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Simulation study of attenuation of ultrahigh frequency electromagnetic wave by salver-shaped insulator in GIS

***Abstract:** We perform a simulation study of attenuation characteristics of ultrahigh frequency (UHF) electromagnetic wave excited by GIS partial discharge in salver-shaped insulator using finite-difference time-domain (FDTD) algorithm. First, the attenuation of UHF electromagnetic wave's electric field signals which is caused by salver-shaped insulator is analysed. It is found that the insulator attenuates electric field strength of UHF electromagnetic wave propagating inside GIS cavity much less significantly as compared with that of UHF electromagnetic wave leaked to outside GIS cavity. Finally, we study the amplitude-frequency characteristics of the gain of electric field signals of UHF electromagnetic wave which is attenuated by the insulator. It is found that UHF electromagnetic wave inside GIS cavity attenuated by the insulator has the frequency above 1000MHz; UHF electromagnetic wave which is leaked to the outside of GIS cavity and attenuated by the insulator has the frequency below 1500MHz and above 3000MHz.*

***Streszczenie**: W artykule przedstawiono wyniki badań symulacyjnych charakterystyki tłumienia fali elektromagnetycznej UHF, generowanej przez wyładowanie niezupełne w aparaturze rozdzielczej typu GIS. W analizie posłużono się algorytmem wykorzystującym metodę różnic skończonych w dziedzinie czasu. Przeprowadzono także badania nad charakterystyką amplitudowo-częstotliwościową wzmocnienia składowego pola elektrycznego fali przy tłumiącym działaniu izolatora. (**Badania symulacyjne tłumienia fali elektromagnetycznej ultra-wysokiej częstotliwości przez izolator rurkowy w GIS**),*

Keywords: GIS, salver-shaped insulator, ultrahigh frequency (UHF), FDTD
Słowa kluczowe: GIS, izolator rurkowy, UHF, metoda różnic skończonych w dziedzinie czasu.

Introduction

Despite the extensive application of gas insulated switchgear (GIS), some insulation defects inside GIS are unavoidable, which may cause partial discharge and result in apparatus failure. Moreover, the pulse slope of PD signals inside GIS can reach ns level [1-4]. The strong electromagnetic interference and the closed structure of GIS will make the weak PD signals difficult to detect. The patterns of partial discharge are diversified, which increases the difficulty in accurately detecting and identifying PD signals. UHF method detects UHF signals generated by partial discharge in GIS and acquires relevant information of PD signals. UHF attracts much attention due to its strong resistance to interference, high sensitivity and the ability to locate PD source and identify fault types [5-9].

High-pressure conductor in GIS is supported by several salver-shaped insulators, which are made of organic polymers with good insulation performance, such as PTFE with high permittivity. When electromagnetic wave signals excited by partial discharge in GIS propagate in salver-shaped insulator, refraction and reflection will occur so as to cause attenuation of the signals passing through the insulators[10-11]. To understand electromagnetic wave attenuation caused by insulators will help us in sensor selection and location of PD sources. We use FDTD algorithm in simulation calculation of characteristics of UHF signal attenuation caused by salver-shaped insulators in GIS. Our research focus is placed on the electric field strength attenuation of UHF electromagnetic wave caused by salver-shaped insulator as well as the amplitude-frequency characteristics of electric field signal gain of the electromagnetic wave attenuated by insulator.

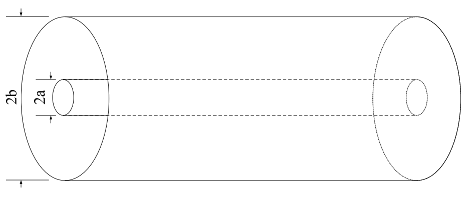


Fig.1.Simplified GIS model

1 Propagation theory of electromagnetic wave in coaxial waveguide

Single-phase GIS can be simplified into a coaxial waveguide with inner diameter of 2a and outer diameter of 2b. Here, a is the radius of the conductor, and b is the inner diameter of GIS cylinder (as shown in Figure 1).

Cylindrical coordinate system is used to describe PD pulse and the excited UHF electromagnetic wave. In order to analyze and calculate the propagation characteristics of electromagnetic wave in coaxial waveguide, the components i_r, i_Φ and i_z of PD pulse current in all directions as well as the components E_r, E_Φ and E_z of excited electric field in all directions should be considered. However, since the high-pressure electric field that generates PD pulse in GIS is radial, PD pulse current tends to develop along the radial direction. In actual applications, UHF sensors are usually installed on GIS shell and the outer wall of coaxial waveguide. E_Φ and E_z tend towards zero to meet the boundary conditions of electric field. For all these reasons, we only study i_r and E_r.

Suppose that PD path is a radial line extending from (r_1, 0, 0) to (r_2, 0, 0) (as shown in Figure 2). At any point in GIS (r, Φ, Z), the electric field strength of each type of electromagnetic wave is given by

(1) $$Er_{TEM} = \frac{Z_0 \ln(r_2/r_1)}{4\pi b \ln(b/a)} I(\omega) e^{-j\omega z/c}$$

(2) $$Er_{TEnm} = \frac{n^2 Z_0}{\pi a J_n(q_{nm})(q_{nm}^2 - n^2)} \times \int_{r1}^{r2} \frac{J_n(q_{nm} r'/a)}{r'} dr' \cos n\phi I(\omega) F_{TEnm}(\omega)$$

(3) $$Er_{TMnm} = \frac{Z_0(2-\delta_0^n)}{2\pi a J_n^{'}(p_{nm}) p_{nm}} \times [J_n(p_{nm} r_2/a) - J_n(p_{nm} r_1/a)] \cos n\phi I(\omega) F_{TMnm}(\omega)$$

Where:

(4) $$F_{TEnm}(\omega) = \frac{-\omega}{\sqrt{\omega^2 - \omega_{nm}^2}} e^{j\frac{z}{c}\sqrt{\omega^2 - \omega_{nm}^2}}$$

(5) $$F_{TMnm}(\omega) = \frac{-\sqrt{\omega^2 - \omega_{nm}^2}}{\omega} e^{j\frac{z}{c}\sqrt{\omega^2 - \omega_{nm}^2}}$$

I(ω) is the expression for frequency domain of PD pulse current; Z_0 is wave impedance of propagation medium; Jn is n-order Bessel function of the first kind; p_{nm} is the m-th root of J_n=0; q_{nm} is the m-th root of J_n'=0,ω_{nm} is the cut-off frequency of higher mode wave,c is the velocity of light.

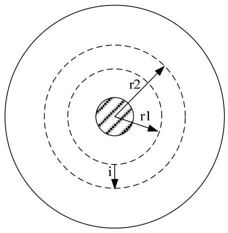
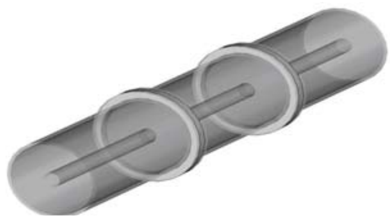


Fig.2.PD path in GIS

2 FDTD algorithm

We implement FDTD algorithm in simulation calculation of characteristics of UHF signal attenuation caused by salver-shaped insulators in GIS. FDTD algorithm solves the problems related to the propagation and reflection of electromagnetic pulse in electromagnetic medium by differentiating Maxwell's equations. The basic procedures are as follows: Yee cells are used to calculate the nodes in computed field; the nodes in electric field and magnetic field are alternately sampled both spatially and temporally. The computed field is divided into total field which contains the scattering body and scattering field which contains only the reflected wave. The two fields are connected by connecting boundary. On the outermost is the special absorbing boundary, and between the two boundaries is the output boundary for conversion between near and far fields. Connecting boundary conditions are adopted for connecting boundary to include the incident wave. Therefore, the incident wave is confined within the total field. Absorbing boundary conditions are adopted at the absorbing boundary to eliminate the non-physical reflected wave on the absorbing boundary[12]. FDTD algorithm adopts absorbing boundary conditions, so that the calculation proceeds within finite space and the program's demand on computer hardware is lowered.

a) Simulation model



b) Waveform of excitation source

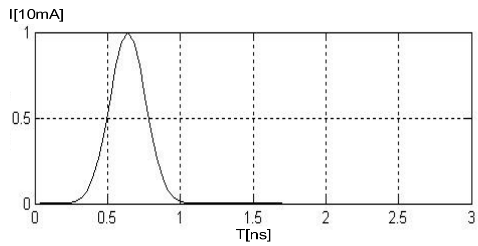


Fig.3.The Simulation model of GIS and the waveform of excitation source

3 Establishment of simulation model

In order to study the propagation characteristics of electromagnetic wave in salver-shaped insulator, we establish the simulation model as shown in Figure 3(a). The model is composed of three segments, with each segment having the length of 1m. The diameter of inner conductor is 10cm, and the shell's inner diameter is 50cm. The middle segment is isolated from the two end segments by a salver-shaped insulator having the thickness of 5cm, inner diameter of 10cm and outer diameter of 54cm. The relative permittivity the salver-shaped insulator is ε=6.

A radial electric discharge pathway is established near GIS shell at one end of GIS model, i.e. at z=0, Φ=0, in order to simulate partial discharge on the shell. The length of the simulated discharge channel is l=10mm. Gaussian pulse with amplitude of 10mA is used to simulate the current. The waveform is shown in Figure 4 (b). An electric field probe is installed at the two sides of the two salver-shaped insulators and on the outer surface of the insulators respectively, i.e. at Φ=0. The position of excitation source as well as the position and No. of probes are shown in Figure 4.

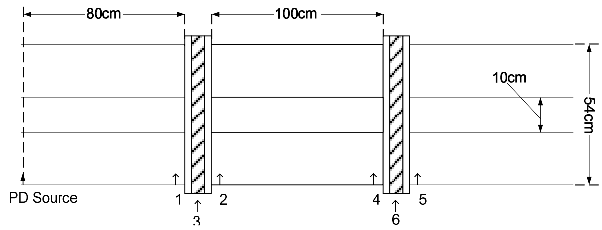
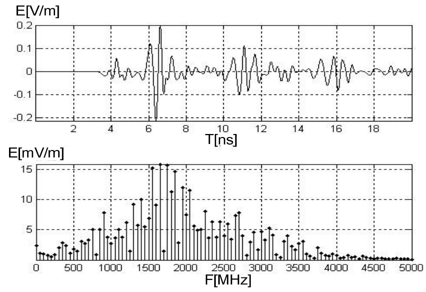


Fig.4.Position of excitation source and probes

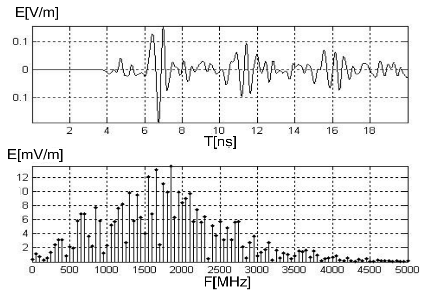
4 Electric field strength attenuation of electromagnetic wave caused by insulators

Electric field signals of electromagnetic wave and the frequency spectra measured at probe 1 and 6 are shown in Figure 5.

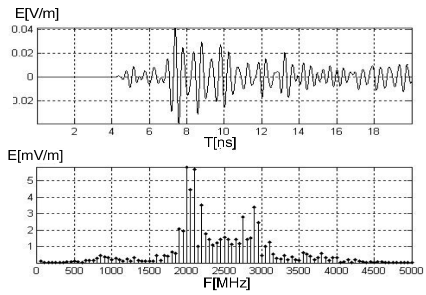
a) Probe 1



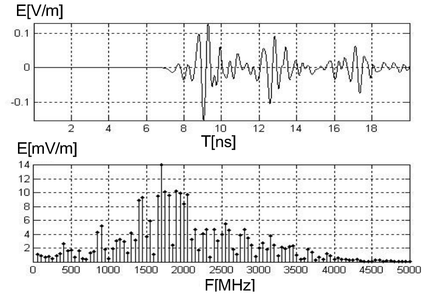
b) Probe 2



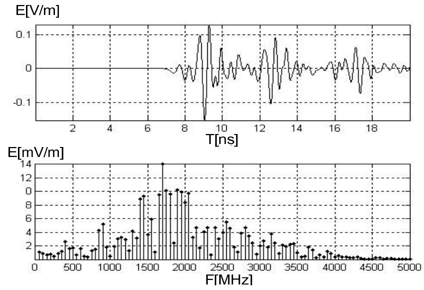
c) Probe 3



d) Probe 4



e) Probe 5



f) Probe 6

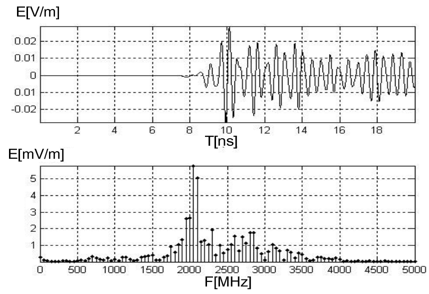


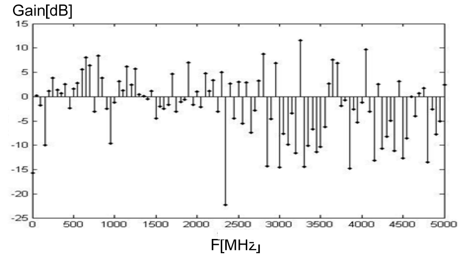
Fig.5.Electric field signals at each probe

The waveform and frequency spectra measured at probe 1, 2, 4 and 5 indicate that UHF signals generated in the middle segment of GIS have the frequency of 300MHz-3000MHz. The frequency of UHF signal measured at probe 3 and 5 is 1500MHz-3000MHz. The peak value of electric field strength measured at probe 1, 2 and 3 is 0.42V/m, 0.35V/m and 0.08V/m. In the simulation model, the electromagnetic wave signals excited by partial discharge pass are attenuated by 1.58dB after passing through the first insulator. The electromagnetic wave signals leaked to outside of the first insulator are attenuated by 14.4dB. The peak value of electric field strength measured at probe 4, 5 and 6 is respectively 0.28V/m, 0.22V/m and 0.06V/m. Thus, the electromagnetic wave signals excited by partial discharge are attenuated by 2.1dB after passing through the second insulator; those leaked to the outside of the second insulator are attenuated by 13.4dB. As we can also see from the figure5, the electromagnetic wave signals inside GIS oscillate periodically, as a result of multiple reflection of electromagnetic wave inside the cavity.

5 Amplitude-frequency characteristics of the electromagnetic field signal gain caused by insulators

Amplitude-frequency characteristics of the electric field signal gain measured by the probes on the front and back of insulators are shown in Figure 6.

a) The gain measured by probe 2 relative to probe 1



b) The gain measured by probe 5 relative to probe 4

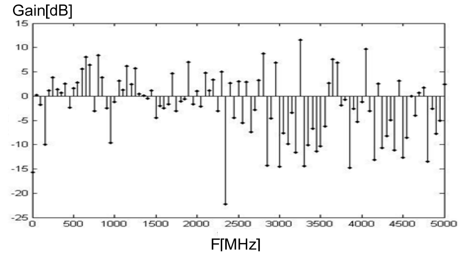
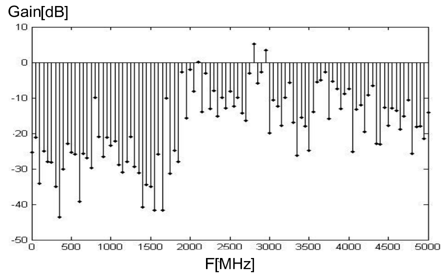


Fig.6.Electric field signal's relative gain measured by the probes on the front and the back of insulators

In GIS cavity, salver-shaped insulators attenuate electromagnetic waves with frequency above 1000MHz. The figure6 shows that, instead of being attenuated, some frequency components are enhanced. This phenomenon occurs as a result of electromagnetic wave's resonance in the cavity enclosed by the two salver-shaped insulators. It is also the reason why electromagnetic wave signals are attenuated more significantly after passing through the second insulator than after passing through the first one.

Amplitude-frequency characteristics of electric field signal gain of the leaked electromagnetic wave are shown in Figure 7.

a) The gain measured at probe 3 relative to probe 1



b) The gain measured at probe 6 relative to probe 4

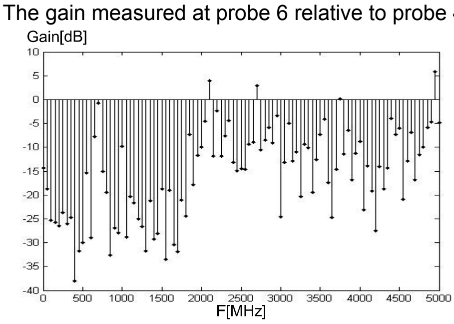


Fig.7.Electric field signal gain of the leaked electromagnetic wave

The attenuated electromagnetic wave signals leaked to the outside of GIS cavity have the frequency below 1500MHz and above 3000MHz. Electromagnetic wave signals with frequency of 1500MHz-3000MHz are less significantly attenuated, which is consistent with the characteristics of frequency spectra of leaked signals.

6 Conclusion

Salver-shaped insulator-caused attenuation of UHF electromagnetic wave excited by partial discharge in GIS has the following characteristics:

(1) The electric field strength of UHF electromagnetic wave propagating inside GIS cavity is much less attenuated by insulators, as compared with that of UHF electromagnetic wave leaked to the outside of GIS cavity;

(2) In GIS cavity, UHF electromagnetic wave signals attenuated by the insulators have the frequency above 1000MHz;

(3) The leaked UHF electromagnetic wave signals which are attenuated by the insulators have the frequency below 1500MHz and above 3000MHz.

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