Partial Discharge Propagation Analysis using Finite Difference Time Domain Technique

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Abstract

Objectives: To analyze the effect of geometry on Partial Discharge (PD) wave propagation. Methods/Statistical Analysis: A Finite Difference Time Domain (FDTD) method has been implemented for simulation of Partial Discharge wave propagation in prototype transformer like geometry. FDTD method provides a solution for a time as well as space regions. In this technique electric field and magnetic field values are calculated in a leapfrog manner. In this paper, Transverse Magnetic (TM) mode has been considered for two-dimension simulation. Findings: This work is an effort to understand effects of obstacles on partial discharge wave propagation. In this paper signal propagation in circular, octagonal, hexagonal and point shaped obstacles has been analyzed. Simulation work extended with aluminium ceramic, iron and mica material to understand the effect of the material on signal propagation. Application/Improvements: Improvisation is possible in the performance of PD detection setup after analyzing and comparing effects of obstacles shape and material on PD signal wave propagation.

Keywords: FDTD, Partial Discharge, Propagation

1. Introduction

The term “Partial Discharge (PD)” is defined by International Electrotechnical Commission (IEC) 60270 (Partial Discharge Measurements) as a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor1. The transformer is essential elements in power system which represents the largest portion of the capital investment in the power system. Reliable operation of a transformer is a very important parameter for power system2. Decreasing dielectric strength is the main factor for faults in the transformer. Mainly electrical, mechanical and thermal stresses reduce the life of insulating material3. Regular PD monitoring gives an accurate indication of the status of the deterioration process. It is very much necessary to have information of PD level and source location to plan maintenance of transformer.

The occurrence of PD results in discharge current or voltage pulse, electromagnetic impulse radiation, ultrasonic impulse radiation and visible or ultraviolet light emission. Accordingly, there are several detection methods that have been developed to measure those phenomena respectively. Electrical4, chemical5, acoustic6 and UHF7 are four well-known PD detection methods. Electrical and chemical detection techniques are conventional while UHF and acoustic detection are relatively new and advanced techniques. PD events generate high-frequency signals which are detected in
UHF methods. These discharges can be understood as extremely fast, transient, electromagnetic pulses in the gigahertz range. The possibility of online partial discharge monitoring is the main advantage of UHF method\(^8\). Secondly, in the UHF range, noise interference with the signal is lower. Propagation analysis of PD signals is a very important parameter for detection system design. This paper analyzed PD signal propagation path using FDTD techniques.

2. FDTD Techniques

FDTD is commonly used in the area of electromagnetic computation. In this paper, FDTD has been implemented to simulate electric field captured by sensors. The FDTD method was first introduced by Yee in 1966\(^9\). After that FDTD technique was developed by Allen Taflve in 1980. Electromagnetic field problems can easily address by FDTD method. In this method, Maxwell's differential equations are solved in time and space. First electric field \((E)\) value is calculated then the magnetic field \((H)\) value is calculated. Such repeated process of solution of \(E\) and \(H\) at different instant of time is called leapfrog manner. At the end, electric and magnetic field values are approximated in complex geometry in time domain.

2.1 Yee's FDTD Algorithm

In FDTD method, differential equations are replaced by finite difference equations. This method provides a numerical solution for a time as well as space regions. Electric field \((E)\) and magnetic field \((H)\) values are calculated within specified simulation dimension and boundary condition. The values of \(E\) and \(H\) are solved in a leapfrog manner. Yee's scheme is more famous than other available schemes due to its flexibility and robustness\(^10\).

As shown in Figure 1, the model is divided into small same size cubes, which is known as Yee's cell. The model region is divided into two grids of separate points. Magnetic field \((H)\) is calculated at one grid and electric field \((E)\) is calculated at the second grid. The basic element of the FDTD space pattern is shown in Figure 1. From which it is observed that electric field and magnetic field are surrounded by each other. Figure 2 shows Yee's algorithm in the form of the flow diagram.

Maxwell's curl equations for isotropic medium are

\[
\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \\
\n\nabla \times \mathbf{H} = \sigma \mathbf{E} + \frac{1}{\mu} \left( \frac{\partial \mathbf{E}}{\partial t} - \frac{\partial \mathbf{E}}{\partial z} \right) \\
\n\frac{\partial \mathbf{H}}{\partial t} = \frac{1}{\mu} \left( \frac{\partial \mathbf{E}}{\partial x} - \frac{\partial \mathbf{E}}{\partial y} \right)
\]

Figure 1. Yee's cell.

Figure 2. The flow diagram of the Yee's algorithm.
\[
\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right) \\
\frac{\partial E_z}{\partial t} = \frac{1}{\epsilon} \left( \frac{\partial H_y}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_z \right) \\
\frac{\partial E_y}{\partial t} = \frac{1}{\epsilon} \left( \frac{\partial H_z}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right) \\
\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon} \left( \frac{\partial H_z}{\partial x} - \frac{\partial H_z}{\partial y} - \sigma E_x \right)
\]

(2c)

As per Yee's notation, grid point in the solution region is \((i, j, k) = (i\Delta x, j\Delta y, k\Delta z)\) where \(\Delta x, \Delta y\) and \(\Delta z\) are the actual grid separations. Any function of space and time is written as \(F(i\Delta x, j\Delta y, k\Delta z, n\Delta t)\) where \(\Delta t\) is time increment, \(n\) is time index and \(\delta\) is spatial increment. Applying central difference approximation to equations (4a) and (4b) to calculate space and time derivatives.

\[
\frac{\partial F_i^n}{\partial x} = \frac{F_i^{n+1/2} - F_i^{n-1/2}}{\delta} \\
\frac{\partial F_i^n(j, k)}{\partial t} = \frac{F_i^{n+1/2}(j, k) - F_i^{n-1/2}(j, k)}{\Delta t}
\]

(4a)

(4b)

### 2.2 Cell Size

The selection of cell size is important in applying FDTD techniques. After selection of cell size, Courant stability condition is applied to decide maximum time steps. Lower side value of cell size must able to give an accurate result at higher frequencies at the same time cell size value should be large enough to implement on a computer. Materials involved affecting the cell size. As permittivity or conductivity of material increases, wavelength decreases. Small cell size required for shorter wavelength.

### 2.3 FDTD Formulation in Two Dimension

Three electric fields \(E_x, E_y, E_z\) and three magnetic fields \(H_x, H_y, H_z\) are used in three-dimensional simulations. In doing two-dimensional simulations, we choose between Transverse Magnetic (TM) or Transverse Electric (TE) mode. Transverse Magnetic mode composed of \(H_x, H_y\) and \(E_z\) while \(E_x, E_y\) and \(H_z\) form Transverse Electric (TE) mode. In this paper, TM mode has been considered for two-dimension simulation. Figure 3 shows interleaving of the electric field \((E)\) and magnetic field \((H)\) in two dimensions.

As per Yee’s notation, grid point in the solution region is \((i, j, k) = (i\Delta x, j\Delta y, k\Delta z)\) where \(\Delta x, \Delta y\) and \(\Delta z\) are the actual grid separations. Any function of space and time is written as \(F(i\Delta x, j\Delta y, k\Delta z, n\Delta t)\) where \(\Delta t\) is time increment, \(n\) is time index and \(\delta\) is spatial increment. Applying central difference approximation to equations (4a) and (4b) to calculate space and time derivatives.

\[
H_{i}^{n+1/2}(i, j, k) = \frac{1}{\sqrt{\epsilon \mu_0}} \left( \frac{\partial E_i^n(j, k)}{\partial y} - \frac{\partial E_i^n(i, k)}{\partial x} \right)
\]

(5a)

\[
D_{i}^n(\omega) = \varepsilon_i(\omega) \cdot E_i^n(\omega)
\]

(5b)

\[
\frac{\partial H_i^n}{\partial t} = \frac{1}{\sqrt{\epsilon \mu_0}} \frac{\partial E_i^n}{\partial x}
\]

(5c)

\[
\frac{\partial H_i^n}{\partial t} = \frac{1}{\sqrt{\epsilon \mu_0}} \frac{\partial E_i^n}{\partial y}
\]

(5d)

\[
H_{i}^{n+1/2}(i, j, k) = H_{i}^{n+1/2}(i, j, k) - 0.5 \left[ E_{i}^{n+1/2}(i, j, k) - E_{i}^{n-1/2}(i, j, k) \right]
\]

(6a)

\[
H_{i}^{n+1/2}(i, j, k) = H_{i}^{n+1/2}(i, j, k) + 0.5 \left[ E_{i}^{n+1/2}(i, j, k) - E_{i}^{n-1/2}(i, j, k) \right]
\]

(6b)

\[
D_{i}^n(\omega) = D_{i}^n(\omega) + 0.5 \left[ E_{i}^{n+1/2}(i, j, k) - E_{i}^{n-1/2}(i, j, k) \right]
\]

(6c)

Electric and magnetic field values are updated from Equation (6) and implemented in MATLAB for signal propagation analysis.

### 3. PD Propagation in Two Dimension using FDTD Technique

Equations (6) are implemented in MATLAB programming to obtain electric field \((E)\) and magnetic field \((H)\). Initial conditions used for simulation are given below.
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- Problem space dimension: 60 × 60 cells,
- Source: Gaussian pulse at center of problem space
- Cell size: 0.01 meter
- Time step: $1.66 \times 10^{-11}$ sec.
- $\epsilon_0$: $8.8 \times 10^{-12}$ farad/meter

Figure 4 shows electric field wave propagation in two dimensions. Figure 4(a) shows simulation result after 60 time steps. As seen the pulse is so far not hit the boundary, so the contour is shown in Figure 4(b) is uniform in problem space. Figure 4(c) shows simulation result after 70 time steps. Here, the pulse is seen to have hit the boundary and the effect of its reflection is clearly visible in the contour plot of Figure 4(d).

Now to study analysis of signals captured by multiple sensors, simulation run with two sensors placed at the different location. The coordinate of sensor-1 and sensor-2 are (2, 2) and (40, 15) respectively as shown in Figure 5(a). Figure 5(b) shows signals captured after 600 time steps by two sensors. It is clearly seen that signals captured by sensor-2 are stronger than sensor-1, as sensor-2 is nearer to the source.

3.1 Effects of Obstacles Shape on PD Signal Propagation

To analyze the effect of obstacles shape and material on the propagation of PD signals two-dimension simulation run with circular shape copper material obstacles at location (20, 20). An effect on signal propagation is seen in Figure 6 after 100 time steps.

![Figure 4](image1.png)
![Figure 5](image2.png)

Figure 4. $E_z$ field in two dimensions. (a) $E_z$ field after $T = 60$ time steps (b) Contour of $E_z$ after $T = 60$ time steps (c) $E_z$ field after $T = 70$ time steps (d) Contour of $E_z$ after $T = 70$ time steps
The pattern of electromagnetic radiation depends on the structure and characteristic of insulating material through which signals propagate as well as dimension and material of obstacles if present. Since the main objective is to analyze the simulation result of electromagnetic pulse propagation through various types of impurities or obstacles. So here in this section, simulation is carried out with various shapes of obstacles with their different position. Moreover, the whole simulation result in this section is carried out for 130 time steps.

From the results shown in Figure 7, it can be observed that PD signals propagation pattern is highly affected by the shape of obstacles and sometimes it can help to locate the source of PD from the knowledge of the geometry of transformer.

3.1 Effects of Obstacles Material on PD Signal Propagation

The results obtained in this work are used to analyze the electromagnetic radiation for PD activities within insulating materials or problem space. The characteristics and pattern of radiated EM waves depend on the media through which it propagates.
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So, in order to investigate the effects of medium and obstacles conductivity, permeability and its permittivity on the electromagnetic wave, here PD signal propagation simulated for various materials like iron, mica, ceramic and aluminium as an obstacles location at coordinate (30, 45) for 130 time steps. From the results shown in Figure 8, it can be observed that propagation path is highly affected by obstacles and its propagation analysis can help to locate the source of PD from the knowledge of transformer geometry.

Figure 7. PD signal propagation with different shape obstacles. (a) Two circular shape obstacles at (50, 30) & (50, 70) (b) Two hexagonal shape obstacles at (30, 30) & (70, 70) (c) Two octagonal shape obstacles at (50, 30) & (50, 70) (d) Point shape obstacles at (20, 40).

Figure 8. PD signal propagation with obstacles having different material. (a) Aluminium as obstacle material (b) Ceramic as obstacle material (c) Iron as obstacle material (d) Mica as obstacle material.
4. Conclusion

The PD pulse propagation studies have been formulated with obstacles using FDTD technique algorithm. FDTD technique has been implemented to simulate PD propagation in two dimensions with different shape and material obstacles in the problem space. It has been observed that pattern of wave propagation is affected by shape and material of obstacles. Analysis and comparison of such set of results may be helpful in designing of reliable PD detection and localization setup. In future simulation work will be extended for real dimension of transformer in three dimension and also possibility of experimental validation of simulated results.

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