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Simulation study of the impact of L-shaped and T-shaped branch of GIS on the propagation of ultrahigh frequency electromagnetic wave

***Abstract**. This article simulates the propagation of ultrahigh frequency (UHF) electromagnetic wave excited by partial discharge in L-shaped and T-shaped branch of GIS using finite-difference time-domain (FDTD) algorithm. We examine the effect of L-shaped and T-shaped branch of GIS on time domain waveform and frequency components of UHF electromagnetic wave. It is found that L-shaped branch of GIS significantly attenuates the electric field strength of UHF electromagnetic wave propagating in GIS cavity. Electromagnetic waves attenuated by L-shaped branch mainly have the frequency of 300MHz-2000MHz or above 3000MHz. Electric field strength of some frequency components is enhanced. When propagating in T-shaped branch, the frequency components of electromagnetic wave are more significantly attenuated along the bending path than along the straight path.*

Streszczenie.** W artykule opisano wyniki symulacji propagacji fali elektromagnetycznej o ultra-wysokiej częstotliwości, wywołanej wyładowaniem niezupełnym w gałęzi typu L i T aparatury rozdzielczej GIS, z wykorzystaniem algorytmu różnic skończonych w dziedzinie czasu (FDTD). Stwierdzono, że gałąź L znacząco osłabia siłę wnikania pola elektrycznego fali elektromagnetycznej UHF w GIS. W gałęzi T, częstotliwości składowe są bardziej tłumione w zagięciach charakterystyki niż na odcinkach prostych. **(Badania symulacyjne wpływu gałęzi typu L i T w aparaturze GIS na propagację fali elektromagnetycznej o ultra-wysokiej częstotliwości).

Keywords: GIS; ultrahigh frequency (UHF), electromagnetic wave; FDTD
Słowa kluczowe: GIS, UHF, fala elektromagnetyczna, FDTD.

Introduction

Gas insulated switchgear (GIS), since its emergence more than 20 years ago, has been widely applied in the power system due to its advantages of small room occupation, high reliability, good security, short installation cycle and long overhaul period throughout the world. Years of experience of GIS operation indicate that, despite the higher operation reliability of GIS, it still has some defects related to the manufacture and assembly of GIS, including free metal particles, needle-like protrusions, needle-shaped protrusions, fixed particles, insulation void, etc.. The existence of these small defects can result in rapid increase of local electric field strength at the time of voltage increase. There is high probability of developing into dangerous electric discharge channels and causing accidents. The research shows that partial discharge (PD) is a sign of GIS insulation breakdown. The detection of partial discharge can help discover insulation defects in GIS as early as possible, so that relevant measures can be taken to prevent accidents.

Partial discharge in GIS in operation is a series of pulse currents with very short rise time. For an individual PD pulse, the rise time can be less than 1ns, and several GHz electromagnetic waves can be excited inside GIS cavity [1-3]. UHF method detects UHF signals generated by partial discharge in GIS and acquires information related to PD signals. UHF method has high resistance to interference, high sensitivity and the ability to locate PD sources and identify fault types. This method has attracted much attention [4-9].

Besides long straight cavity structure, GIS also contains bending angle structure, namely, L-shaped branch and T-shaped branch. The propagation of UHF electromagnetic wave excited by partial discharge will be affected at the angle of bend. Using FDTD algorithm, we perform simulation calculation of UHF electromagnetic wave propagation in L-shaped and T-shaped branch of GIS. The research focus is on the impact of bending angle on time domain waveform and frequency components of electromagnetic wave.

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).

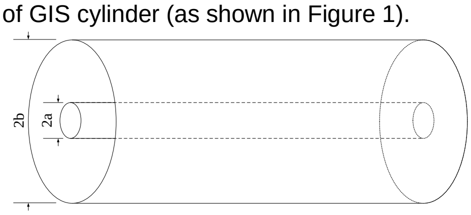


Fig.1. Simplified GIS model

According to microwave theory, there are also other higher mode waves apart from transverse electromagnetic (TEM) wave at sufficiently high frequency. Higher mode wave can be divided into transverse electric wave and transverse magnetic wave, which propagate in the frequency range above the cut-off frequency. The cut-off frequency of each higher mode wave depends on the size and propagation medium of coaxial waveguide. Electromagnetic wave excited by PD pulse in GIS is the synthesis of TEM wave, TE wave and TM wave. These waves contain large quantity of higher mode components. Therefore, TEM wave, TE wave and TM wave should be separately studied.

Cylindrical coordinate system is used to describe PD pulse and the excited UHF electromagnetic wave. Suppose the PD route is a radial line extending from (r_1,0,0) to (r_2,0,0) (as shown in Figure 2). Then, at any point (r,Φ,Z) in GIS, 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 the frequency domain of PD pulse current; Z_0 is wave impedance of propagation medium; J_n 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.

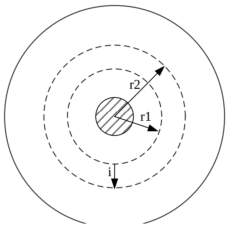


Fig.2. PD path in GIS

2 FDTD algorithm

We perform simulation calculation of attenuation characteristics of UHF signals excited by partial discharge in GIS when propagating in L-shaped branch. FDTD algorithm solves the problems related to the propagation and reflection of electromagnetic wave in medium by differentiating Maxwell's equations. The basic procedures are as follows: Yee cells are used to calculate the nodes in regional space; Maxwell rotation equation is discretized by central difference approximation and calculated by alternate sampling.

Yee cells, which reflect the spatial arrangement of nodes in electric field and magnetic field in FDTD discretization, are shown in Figure 3.

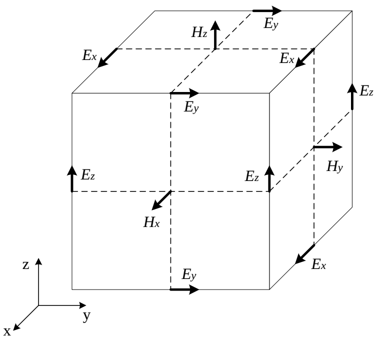


Fig.3. Yee cells in FDTD discretization

We can see that each component of magnetic field is surrounded by four components of electric field. Similarly, each component of electric field is surrounded by four components of magnetic fields. Electric field and magnetic fields are alternately sampled, at an interval of half step length. Thus, Maxwell rotation equation is discretized into explicit differential equation, which can be iteratively solved. Given the initial value of electromagnetic problem, FDTD algorithm can be used to obtain the distribution of electric and magnetic fields in space at each time in a stepwise manner.

Moreover, FDTD algorithm is performed with absorbing boundary conditions. Therefore, the calculation proceeds in finite spatial range[10]. In doing this, we bring down the demand of program on computer hardware.

3 Simulation of propagation of electromagnetic wave in L-shaped branch

3.1 Establishment of simulation model

The simulation model of L-shaped branch is established as shown in Figure 4(a). The model is composed of three segments. The length of segments at the two ends is 1m; the diameter of inner conductor is 10cm, and the shell's inner diameter is 50cm. The middle segment is an L-shaped branch, with two arms extending for 1m respectively. The two arms are respectively isolated by a basin-type insulator having a thickness of 5cm, outer diameter of 54cm and dielectric strength ε=6. An electric field probe is respectively installed at the two arms of L bend, i.e. at Φ=0. The position of excitation source and the position and No. of probes are shown in Figure 4 (b).

a) Simulation model

b) Position of excitation source and probes

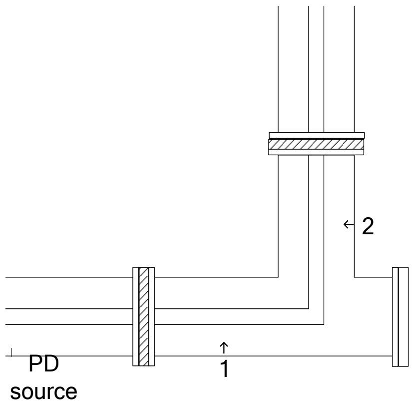


Fig.4. Simulation model of L-shaped branch

The length of simulated discharge channel is l=10mm; Gaussian pulse is used to simulate the current according to the expression below:

(6) $$i(t) = I_0 e^{-(t-t_0)^2/2\sigma^2}$$

t_0=0.6ns, I_0=10mA and σ=0.122; the amplitude is 10mA; the waveform is shown in Figure 5.

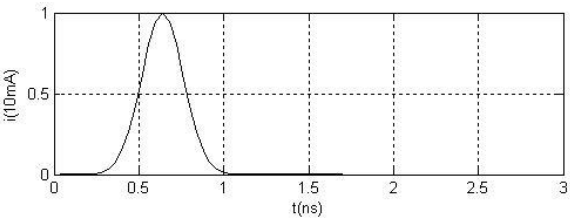


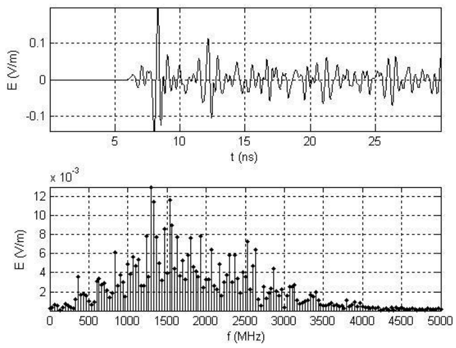
Fig.5. Waveform diagram of excitation source

3.2 Effect of L-shaped branch on electric field strength and frequency components of electromagnetic wave

Figure6 shows electric field waveforms of electromagnetic wave and frequency spectra measured by probe 1 and 2.

From the waveforms and frequency spectra measured at probe 1 and 2 we can see that the frequency of UHF signals is 300MHz-3000MHz. The peak value of electric field strength measured at probe 1 and 2 is respectively 0.34V/m and 0.16V/m. Thus, we can know that UHF signals, after passing through L-shaped branch, are significantly attenuated by about 6.8dB.

a) Probe 1



b) Probe 2

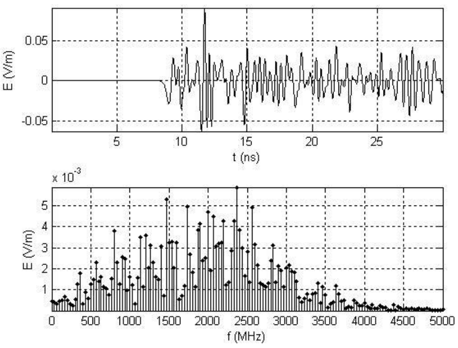


Fig.6. Electric field waveforms of electromagnetic wave and frequency spectra measured by the probes

Amplitude-frequency characteristics of t electric field signal gain before and after electromagnetic wave's passing through L-shaped branch are shown in Figure 7.

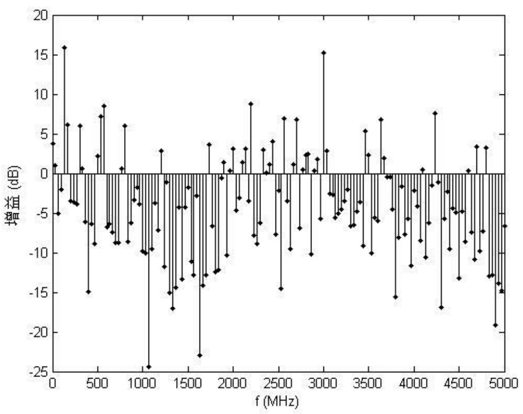


Fig.7. The gain of electric field signals at probe 2 relative to that at probe 2

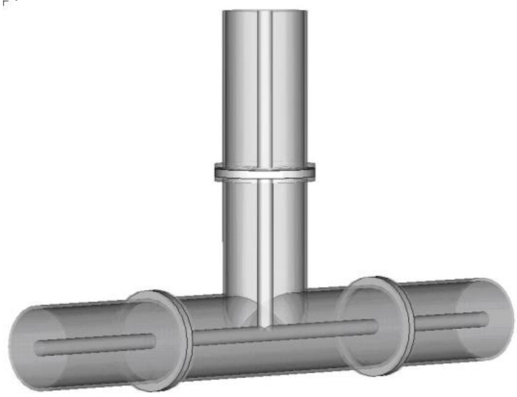
Figure 7 shows that, in GIS cavity, electromagnetic wave propagating in L-shaped branch with frequency of 300MHz-2000MHz and above 3000MHz is attenuated. Components with frequency of 2000MHz-3000MHz are less significantly attenuated. Instead of being attenuated, some components are enhanced, which may be due to the resonance of electromagnetic wave in the cavity.

4 Simulation experiment of propagation of electromagnetic wave in T-shaped branch

4.1 Establishment of simulation model

The simulation model of T-shaped branch is established as shown in Figure 8 (a). The model is composed of four parts. The middle is a T-shaped coaxial structure, with straight arm extending for 2m and vertical arm extending for 1m. A basin-type insulator is installed at the three ends of T-shaped structure, with each end having a coaxial structure extending 1m outwards. Diameter of the inner conductor is 10cm, and the shell's inner diameter is 50cm. The basin-type insulator has thickness of 5cm, outer diameter of 54cm and dielectric strength ε=6. An electric field probe is installed at the front and back of the T-shaped branch on the straight arm and at the vertical arm, respectively, i.e. at Φ=0. The position of excitation source and the position and No. of probes are shown in Fig. 8 (b).

a) Simulation model



b) Position of excitation source and probes

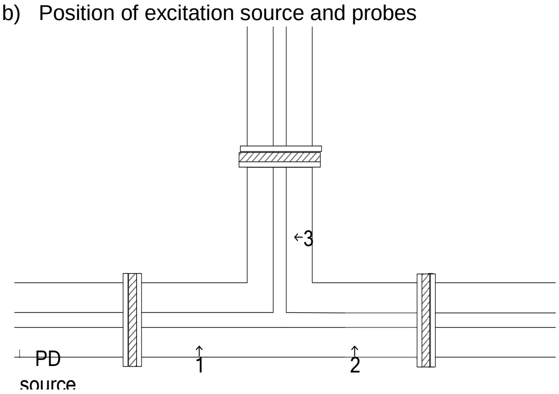


Fig.8. Simulation model of T-shaped branch

The excitation source is located at the same position as in the simulation experiment with L-shaped branch.

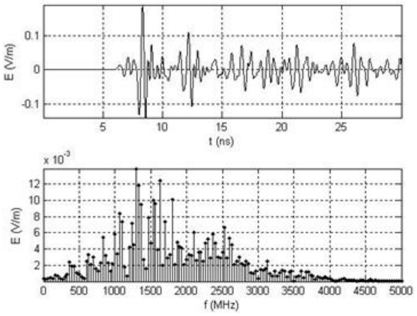
4.2 Effect of T-shaped branch on electric field strength and frequency components of electromagnetic wave

Electric field signals of electromagnetic wave and the frequency spectra measured by probe 1 and 3 are shown in Figure 9.

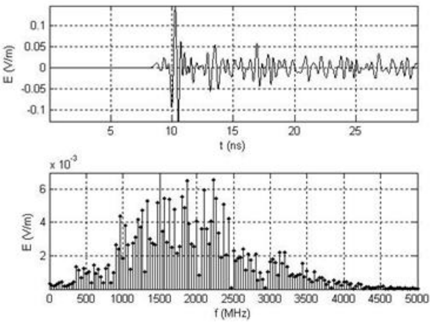
The peak value of electric field strength measured at probe 1, 2 and 3 is respectively 0.33V/m, 0.28V/m and 0.14V/m. When the electromagnetic wave signals excited by partial discharge passes through T-shaped branch, the signals propagating to the other end of the straight arm are attenuated by about 1.4 dB, and those propagating to the vertical arm are attenuated by about 7.4dB. Electromagnetic wave propagating to the vertical arm through T-shaped branch is more significantly attenuated than that propagating to the other end of the straight arm.

From Figure 10, we can see that, in GIS cavity, some frequency components of electromagnetic signals passing through T-shaped branch are enhanced instead of being attenuated. This phenomenon can be explained by the resonance of electromagnetic wave in the cavity enclosed by the three basin-type insulators at the ends of T-shaped branch.

a) Probe 1



b) Probe 2



c) Probe 3

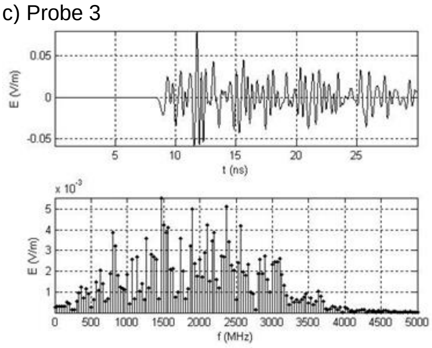
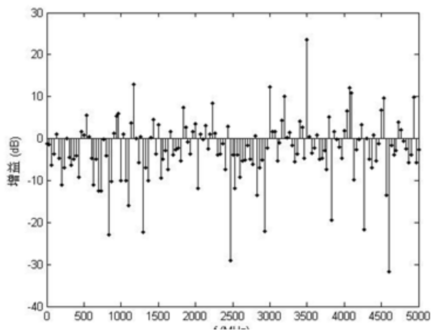


Fig.9. Waveforms and frequency spectra of electric field strength at each probe

a) Probe 2 relative to probe 1



b) Probe 3 relative to probe 1

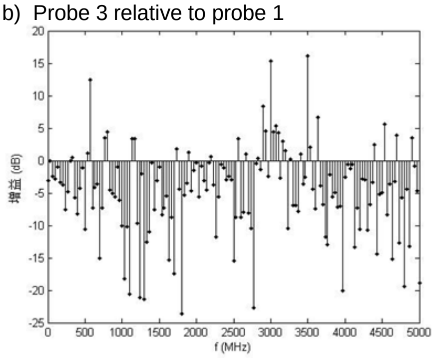


Fig.10. Amplitude-frequency characteristics of the gain of electric field signals measured by the probe at the front and back of T-shaped branch

5 Conclusion

We perform simulation study of the propagation of electromagnetic wave in L-shaped and T-shaped branch of GIS. The changes of electric field waveform and frequency components of electromagnetic wave after passing through two branches are analyzed. The following conclusions are obtained:

(1) When the electromagnetic wave passes through L-shaped and T-shaped branches, the amplitude of electric field strength is attenuated.

(2) In GIS cavity, L-shaped branch attenuates electromagnetic wave with frequency of 300MHz-2000 and above 3000MHz.

(3) Resonance in GIS cavity enhances the electric field strength of some frequency components UHF electromagnetic wave after passing through L-shaped and T-shaped branch;

(4) In T-shaped branch, frequency components are more significantly attenuated along the bending path than along the straight path.

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