHF) method is a partial discharge (PD) detection method by using sensor to receive UHF electromagnetic (EM) wave excited by PD. The detection frequency is usually between 300 MHz and 3 GHz, which can effectively avoid the influence of the external line corona, radio, and other EM interference. Therefore, the UHF method has high detection sensitivity. In addition, this method can be used to locate the PD source and identify the types of insulation defects. It has been widely used in PD detection in GIS [1–4].

Although the chamber of GIS can be regarded as a coaxial structure composed with a high-voltage conductor and a grounded enclosure, there are still multiple reflections and refractions in the propagation process of PD-induced UHF signals. Owing to the existence of the components with complex structure in GIS, such as L-section and T-branch-part, insulator, circuit breaker, and disconnector, the distribution of EM field will be complicate. Meanwhile, the propagation characteristics of UHF signals in GIS will be effected by these components in GIS. At present, the propagation characteristics of UHF signals have been analysed by experimental measurements or simulation in many researches [5–11], which have considered the influence of insulator types [12, 13], different gap lengths of disconnectors [14], L-section, T-branch-part [15–18], and so on. Most of the studies concentrate on one voltage level, and are mainly about the axial direction quantities of PD-induced UHF signals. However, due to the different radius of the conductor, the cut-off frequency of EM wave mode component will be different in GIS under various voltage classes. Moreover, the propagation characteristics of the UHF signals are also different. It is also necessary to study the propagation characteristics of UHF signals in different radial directions due to the various positions of sensor. The changes of high-voltage conductor radii which are rarely considered before also have significant effect on propagation characteristics.

The simulation models of GIS under different voltage classes are established based on FDTD method in this paper. The influences of disconnector gap and high-voltage conductors on propagation characteristics of PD-induced UHF signals in different axial positions and circumferential angles under various voltage classes have been investigated. The propagation characteristics of PD-induced UHF signals in a 220 kV GIS are studied by experiment at the disconnector switch closed and open situation. The simulation results are compared with the experimental results to prove the reliability of the simulation.

2 Propagation of EM wave in GIS

The structure of GIS can be regarded as a high-voltage conductor with a grounded enclosure, which can be approximated as coaxial waveguide. A circular waveguide is formed when the gap of disconnector switch exists in the high-voltage conductor. The propagation of EM wave in coaxial waveguide and circular waveguide is theoretically analysed in this section.

PD in GIS can excite transverse electric and magnetic (TEM) wave, transverse electric (TE) wave, and transverse magnetic (TM) wave. TEM waves, TE waves, and TM waves can all propagate in coaxial waveguide. The potential function of TEM wave satisfies the Laplace equation of two-dimensional static field in cylindrical coordinate system:

\[
\nabla^2 \psi = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \phi^2} = 0
\]

In the formula, \( r, \phi, \) and \( z \) represent the three variables of the cylindrical coordinate system. The propagation speed of TEM wave has no relationship with frequency. TEM wave at any wavelength can propagate in coaxial waveguide.

In cylindrical coordinate system, the potential function of TE wave satisfies the following equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \phi^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 \psi = 0
\]

where \( k \) represents the propagation constant of EM waves in an infinite space. The expression of the TE wave mode component cut-off frequency is shown in Table 1. Where \( a \) and \( b \) represent the radius of the inner and outer conductor, respectively.
Table 1  Cut-off frequency of TE wave mode component in coaxial waveguide (MHz)

| m   | 1     | 2     | 3     |
|-----|-------|-------|-------|
|      | \(\pi(a+b)\) | \(\pi(a+b)\) | \(\pi(a+b)\) |
| cut-off frequency | 308.36 | 583.11 | 824.68 |

| m   | 4     | 5     | 6     |
|-----|-------|-------|-------|
| cut-off frequency | \(\pi(a+b)\) | \(\pi(a+b)\) | \(\pi(a+b)\) |
| \(\pi(a+b)\) | 1049.62 | 1267.71 | 1482.53 |

Table 2  Cut-off frequency of TM wave mode component in coaxial waveguide (MHz)

| m   | 0     | 1     | 2     |
|-----|-------|-------|-------|
| cut-off frequency | \(b-a\) | \(b-a\) | \(b-a\) |
| \(b-a\) | 147.69 | 156.68 | 180.41 |

| m   | 3     | 4     | 5     |
|-----|-------|-------|-------|
| cut-off frequency | \(b-a\) | \(b-a\) | \(b-a\) |
| \(b-a\) | 212.71 | 248.85 | 286.27 |

Table 3  Cut-off frequency of TE wave mode component in circular waveguide (MHz)

| m   | 0     | 1     | 2     |
|-----|-------|-------|-------|
| cut-off frequency | \(\pi(a+b)\) | \(\pi(a+b)\) | \(\pi(a+b)\) |
| \(\pi(a+b)\) | 1148.80 | 551.92 | 915.57 |

Table 4  Cut-off frequency of TM wave mode component in circular waveguide (MHz)

| m   | 0     | 1     | 2     |
|-----|-------|-------|-------|
| cut-off frequency | \(\pi(a+b)\) | \(\pi(a+b)\) | \(\pi(a+b)\) |
| \(\pi(a+b)\) | 721.00 | 1148.80 | 1539.73 |

The solving process of TM wave in coaxial waveguide is similar to that of TE wave. The expression of the TM wave mode component cut-off frequency is shown in Table 2.

Since only one conductor exists in circular waveguide, which cannot form a two-dimensional steady-state field, TEM wave cannot propagate in circular waveguide. TE and TM wave in circular waveguide both satisfy (2). Different from coaxial waveguide, a typical defect in GIS. A 30 mm long metal protrusion was used as the discharge model on the surface of the vertical high-voltage conductor at the range of 100 mm from the model port in this paper. A Gaussian current pulse with an amplitude of 1 A and a load of 50 Ω was applied to the defect. The pulse can radiate high-frequency EM signal which was attenuated to −80 dB at 3 GHz. The time domain waveform and spectrum are shown in Fig. 2.

3 Influence of disconnector on propagation of PD signals in different radial directions

3.1 Simulation model

To study the influence of the disconnector on PD-induced UHF signals in GIS under different voltage classes, the 110, 220, and 500 kV GIS are simulated, respectively. The simulation model of GIS is shown in Fig. 1. The high-voltage conductor radii are set as, respectively equal to 100, 170, and 300 mm. The effects of the gap lengths of disconnector in 110 and 220 kV GIS are both equal to 150 mm, and that in 500 kV GIS is set as 300 mm. The non-reflecting and absorbing boundary perfectly matched layers are set at both ends of the GIS cavity. The detection points are set every 100 mm and marked as a label of 1–17, respectively, along the conductor axis. The distribution of UHF signals on the circumference is related to the angle, so the detection points close to the enclosure of GIS are set in three radial directions. The angles of the detection points and PD source are equal to 0, 90, and 180°, respectively. The load impedance of the detection points in the simulation model is 50 Ω to match the output cables.

The metal protrusion on high-voltage conductor is a typical defect in GIS. A 30 mm long metal protrusion was used as the discharge model on the surface of the vertical high-voltage conductor at the range of 100 mm from the model port in this paper. A Gaussian current pulse with an amplitude of 1 A and a load of 50 Ω was applied to the defect. The pulse can radiate high-frequency EM signal which was attenuated to −80 dB at 3 GHz. The time domain waveform and spectrum are shown in Fig. 2.

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3.2 Influence of disconnector switch open and closed type in 110 kV GIS

The signals in three directions are normalised with that in the direction of 0°, as is shown in Fig. 3. At disconnector switch open type, peak-to-peak value, and the energy accumulated in 200 ns of UHF signals attenuate significantly in the directions of 0, 90, and 180° after signals passing through the disconnector. In front of the gap, the EM wave energy is enhanced due to the reflection caused by the change of waveguide characteristic impedance at the gap.

The attenuation degree of average peak-to-peak value and energy behind the gap at disconnector switch open and closed type in 110 kV GIS is shown in Table 5. The peak-to-peak value reduces ∼30% at disconnector switch open type compared with that at closed type. Furthermore, the energy reduces ∼60%, and that in the direction of 90° reduces most.

The spectrum of different directions UHF signals at disconnector switch open type in 110 kV GIS is shown in Fig. 4. Since there is no high-voltage conductor at the gap of disconnector, EM wave will propagate in circular waveguide instead of coaxial waveguide. TEM wave of UHF signals cannot propagate in circular waveguide, so peak-to-peak value and the energy of UHF signals attenuate obviously. The signals in directions of 0 and 180° contain each mode component of TEM1 wave, so TEM wave is mainly concentrated <698 MHz which is the cut-off frequency of...
TE11 wave. While the UHF signal in the direction of 90° does not contain TE11 and TE31 mode components, TEM wave in this direction is mainly concentrated below 1.3 GHz which is the cut-off frequency of TE21 wave. That is to say, the TEM wave in this direction has a larger proportion in UHF signals. Therefore, UHF signals in the direction of 90° attenuate the most.

3.3 Influence of disconnector switch open and closed type in 220 kV GIS

The propagation characteristics of PD signals at disconnector switch open and closed type in 220 kV GIS are shown in Fig. 5. The peak-to-peak value and the energy of UHF signals attenuate at disconnector switch open type. Nevertheless, the attenuation of 0 and 90° directions in the 220 kV GIS is not as obvious as that in 110 kV GIS. The energy of signals is slightly increased in front of the disconnector gap.

The attenuation degree of average peak-to-peak value and energy behind the gap at disconnector switch open type in 220 kV GIS is shown in Table 6. The peak-to-peak value and energy of UHF signals in directions of 180° reduces 20% at disconnector switch open type compared with that at closed type, when the value declines 10% in the direction of 0 and 90°. The energy of UHF signals reduces 30% in directions of 180°, and that reduce around 20% in the other two directions. The attenuation of signals in the direction of 90° is the lowest, and that in the direction of 180° is the highest. The attenuation of the three directions in 220 kV GIS is not as obvious as that in 110 kV GIS.

The spectrum of UHF signals in different directions at disconnector switch open type in the 220 kV GIS is shown in Fig. 6. The cut-off frequency of TE11 wave which is equal to 440 MHz in the 220 kV GIS is lower than that in the 110 kV GIS. Therefore, the smaller TEM wave proportion in UHF signals leads to the lower signals attenuation in the 220 kV GIS. The signals between the cut-off frequency of TE11 wave and that of TE21 wave in the 220 kV GIS contain not only TE11 wave, but also partial TEM wave in 0 and 180° directions. In addition, the contents of TEM wave of these two directions are strengthened since the EM wave become more prone to reflect in the 220 kV GIS of which the cavity is larger compared to that of the 110 kV GIS. Besides, the TEM wave contents in the direction of 180° are greater than those in 0° direction. Therefore, at disconnector switch open type, the attenuation of signals in 180° direction is the highest, followed by 0° direction, and the attenuation of signals in 90° direction is the lowest, which is different from that of 110 kV.

3.4 Influence of disconnector switch open and closed type in 550 kV GIS

The propagation characteristics of PD signals at disconnector switch open and closed type in 550 kV GIS are shown in Fig. 7. The peak-to-peak value and the energy accumulated in 200 ns after signals passing through the disconnector gap, and that attenuate most significantly in 180° direction.

Table 6 Attenuation degree of UHF signals at disconnector switch open and closed type in 220 kV GIS

|                | 0°  |         | 90° |         | 180° |         |
|----------------|-----|---------|-----|---------|------|---------|
| peak-to-peak   | %   | %       | %   | %       | %    | %       |
| value          | 73  | 64      | 61  | 54      | 80   | 60      |
| energy         | 97  | 74      | 88  | 68      | 99   | 67      |

Fig. 5 Propagation characteristics of PD signals at disconnector switch open and closed type in 220 kV GIS

(a) Peak-to-peak value, (b) The energy accumulated in 200 ns

Fig. 6 Spectrum of UHF signals in different radial directions at disconnector switch open type

(a) 0°, (b) 90°, (c) 180°

Fig. 7 Propagation characteristics of PD signals at disconnector switch open and closed type in 550 kV GIS

(a) Peak-to-peak value, (b) The energy accumulated in 200 ns
4.2 Influence of conductor diameter increasing on the propagation of UHF signals

When the PD source is located on the thinner side of the conductor, high-voltage conductor diameter will increase in the propagation process of PD signals. In this section, the variation of PD signal propagation characteristics is analysed when the high-voltage conductor radius changes from 54 to 70 mm and from 54 to 80 mm in the 220 kV GIS.

4.2.1 Peak-to-peak value: The influence of conductor diameter increasing on peak-to-peak value in three radial directions is shown in Fig. 11. In the direction of 0° and 90°, the influence of conductor diameter increasing on peak-to-peak value is not obvious. The peak-to-peak value decreases slightly with conductor diameter increasing in the direction of 180°. The more the conductor diameter increases, the larger peak-to-peak value attenuation is.

4.2.2 Energy accumulated in 200 ns: The influence of conductor diameter increasing on energy accumulated in 200 ns is shown in Fig. 12. The larger the diameter of the conductor is, the larger attenuation of the UHF signals is behind the conductor radius change position. The energy attenuation in the direction of 180° is the highest.

4.3 Influence of conductor diameter decreasing on the propagation of UHF signals

In this section, the variation of PD signal propagation characteristics is analysed when the PD source is located on the thicker side of the conductor in the 220 kV GIS.

4.3.1 Peak-to-peak value: The influence of conductor diameter decreasing on peak-to-peak value in three radial directions is shown in Fig. 13. Before the conductor radius change position, the peak-to-peak value of UHF signal has no obvious variety, and that behind the conductor radius change position attenuates in all radial directions.

### Table 7  Attenuation degree of UHF signals at disconnector switch open and closed type in 550 kV GIS

|                  | Closed, % | Open, % | Closed, % | Open, % | Closed, % | Open, % |
|------------------|-----------|---------|-----------|---------|-----------|---------|
| peak-to-peak value |           |         |           |         |           |         |
| energy           | 40        | 35      | 82        | 71      | 128       | 73      |
|                  | 70        | 50      | 94        | 86      | 160       | 82      |

Fig. 8 Spectrum of UHF signals in different radial directions at disconnector switch open type (a) 0°, (b) 90°, (c) 180°

Fig. 9 Comparison of peak-to-peak value at disconnector switch open type in different voltage classes GIS (a) 0°, (b) 90°, (c) 180°

because that the cut-off frequency of TE11 wave in the 550 kV GIS is lower than that in the 220 kV GIS. Therefore, the proportion of TEM wave in the 500 kV GIS is smaller than that in the 220 kV GIS. As a result, the attenuation of signals is also smaller after passing through the disconnector gap, as is shown in Figs. 5a and b. However, the signals attenuation of 180° direction in the 550 kV GIS is greater than that in the 220 kV GIS. This is because the reflection in GIS cavity makes signals of the 550 kV GIS stronger than that of the 220 kV GIS in 180° direction at disconnector switch closed type. However, due to the existence of the disconnector gap at switch open type, the changes of signals propagation and EM wave boundary conditions weaken the reflection, so that the attenuation in 180° direction is large.

3.5 Comparison of propagation characteristics at disconnector switch open type in different voltage classes GIS

Referring to the peak-to-peak value at disconnector switch closed type, the peak-to-peak value of UHF signals at disconnector switch open type in different voltage classes GIS is normalised. The result is shown in Fig. 9. The cut-off frequency of TE11 wave in the 110 kV GIS is higher than that in the 220 kV GIS. In other words, the proportion of TEM wave contents in the 110 kV GIS is larger. Therefore, the signals attenuation in the 220 kV GIS is smaller than that in the 110 kV GIS at disconnector switch open type. The higher voltage class of GIS is, the smaller attenuation of peak-to-peak value in 0 and 90° directions is. In 180° direction, the attenuation of peak-to-peak value in the 220 kV GIS is smaller than that in the 110 kV GIS, but the degree of the 500 kV GIS is the largest.

4 Influence of different high-voltage conductor diameter on PD signals propagation

4.1 Simulation model

In practice, the diameters of high-voltage conductor on both sides of the disconnector are not the same at switch closed type. The high-voltage shields of some components also increase the diameter of high-voltage conductor. The change of high-voltage conductor diameter in GIS leads to the variation of waveguide impedance and the UHF signal propagation. The effect of high-voltage conductor diameter on PD signals propagation characteristics in the 220 kV GIS is investigated in this section. The simulation model is shown in Fig. 10. The setting of PD source and detection points is the same as that of the model shown in Fig. 1.

4.2 Influence of conductor diameter increasing on the propagation of UHF signals

When the PD source is located on the thinner side of the conductor, high-voltage conductor diameter will increase in the propagation process of PD signals. In this section, the variation of PD signal propagation characteristics is analysed when the high-voltage conductor radius changes from 54 to 70 mm and from 54 to 80 mm in the 220 kV GIS.

4.2.1 Peak-to-peak value: The influence of conductor diameter increasing on peak-to-peak value in three radial directions is shown in Fig. 11. In the direction of 0° and 90°, the influence of conductor diameter increasing on peak-to-peak value is not obvious. The peak-to-peak value decreases slightly with conductor diameter increasing in the direction of 180°. The more the conductor diameter increases, the larger peak-to-peak value attenuation is.

4.2.2 Energy accumulated in 200 ns: The influence of the 200 kV GIS conductor diameter increasing on the energy accumulated in 200 ns is shown in Fig. 12. The larger the diameter of the conductor is, the larger attenuation of the UHF signals is behind the diameter change position, and the more the energy increases before the diameter change position. The energy attenuation in the direction of 180° is the highest.

4.3 Influence of conductor diameter decreasing on the propagation of UHF signals

In this section, the variation of PD signal propagation characteristics is analysed when the PD source is located on the thicker side of the conductor in the 220 kV GIS.

4.3.1 Peak-to-peak value: The influence of conductor diameter decreasing on peak-to-peak value in three radial directions is shown in Fig. 13. Before the conductor radius change position, the peak-to-peak value of UHF signal has no obvious variety, and that behind the conductor radius change position attenuates in all radial directions.

Fig. 10 Simulation model at disconnector switch closed type

Fig. 11 Influence of 200 kV GIS conductor diameter increasing on peak-to-peak value (a) 0°, (b) 90°, (c) 180°

Table 7  Attenuation degree of UHF signals at disconnector switch open and closed type in 550 kV GIS
4.3.2 Energy accumulated in 200 ns: The influence of the 200 kV GIS conductor diameter decreasing on the energy accumulated in 200 ns is shown in Fig. 14. The effect of conductor diameter decreasing is similar with that of conductor diameter increasing. In front of the diameter change position, the energy of signals rises up with the conductor thickness increasing. Behind the change position, the energy attenuation raises with the diameter increasing.

5 Experimental verification

In order to verify the reliability of simulation, the experiments about the effect of disconnector in the 220 kV GIS have been performed. The results of experiments which are analysed in time domain and frequency domain are compared with those of simulation to strengthen the credibility of the conclusions based on the FDTD method.

5.1 Experimental set-up

Fig. 15 illustrates a configuration of the experimental set-up. A 220 kV GIS filled with SF6 gas at 0.25 MPa performs as the test apparatus in this paper. Five basin type insulators with thickness of 40 mm are mounted in the GIS. The spacing between each two insulators is ~600 mm. The length of the GIS chamber is equal to 3590 mm. The radius of the high-voltage conductor is 54 mm. The inner diameter of the GIS chamber is 170 mm. A floating electrode is set as the PD source at T-branch part which is on the top right of the GIS. The distance between the PD source and the high-voltage conductor is 30 mm. The disconnector gap distance is equal to 100 mm. Sensors are installed outside insulators, as is shown in Fig. 15.

5.2 Experimental result

The waveform in time domain and spectrogram of the UHF signals at disconnector switch open and closed type is shown in Fig. 16. It can be seen that in the 220 kV GIS, the PD-induced UHF signals generated by the floating electrode have obvious attenuation at disconnector switch open type. The TEM wave below the cut-off frequency of the TE11 wave is greatly attenuated, while the TE wave components of high-frequency have no obvious attenuation. The measured signals contain many low-frequency noise signals due to the EM interference in the surrounding environment.

5.3 Simulation result

In order to verify the credibility of simulation, a model of the 220 kV GIS tested in experiment is built and analysed by using the FDTD method. The simulation results of waveform in time domain and the spectrogram of the UHF signals at disconnector switch open and closed type are shown in Fig. 17. The TEM wave concentrated below the cut-off frequency of the TE11 wave is attenuated obviously at disconnector switch open type, while the high-frequency components of the EM have no significant change. It is found that the simulation results are similar to the experimental results. The simulation in this paper can simulate the propagation of PD signals in practice, and draws a conclusion which can match up the actual situation.

6 Conclusion

In this paper, the propagation characteristics of the PD-induced UHF signals are studied. The influences of disconnector and high-voltage conductor on the propagation characteristics of the UHF

Fig. 12 Influence of 200 kV GIS conductor diameter increasing on the energy
(a) 0°, (b) 90°, (c) 180°

Fig. 13 Influence of 200 kV GIS conductor diameter decreasing on peak-to-peak value
(a) 0°, (b) 90°, (c) 180°

Fig. 14 Influence of 200 kV GIS conductor diameter decreasing on the energy
(a) 0°, (b) 90°, (c) 180°

directions. The attenuation in 180° direction is the most significant.

The PD signals are recorded by oscilloscope (Tektronix, TDS7104, 1 GHz, 5 GS/s) and a spectrum analyzer.
signal in different radial directions are analysed by simulation. The conclusions are as follows:

i. The TEM wave cannot propagate in the gap, resulting in the attenuation of the UHF signals in the propagation process. The signals passing through the gap of disconnectors are concentrated above the cut-off frequency of the TE11 wave at switch open type. The phenomenon exists in the 110, 220, and 500 kV GIS. The lower the voltage class is, the higher the attenuation of signals is.

ii. The energy will attenuate behind the conductor radius change position, and will enhance before the conductor radius change position when the diameter of the conductor changes. The attenuation of 180° direction is the most significant compared to that of other radial directions.

iii. For the same model, TEM wave below the cut-off frequency of TE11 attenuates after signals passing through the disconnectors gap, while high-frequency signals reduce slightly. The simulation and experiment can draw similar conclusions, which proves the reliability of the simulation.

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192

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