Analysis of Electromagnetic Wave Characteristics of PD in Transformer

Wenzhi Chang, Tingyu Gao, Fei Du, Shuai Yuan, and Guangzhen Wang

Abstract Ultra-high frequency (UHF) technology is a partial discharge (PD) test technology based on spatial electromagnetic field coupling. It can detect the partial discharge of equipment by detecting the electromagnetic wave signal radiated by PD. It has strong anti-interference ability and high detection sensitivity. Due to the complex internal structure of the transformer, various metal structures may affect the propagation of radiated electromagnetic waves. Therefore, it was necessary to investigated the propagation law of electromagnetic waves inside the transformer. In this article, a simplified model of transformer's internal structure was established. The Gaussian current source was used to simulate the PD source. Moreover, the finite difference time domain (FDTD) method was used to simulate the propagation characteristics of the ultra-high frequency electromagnetic wave inside the transformer. The results showed that the electromagnetic wave was seriously distorted during the propagation of the iron core, the high and low voltage windings, and the signal amplitude attenuation was serious. Increasing the amplitude of the pulse current, the peak value of the radiation length increased. And it still had the same attenuation law after passing through the obstacle.

Keywords Transformers · PD · UHF · Electromagnetic · FDTD

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1 Introduction

Power transformer was a key component of power system and played a very important role in the safe and stable operation of power grid. As more and more transformers approach their life expectancy, it was very important to detect their insulation state. Partial discharge (PD) was one of the main causes of insulation failure. Therefore, PD detection was a sensitive and effective method to evaluate power transformers.

Ultra-high Frequency (UHF) technology realized the detection of PD by detecting the electromagnetic wave signal. It had strong anti-interference ability and high detection sensitivity. As a PD test technology based on spatial electromagnetic field coupling, it could realize the real PD online detection, and could locate the PD fault source [1–11]. Due to the complex internal structure of the transformer, the electromagnetic wave signal was affected by the core, winding, box body and oil-paper insulation medium during the propagation process, resulting in changes in the amplitude, energy, spectrum and propagation time of the UHF signal. Therefore, it was necessary to investigate the propagation characteristics of electromagnetic waves in transformers.

References [12] and [13] used the Finite Difference Time Domain (FDTD) method to simulate the propagation of UHF signal of PD in Gas Insulated Switchgear (GIS), and obtained relevant conclusions. Due to the internal structure of the transformer was much more complex than the coaxial waveguide structure of GIS, the analysis method was not applicable to the transformers. In [14], the propagation characteristics of UHF signal in transformer were studied by means of actual measurement, and good results were obtained. However, the random influence of interference in actual measurement was relatively large, which had influence on the accuracy of the results.

The propagation loss of UHF electromagnetic wave in the oil-paper composite insulation medium inside the transformer was very small, which could be approximated as lossless propagation [10]. In this article, the actual core winding structure was reasonably simplified, and a computer model conforming to the actual structural characteristics was established and explored the attenuation and distortion of UHF signal by transformer structural components.

2 Propagation Characteristics of Electromagnetic Wave of PD

PD signal could be regarded as an electromagnetic wave signal emitted by power supply. When PD occurred in the insulating medium, the generated current pulse excited electromagnetic radiation, which followed the Maxwell electromagnetic field basic equation. Dynamic vector potential and dynamic scalar potential were introduced to analyze the time-varying electromagnetic field generated by PD. At this time, the basic equations were transformed into dynamic potential equations.

$$\nabla^2 \vec{A} = -\mu \vec{\delta_C} + \nabla\left(\mu\varepsilon \frac{\partial \varphi}{\partial t}\right) + \nabla\left(\nabla \cdot \vec{A}\right) + \mu\varepsilon \frac{\partial^2 \vec{A}}{\partial t^2} \tag{1}$$

$$\nabla^2 \varphi + \nabla \cdot \frac{\partial \vec{A}}{\partial t} = -\frac{\rho}{\varepsilon} \tag{2}$$

where $\vec{A}$ was dynamic vector, Wbm^{-1}; φ was dynamic scalar, V; μ was magnetic permeability of medium, ε was dielectric constant of medium; $\vec{\delta_C}$ was current density, A/m^2; ρ was excitation source, C/m^3. (1) represented the relationship between the dynamic potential and the excitation source ρ and the current density $\vec{\delta_C}$.

3 Principle of FDTD

The FDTD for solving electromagnetic field problems was based on the finite-difference discretization of Maxwell's curl equations in the time and space domains. The central finite-difference scheme with two-order accuracy was used to approximately replace the original differential equation. The parameters of the FDTD method were given by the spatial grid. Only the medium parameters of the corresponding spatial points were given, the complex electromagnetic structure could be simulated.

Mesh generation was the key problem of FDTD. Yee proposed to use a grid structure with half a step difference in space and time domains. The current electric and magnetic field values were obtained by using the magnetic and electric field values of the previous moment through a leap-frog step, and this process was calculated throughout the whole space at each moment, so the solution of the electric and magnetic field values changing with time in the whole space domain could be obtained [8].

When applying this method, it was not necessary to solve the Green's function of the problem. By using pulse source as excitation, combined with Fourier transform, only one calculation was needed to obtain the response of various effective frequencies contained in the pulse. Compared with the frequency domain method, it would save a lot of calculation time. Therefore, the FDTD method was more suitable for the analysis of the PD electromagnetic wave propagation process inside the transformer than other methods.

4 Simulation Model Design

Large power transformer had high voltage level, large capacity and complex structure. In order to meet the needs of computer simulation, its structure must be simplified. The body structure of the double-layer winding of the core outer sleeve with relatively

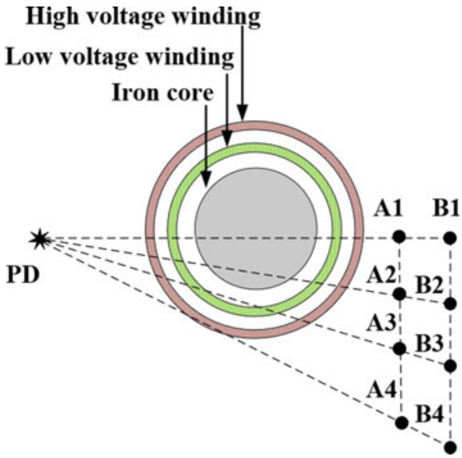
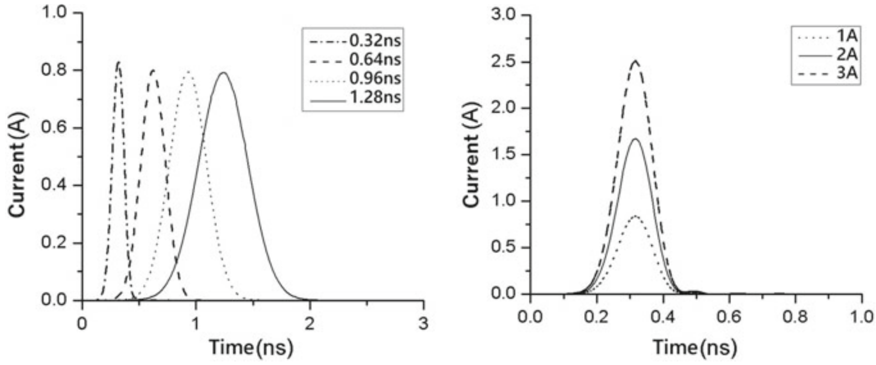


Fig. 1 The model cross-sections and observation points

simple structure was selected as the simulation prototype, and some factors that had no significant effect on the propagation of electromagnetic wave were ignored (such as insulation cardboard and insulation oil, winding and core production process, etc.). The conductive solid cylinder was used to simulate the transformer core, and the concentric double-layer spiral coil structure was used to simulate the low–high voltage winding of the transformer. And the number of low voltage winding turns was small, the pitch was large; the number of turns of the high-voltage winding was large and the pitch was small [9]. The simulation model was shown in Fig. 1.

The simulation parameter: the core was an ideal conductor cylinder of $\Phi 60 * 90$ cm; the inner coil size was Φ 35 * 50 cm, the wire diameter was 2 cm, and the turn spacing was 0.8 cm; the outer spiral coil size was Φ 40 * 50 cm, the wire diameter was 1.2 cm, and the turn spacing was 0.4 cm; line current source was 2 cm long, located outside the winding; gaussian pulse current excitation; subdivision grid: $0.5 \times 0.5 \times 0.5$ cm; time step: 9.629 ps; the highest frequency used in the simulation was 6 GHz.

When PD occurred in the transformer, discharge signals of different frequencies were generated, and the frequency of the ultra-high frequency signal could reach 2 GHz. In the simulation, Gaussian pulse was used to simulate the actual PD signal. The PD source could be simulated by a line current source, and the line current source could be equivalent to a series of element currents. For transient electromagnetic field signals, Gaussian signals could be used to simulate actual PD signals. The time domain signals of Gaussian pulse currents with different pulse widths and amplitudes were shown in Fig. 2.



(a) Gauss current element with different pulse widths.

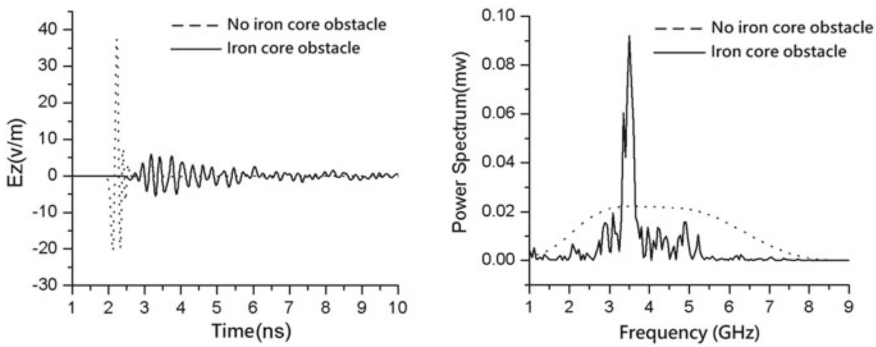
(b) Gauss current element with different amplitudes.

Fig. 2 Time domain waveforms of Gauss pulse function

5 Analysis of Simulation Results

Some electromagnetic waves were reflected on the surface of the core, and some of the reflected waves were diffracted on the surface and propagate to the shadow area. The other part was folded and reflected back and forth between the core and the winding, leading to an increase in the intensity of the radiation field between the core and the winding, and the signal waveform was seriously distorted. Different colors in the image represented different radiation field intensity. The time domain waveform and spectrum of the radiation field at the B_2 observation point were shown in Fig. 3.

A series of refraction, reflection and diffraction phenomena would occur when the electromagnetic wave passed through the core, the high and low voltage winding



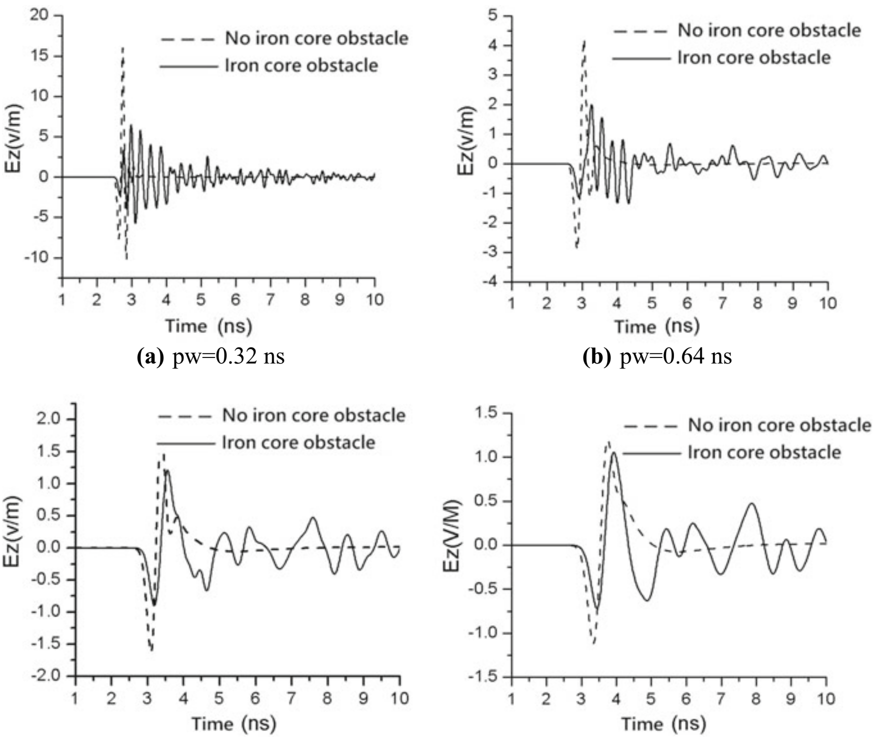
(a) Time domain waveforms

(b) Spectrums

Fig. 3 The effects on time domain waveforms and frequency spectrums by core and windings structure

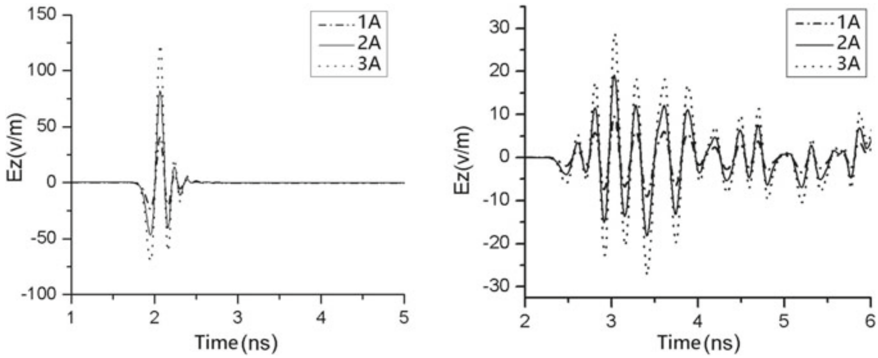
structure. In the process of diffraction, the proportional relationship determined the characteristics of the diffraction. In order to investigate the influence of core and winding structure size on the propagation characteristics, the propagation law of radiated electromagnetic wave signals excited by different pulse width current elements in core and windings structures was compared and analyzed. The Gaussian pulse current element with pulse different width and amplitude of 1 A was taken as the excitation, and the other simulation parameters were the same. The time domain waveforms of the current elements corresponding to the three pulse widths were shown in Fig. 2a. The radiation field waveform at the observation point A_4 was shown in Fig. 4.

It could be clearly seen in Fig. 4 that as the pulse width of the pulse current element increases, the radiated electromagnetic field became weaker and weaker, but the difference in the waveform of the electromagnetic wave radiation field at the same observation point with or without the core winding structure became smaller and smaller. After the electromagnetic wave excited by the 1.28 ns pulse width current source passed through the core winding structure, its waveform was basically



(a) pw=0.32 ns **(b)** pw=0.64 ns **(c)** pw=0.96 ns **(d)** pw=1.28 ns

Fig. 4 The propagation of electromagnetic incited by different pw pulse current element cross core and windings structure (observation point A_4)



(a) Without core and windings structure **(b)** With core and windings structure

Fig. 5 Time domain waveforms of electromagnetic radiation with different amplitudes whether core and windings structure is existences

consistent with the waveform without the core winding structure, and the amplitude decreased very little. It could be seen that with the same amplitude, the larger the pulse width, the smaller the radiation field intensity excited by the current source. As the pulse width increased, the wavelength wave increased, and the diffraction effect on the obstacle was enhanced. After passing through the core and the high and low voltage winding structure, the waveform was closer to the case without the core winding structure.

In order to study the influence of the amplitude on the radiated electromagnetic wave signal, the radiation field was simulated when the amplitude was 1 A, 2 A, and 3 A, respectively. The pulse width of the current source was 0.32 ns. The time domain waveform of the pulse current element was shown in Fig. 2b, and the other simulation parameters were set the same.

Figure 5 showed the signal waveform at the A_1 observation point. It could be seen that the pulse width of the current element was the same, and the amplitude of the current was changed. The amplitude of the radiation field was proportional to the amplitude of the pulse current element, but the propagation characteristics did not change when passing through the obstacle.

6 Conclusion

In this article, the FDTD was used to simulate and analyzed the propagation characteristics of UHF electromagnetic waves inside the transformer. The following conclusions were drawn:

(1) The pulse current generated by PD of transformer could excite UHF electromagnetic wave. The pulse width and amplitude of pulse current had great influence on the radiation characteristics of electromagnetic wave.

(2) A series of phenomena such as reflection, refraction and diffraction of UHF electromagnetic waves occurred in the core, high and low voltage winding structures, resulting in serious distortion of the waveform of electromagnetic waves and serious attenuation of signal amplitude.
(3) When the pulse width of the pulse current element increased, the amplitude of the radiation field decreases, but the diffraction ability of the radiated electromagnetic wave to the obstacle was enhanced, and the waveform after passing through the obstacle was closer to that without the obstacle.
(4) Increasing the amplitude of the pulse current, the peak value of the radiation field increased, but the change rule after passing through the obstacle was the same.

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