Towards Development of Competence in Simulation and Measurement of Partial Discharge Signals in the UHF Range

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Abstract—Partial discharge (PD) is one of the main causes for eventual equipment failure and it occurs where the electric field exceeds the local dielectric strength of the insulation. The Finite Difference Time Domain (FDTD) technique, which is a widely used electromagnetic computational method, can be also used to model propagation of PD generated in the form of a Gaussian pulse. Perfectly matched layer (PML) is a flexible and efficient absorbing boundary condition (ABC) and can be incorporated in simulation for absorption of the outgoing waves. PD generates electromagnetic waves having considerable energy in the UHF range which can be captured with the help of antennas fitted on transformer tank walls. The PD signals so captured have advantages such as higher sensitivity as compared to conventional electrical method, and they can also be measured online. Simulation and experimental investigation has been done to study the possibility of capturing PD signals in the UHF range.

I. INTRODUCTION

Power transformers are one of the most important and expensive elements of power system. Severe conditions, such as lightning strikes, switching transients and short-circuits, can lead to an immediate failure especially for aged transformers. Their insulation strength can degrade to the point that they cannot withstand system events such as short-circuit faults or transient over-voltages [1]. Insulation degradation is frequently linked to partial discharges (PD).

The method of detection of PD may be electrical, chemical, acoustic, UHF or a combination of these methods [2, 3]. In conventional method like the electrical method, the detection circuit focuses on the capturing of electrical pulses created by the current streamer in the void. It calculates the apparent charge by measuring and integrating the PD current in the measuring/detecting impedance. In chemical method, tests like High Performance Liquid Chromatography (HPLC) and Dissolved Gas Analysis (DGA) are employed to detect the gases and chemical components produced due to the breakdown of voids. PD produces mainly hydrogen whereas arcing faults produce mainly acetylene gas. Since PD is also accompanied by electromagnetic waves at ultra high frequency (300 MHz to 1500 MHz) and sound waves, relatively newer non-conventional methods like UHF and acoustic, have also been employed for detection and localization.

In this paper, first the details of finite-difference time-domain (FDTD) technique are outlined. The results of the implementation of this method for propagation of PD pulse are shown. Also, the use of perfectly matched layer (PML) as a boundary condition in this problem is demonstrated. Along with the development of competence in simulation, an experimental setup has been simultaneously developed. The results of a few initial experiments have been reported, and the possible direction of future research has also been identified.

II. F INITE DIFFERENCE TIME DOMAIN TECHNIQUE (FDTD)

In 1966 Yee [4] proposed a technique to solve Maxwell’s curl equations using FDTD technique which was further developed by Taflove. The FDTD formulation is a convenient method for solving electromagnetic field problems. FDTD, which is widely applied to the field of electromagnetic computation, can be used to simulate the electric and magnetic fields that are measured by sensors. The equations are solved in a leapfrog manner: the electric field is computed for a given instant in time, then the magnetic field is obtained for the next instant in time, and the process is repeated over and over again. The finite difference technique is based on approximations which permit replacing differential equations by finite difference equations. These finite difference approximations are algebraic in form and they relate the value of the dependent variable at a point in the solution region to the values at some neighboring points [4, 5]. The basic steps involved are:

a) Dividing the solution region into a grid of nodes: The commonly used grid patterns are rectangular, skew, triangular and circular grid

b) Approximating the given differential equation by its finite difference equivalent that relates the dependent variable at a point in the solution region to its values at the neighboring points

c) Solving the difference equations subject to the prescribed boundary and initial conditions.

Maxwell’s equations for an isotropic medium can be written as [5, 6],

\[ \mathbf{\nabla} \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \]  
(1)

\[ \mathbf{\nabla} \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \]  
(2)

where ‘\(E\)’ is the electric field (V/m), ‘\(H\)’ the magnetic field (A/m), ‘\(\varepsilon\)’ is the dielectric constant (F/m), ‘\(\mu\)’ permeability (H/m) and ‘\(\sigma\)’ conductivity (S/m) of the media. Following Yee’s notation, a grid point in the solution region is defined as a function of space and time and central difference approximation is applied [6] to discretize the Maxwell’s equations that can be implemented in MATLAB.
Absorbing boundary conditions (ABCs) are needed to keep outgoing electric field ‘E’ and magnetic field ‘H’ from being reflected back into the problem space. As the wave propagates outward, it will finally come to the edge of the problem space. ABC avoids reflections at the boundary, which is useful at least in initial stages of this work. If needed, reflective boundary conditions can be separately tackled in the future. One of the efficient ABCs that can be used is a perfectly matched layer (PML) [5].

A typical PD pulse can be numerically simulated by a Gaussian function as [7],

\[
i(t) = I_o \exp \left[ \frac{-(t-t_0)^2}{2\sigma^2} \right]
\]

where \(I_o\) is amplitude, \(t_0\) is the time instant measured at the center of the pulse, \(\sigma\) is the characteristic waveform parameter which describes the current pulse width at half maximum value, which for a PD pulse is equal to 2.36 \(\sigma\).

III. SIMULATION IN TWO DIMENSIONS

1) Two dimensional simulation results in free space: The problem space was divided into 60 x 60 cells, with each cell having a length of \(dx = 1\) cm. Figure 1 has been obtained by simulation of a Gaussian pulse at the center of the grid. It is obtained after 30 time steps in free space. The time step is taken as \(dt = dx/(2c)\), where \(c\) is the speed of light in that medium. This step size is decided by the Courant condition for two-dimensions. The pulse is seen to yet reach the boundary. In free space, relative permeability is \(\mu_r = 1\), relative permittivity is \(\varepsilon_r = 1\) with conductivity \(\sigma = 0\).

2) Two dimensional simulation results in free space without PML: Figure 2 shows results that have been obtained after 100 time steps in free space without the absorbing boundary conditions i.e. without PML. Here the pulse is seen to have reached the boundary and reflected. The contour in Fig. 2 is neither concentric nor symmetric about the center.

3) Two dimensional simulation results in free space with PML: In Fig. 3 an eight cell PML has been used. Comparison of Fig. 2 and Fig. 3 shows how the reflections get eliminated with PML. The outgoing contour of Fig. 3 is circular and only when the wave gets within the eight cells (PML) of the problem space, does the phase front depart from its circular nature.

4) Two dimensional simulation results in oil with obstructions: A real transformer will contain oil as the insulating medium and also obstructions for the radiated wave, like the winding and core. Here such obstructions are simulated by two representative and scaled down circular objects of 6 cm radius centered at (15, 30) and (45, 30).

This simple geometry is assumed for verification of the algorithm. An oil medium with relative permeability \(\mu_r = 1\), relative permittivity \(\varepsilon_r = 2.2\) and conductivity \(\sigma = 0\), and two circular obstructions with relative permeability \(\mu_r = 1\), relative permittivity \(\varepsilon_r = 1\) and conductivity \(\sigma = 5.8x10^7\) (S/m) representing simplified copper winding structure are considered. In Fig. 4 ‘\(E_z\)’ field propagation contour, with pulse originated at (30, 30), after 100 time steps is shown. The wave takes a path along the surface of the obstruction which may be the shortest route for the wave travel.
In the literature, Gaussian pulse has been used to describe the current due to PD [7]. Hence the propagation due to a Gaussian current pulse has been studied here. Consequently, there is no single frequency propagation. Instead, the disturbance generated due to all the frequencies present in the spectrum of this impulse is relayed along the mathematical grid in the simulation. Since the current used for simulation has a nature similar to that of the PD pulse, the signals received at the hypothetical sensors will help understand the signals that may be expected in reality. However, from FDTD perspective, cell size has to be lesser than \( \frac{1}{10} \)th of wavelength for the highest frequency. Hence, the shortest wavelength that will be suitably captured is 0.1 m, which is equivalent to a frequency of 3 GHz in air, and very close to 2 GHz for oil.

Thus, these FDTD simulations can help understand PD UHF wave propagation. Eventually, such an analysis tool is expected to help in detecting the PD source location using UHF signals. There have been efforts in acquiring competence in UHF signal measurement as outlined in the following section.

IV. LABORATORY UHF PD MEASUREMENT

The conventional electrical method IEC 60270 for PD detection is well developed. Since the rise times of PD are very short in time (nano seconds range), electromagnetic waves in the giga – hertz range are emitted during a PD event. The UHF signals have very moderate damping compared to acoustic, electrical signals and since the tank itself acts as a faraday cage, it enhances the signal quality by eliminating other external interference. Also, making additional provision for three or four UHF sensors when a new transformer is being manufactured would add negligible cost [9]. Adapting the transformer tank to enable UHF band (300 to 3000 MHz) monitoring requires that dielectric windows be made in the wall to allow PD signals from within to reach the sensors. Passive UHF sensors can then be installed externally, with coaxial cables linking them to connectors that can be accessed while the transformer is in operation. UHF diagnostic techniques would then become available for on-line monitoring to complement the existing handicap of off-line measurements.

A tank enclosing the electrodes to emulate transformer environment has been fabricated locally and is shown in Fig. 5. The size of the prototype tank (made of 16 gauge thick mild steel) is 500 mm (length), 500 mm (width), 380 mm (height). It is designed for a maximum operating voltage of 40 kV. A copper coil with the inner and outer diameters as 180 mm and 220 mm is also procured. Placing it around the electrode arrangement brings the experimental environment closer to the real transformer. The sensor used to measure PD here is a UHF antenna. It is also very advantageous to select a broadband antenna since it increases sensitivity of measurements. In a substation environment, background noise is low for signals above 200 MHz and corona in air is detectable above 400 MHz [8, 9]. For experimental purpose a broadband antenna capable of measuring signals up to 2 GHz and a spectrum analyzer having 100 KHz to 6 GHz frequency range have been procured. A preamplifier is also connected to enhance the detection sensitivity.
Case 1: Point – Plane electrode separated 21 mm apart without coil

Tank is energized without the coil, with point electrode at high voltage and plane electrode at earth potential separated by a distance of 21 mm. The position of antenna is kept on the inside tank wall, almost 125 mm from ground, at a line of sight distance from the electrode gap. The attenuation is set at 0 dB, reference at -40 dBm and grass was found to be at -80 dBm in all the cases. At a voltage of about 10.8 kV, strong continuous discharge signals started to appear in the 100 MHz to 1500 MHz range. It is observed that the signals are very strong, almost 25 dB above the grass level in the 500 MHz to 800 MHz range and the signals are also present beyond the 1 GHz range. Mobile signals were also recorded in the 800 MHz to 1000 MHz along with discharge signals. Since the frequency spectrum of the mobile communications system is known, the signals obtained in that range were disregarded. The detected UHF signals are shown in Fig. 7. Simultaneously electrical detection system showed intermittent, yet strong discharge pattern in the negative half of the power cycle as represented in Fig. 8.

Case 2: Plane - Point electrode, 21 mm apart without coil

The electrode positions are interchanged with plane electrode at high voltage and point electrode at ground separated 21 mm apart. Figure 9 shows the observed waveform when 11 kV is applied. Strong and continuous signals are captured in the UHF range of 300 MHz to 1500 MHz.

Simultaneously electrical signals are also observed. Strong intermittent signals are present at the positive half of the power cycle of the ellipse of the oscilloscope as represented in Fig. 10.
Case 3: Point–Plane electrode, 21 mm apart with coil

The point – plane electrode separated by 21 mm is energized with the coil surrounding the electrodes. The antenna is at the same position as in case 1. The coil, now obstructs the line of sight, between the source of PD and the antenna. At 10.3 kV distinct discharge signals, as in case 1, are captured and shown in Fig. 11. The intensity, characteristics and attenuation of the captured PD signal would be determined by the obstacles between the source and the sensor. Experimental studies reported in [10] indicate that an aperture in any obstacle allows propagation of UHF signals. In the present case, a gap between two turns of the coil may be allowing the wave propagation. Additionally, reflections from other metallic surfaces may also contribute to the captured signal. Thus, in a real transformer a perfect line of sight may not be essential to detect the UHF signals.

Case 4: Plane - Point electrode, 35 mm apart without coil

The distance between the electrodes is increased to 35 mm and voltage is kept at 12.7 kV. Strong and continuous signals are detected only by the UHF method as shown in Fig. 12. At this voltage level, discharge signals are not detected by the electrical method. All other settings like attenuation and reference are kept same as in the previous cases. Background noise is observed, as earlier, at -80 dBm. When the voltage level is increased to 14.26 kV both electrical and UHF method displayed continuous discharges. The above observation advocates the use of UHF method for better sensitivity, which can additionally provide an online solution for transformer condition monitoring and diagnostics. The disadvantage of UHF method compared to the electrical one, is its inability to provide the magnitude of apparent charge. The complementary advantages of both these methods should be utilized for efficient and reliable PD detection.

Detailed analysis of signals in the frequency domain may be further pursued for getting a greater insight of PD phenomenon and correlation between signals obtained using the UHF method and the conventional electrical method.

V. CONCLUSIONS AND FUTURE WORK

The non-conventional electromagnetic (UHF) method can be of greater advantage if used as an onsite and online PD detection method due to its higher sensitivity and immunity against disturbances and noise. PD pulse propagation has been studied using FDTD. The algorithm implemented in MATLAB has been used successfully to simulate PD propagation in two dimensions in free space and with a geometry representing obstructions in the domain, along with absorbing boundary conditions. It has been experimentally validated that PD signals exist in the UHF range and they have been captured in a frequency range of 300 MHz to 1200 MHz. Even though the coil surrounds the electrodes, distinct discharge signals are recorded by the UHF antenna. It is observed that the UHF PD signals are detected strongly even at voltages where electrical method is not able to sense them.

As a future work, the methodology used in simulation can be extended to three dimensions along with absorbing boundary conditions and actual dimensions of a transformer may be incorporated. An experimental study for detection and localization is also proposed using the UHF triggered acoustic TDOA measurements approach. More experiments can be conducted on the model using different electrode configurations for different gap distances, to capture signals in the UHF range and cross-correlate them with the conventional IEC 60270 method. By doing so, the advantages of both the methods could be utilized.

REFERENCES


