Three-Dimensional Simulation of UHF Signal Propagation in Transformer using FDTD Method

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Abstract- **Partial discharge in transformer can be detected and localized on-line using UHF technique. The first step for achieving this goal particularly the PD localizing is creation of simulation environment. In this paper three dimensional simulation is done using the FDTD method. The created simulation environment by FDTD was compared with CST software. The results of the two simulation environment had a good match with together. Consideration of the transformer active part is the feature of this simulation. Simulation results show that UHF electromagnetic (EM) waves can transmit from the radial ducts width between adjacent coils of high voltage winding. It was observed that the energy of received signal is proportional the oil duct width. Also it was observed that if the PD current pulse is steeper, signal energy and peak of the received signal would be reduced.**

I. INTRODUCTION

Power transformers are strategically important components used in the power transmission network. Their failure due to insulation breakdown can lead to serious consequences. PD is a pre-cursor to arcing or final transformer failure. Its detection is an effective means of verifying the insulation performance of power transformers [1, 4].

There are Different methods for detection of partial discharge. These methods are classified two categories of electrical and non-electrical methods. Non-electrical detection methods include acoustic signal detection, dissolved gas analysis and light detection. Dissolved gas analysis (DGA) is routinely employed to detect internal electrical discharging in power transformers. DGA can provide some information about the nature and severity of the PD [2]. However, knowledge of the PD location (which cannot be obtained from DGA) would be a great help to the specialists who must make decisions about remedial action [2].

Electrical methods include the use of capacitive sensors, inductive sensors and detection of UHF signals. UHF PD detection has been continuously applied in GIS monitoring but recently some researches have been made to apply this method for PD detection of power transformer [1]. This technique can be expected to realize wide range and high sensitive measurement of PD with less influence from external noise [1]. The following issues have been investigated by research in this area:

1) Simulating propagation of UHF signal [1, 3, 4, 5].
2) Locating of PD using UHF method [4, 6].
3) Different antennas designed with various bandwidths at UHF frequency range [7, 8].
4) Evaluation of the measurements sensitivity performed using UHF method [9].

Simulation of UHF signal propagation is done in many papers, but these simulations did not fully consider transformer active part.

In this paper three dimensional simulation is made using the Finite-difference time-domain (FDTD) method. The FDTD is widely used in Electromagnetic computation to simulate the electrical field which can be measured by sensors, when PD occurs inside transformers [1].

The feature of this simulation is considering the transformer active parts like core, windings and insulations. The simulation environment created by FDTD is validated comparing with commercial CST software which can solve transient electromagnetic field tasks in time and frequency domains using a Finite Integration Technique (FIT) [10]. The results of this comparison show good match between proposed FDTD based simulations and CST.

UHF EM waves of PDs which occur inside the windings could transmit to the outer area that UHF antennas are mounted through radial oil ducts between adjacent coils of windings. The energy of detected UHF signal for such PD defects depends strongly on the breadth of these ducts. In this paper the effects of the breadth of oil ducts on UHF PD measurement is investigated. It is proved that greater duct breadth would lead to greater signal energy using the FDTD based simulation method.

II. FDTD METHOD

FDTD is an effective transient EM wave simulation method with extensive applicability and easy to realize [3]. In 1966 Yee proposed a technique to solve Maxwell's curl equations using FDTD technique. Yee's method has been used to solve numerous scattering problems on microwave circuits, dielectrics, and etc. Initially there was little interest in the FDTD method, probably due to a lack of sufficient computing resources. However, with the advent of low cost, powerful computers and advances to the method itself, the FDTD technique has become a popular method for solving electromagnetic problems [1].

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In this paper the method which is used is Yee method. In this method the simulation environment is divided into small Yee cells and the dimension of the cell is $\Delta x = \Delta y = \Delta z = \delta$. In Fig.1 the structure of this method is shown. In such way the number of divisions of simulated area in x, y and z direction are N_x , N_y and N_z respectively. In this structure each point is located in:

$$(i, j, k) = (i\Delta x, j\Delta y, k\Delta z) \tag{1}$$

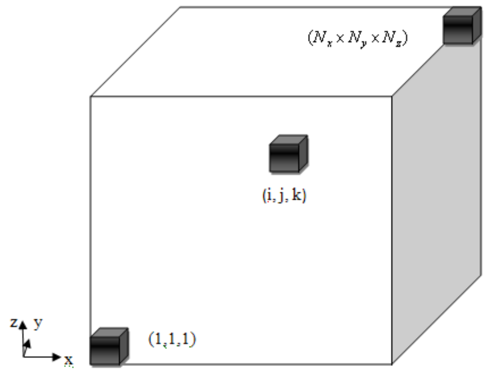

Fig. 1: Yee cell which is used in the simulation

The electric and magnetic fields are calculated from equations (2) to (7) [11].

$$\begin{aligned} H_x^{n+\frac{1}{2}}(i,j,k) &= \frac{2\mu_x(i,j,k)-\Delta t\sigma_x^m(i,j,k)}{2\mu_x(i,j,k)+\Delta t\sigma_x^m(i,j,k)} H_x^{n-\frac{1}{2}}(i,j,k) \\ &+ \frac{2\Delta t}{(2\mu_x(i,j,k)+\Delta t\sigma_x^m(i,j,k))\Delta z}(E_y^n(i,j,k+1) - E_y^n(i,j,k)) \\ &- \frac{2\Delta t}{(2\mu_x(i,j,k)+\Delta t\sigma_x^m(i,j,k))\Delta y}(E_z^n(i,j+1,k) - E_z^n(i,j,k)) \end{aligned} \tag{2}$$

$$\begin{aligned} H_y^{n+\frac{1}{2}}(i,j,k) &= \frac{2\mu_y(i,j,k)-\Delta t\sigma_y^m(i,j,k)}{2\mu_y(i,j,k)+\Delta t\sigma_y^m(i,j,k)} H_y^{n-\frac{1}{2}}(i,j,k) \\ &+ \frac{2\Delta t}{(2\mu_y(i,j,k)+\Delta t\sigma_y^m(i,j,k))\Delta z}(E_x^n(i,j,k+1) - E_x^n(i,j,k)) \\ &- \frac{2\Delta t}{(2\mu_y(i,j,k)+\Delta t\sigma_y^m(i,j,k))\Delta x}(E_z^n(i+1,j,k) - E_z^n(i,j,k)) \end{aligned} \tag{3}$$

$$\begin{aligned} H_z^{n+\frac{1}{2}}(i,j,k) &= \frac{2\mu_z(i,j,k)-\Delta t\sigma_z^m(i,j,k)}{2\mu_z(i,j,k)+\Delta t\sigma_z^m(i,j,k)} H_z^{n-\frac{1}{2}}(i,j,k) \\ &+ \frac{2\Delta t}{(2\mu_z(i,j,k)+\Delta t\sigma_z^m(i,j,k))\Delta x}(E_y^n(i+1,j,k) - E_y^n(i,j,k)) \\ &- \frac{2\Delta t}{(2\mu_z(i,j,k)+\Delta t\sigma_z^m(i,j,k))\Delta y}(E_x^n(i,j+1,k) - E_x^n(i,j,k)) \end{aligned} \tag{4}$$

$$\begin{aligned} E_x^{n+1}(i,j,k) &= \frac{2\varepsilon_x(i,j,k)-\Delta t\sigma_x^e(i,j,k)}{2\varepsilon_x(i,j,k)+\Delta t\sigma_x^e(i,j,k)} E_x^n(i,j,k) \\ &+ \frac{2\Delta t}{(2\varepsilon_x(i,j,k)+\Delta t\sigma_x^e(i,j,k))\Delta y}(H_z^{n+\frac{1}{2}}(i,j,k) - H_z^{n+\frac{1}{2}}(i,j-1,k)) \\ &- \frac{2\Delta t}{(2\varepsilon_x(i,j,k)+\Delta t\sigma_x^e(i,j,k))\Delta z}(H_y^{n+\frac{1}{2}}(i,j,k) - H_y^{n+\frac{1}{2}}(i,j,k-1)) \end{aligned} \tag{5}$$

$$\begin{aligned} E_y^{n+1}(i,j,k) &= \frac{2\varepsilon_y(i,j,k)-\Delta t\sigma_y^e(i,j,k)}{2\varepsilon_y(i,j,k)+\Delta t\sigma_y^e(i,j,k)} E_y^n(i,j,k) \\ &+ \frac{2\Delta t}{(2\varepsilon_y(i,j,k)+\Delta t\sigma_y^e(i,j,k))\Delta z}(H_x^{n+\frac{1}{2}}(i,j,k) - H_x^{n+\frac{1}{2}}(i,j,k-1)) \\ &- \frac{2\Delta t}{(2\varepsilon_y(i,j,k)+\Delta t\sigma_y^e(i,j,k))\Delta y}(H_z^{n+\frac{1}{2}}(i,j,k) - H_z^{n+\frac{1}{2}}(i-1,j,k)) \end{aligned} \tag{6}$$

$$\begin{aligned} E_z^{n+1}(i,j,k) &= \frac{2\varepsilon_z(i,j,k)-\Delta t\sigma_z^e(i,j,k)}{2\varepsilon_z(i,j,k)+\Delta t\sigma_z^e(i,j,k)} E_z^n(i,j,k) \\ &+ \frac{2\Delta t}{(2\varepsilon_z(i,j,k)+\Delta t\sigma_z^e(i,j,k))\Delta x}(H_y^{n+\frac{1}{2}}(i,j,k) - H_y^{n+\frac{1}{2}}(i-1,j,k)) \\ &- \frac{2\Delta t}{(2\varepsilon_z(i,j,k)+\Delta t\sigma_z^e(i,j,k))\Delta y}(H_x^{n+\frac{1}{2}}(i,j,k) - H_x^{n+\frac{1}{2}}(i,j-1,k)) \end{aligned} \tag{7}$$

In these equations, Δt is time step, n is time index, H is magnetic field, E is electric field, ε is permittivity, μ is permeability, σ is conductivity. To yield accurate results, the grid spacing δ in the finite difference simulation must be less than the wavelength, usually less than $\lambda/10$. The stability condition relating the spatial and time step size is:

$$V_{max}\Delta t \le \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \tag{8}$$

Where V_{max} is the maximum velocity of the wave. Having derived the FDTD updating equations, a time marching algorithm can be constructed as illustrated in Fig.2 [11].

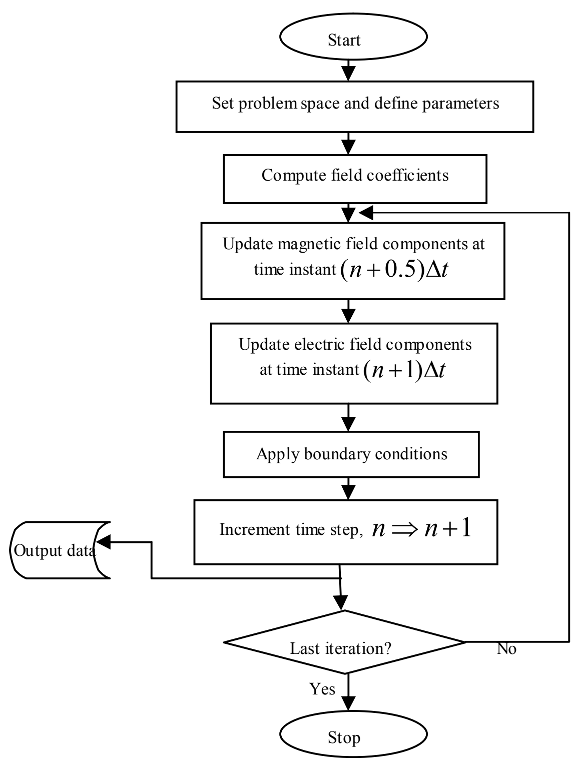

Fig.2: Explicit FDTD procedure [11].

III. VERIFICATION OF FDTD SIMULATION ENVIRONMENT BY USING CST SOFTWARE

According to the algorithm that presented in the previous section, the program for UHF signal propagation simulation was written in C++ environment. In this simulation dipole antenna is used for PD modeling. The theory analysis and practical measurement show that PD signals have a very steep wave front of 1~10 ns. So a typical pulse for exciting the antenna can be simulated by Gauss function as following [12]:

$$i(t)=I_0\exp[-(t-t_0)^2/(2\sigma^2)] \quad (9)$$

Where I_0 is amplitude, t_0 is the initial time, σ is characteristic waveform parameter which describing the pulse width at half maximum value (PWHM), the PWHM of PD pulse is equal to 2.36σ. It has been proved that this parameter is closely correlated to the geometric shape and insulation intensity of PD gap. Generally, smaller defect geometry dimension, causes steeper PD pulse wave front. Accordingly, PD current waveform parameter σ would be smaller too. Hence, the characteristic parameter σ of PD pulse current can help us to understand the PD state [12].

To evaluate the proposed method, a $50\times50\times450\,mm^3$ volume is considered to simulate oil filled tank. The space step in this method is chosen to be $\Delta x=\Delta y=\Delta z=5\,mm$ and the time step according to equation (8) is set to $\Delta t=9.6292\times10^{-12}$. The setting in CST was so applied that the number of its meshes to be equal with that in proposed simulation environment. The radiating source point is set at the point (25, 25, 225) in space coordination. Fig. 3 shows the simulating environment in CST. The radiating source is energized by a current wave form shown in Fig. 4. In Fig. 5a and 5b the electric fields in two different positions in the space are depicted. It is clear from these figures that the results have good accordance with each other.

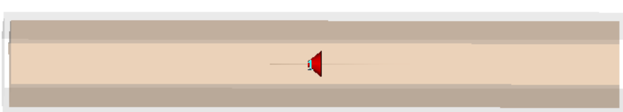

Fig.3: Simulated environment in CST to confirm the FDTD method accuracy

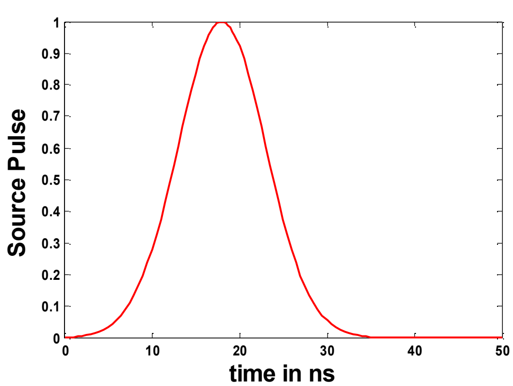

Fig.4: Excitation pulse

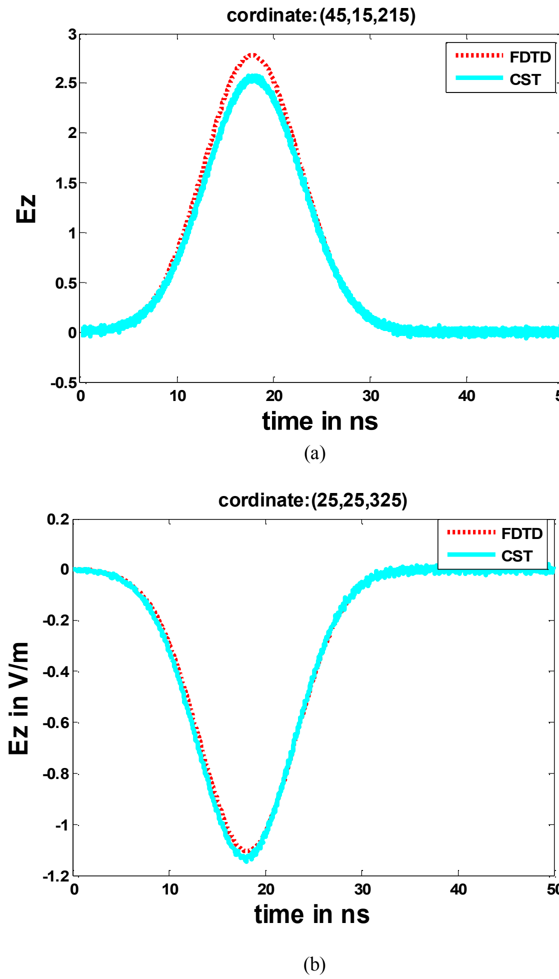

Fig.5: The achieved results for received signals in CST and FDTD method in different sensor position a) sensor location: (45, 15,215) b) sensor location: (25, 25,325)

IV. FDTD SIMULATION OF TRANSFORMER

To study the effect of active part inside the transformer, a distribution transformer was simulated using FDTD method. The dimensions of this transformer extracted from [13] are shown in table 1. Fig. 6 shows a cross view of this transformer. Some cylinders were used to simulate the limbs and yokes of transformer core in FDTD environment. Fig. 7a, 7b and 7c show the cross view of simulated transformer. Tangential electrical fields and vertical magnetic fields in FDTD environment were set to be zero in the boundaries of the core. Same considerations were applied to simulate windings. Different dielectric constants in different space positions were considered to simulate various insulating materials inside transformer tank. The same time and space steps with those used in previous section were applied.

V. Investigating the Effects of Gap Between the Coils in Acquired UHF Signal

To investigate the effects of oil duct between the adjacent coils of the winding in electromagnetic wave propagation, one single gap in the windings was simulated. In such a way, the winding was assumed to be constructed of two equal up and down cylinders (Fig. 7b and 7c). Afterwards, different gap widths were chosen to study the effect of the oil duct width on UHF wave propagation. In FDTD environment, the radiating source is placed in (90, 400,200) space coordination (Fig 7a), and is energized with a current wave form with characteristics of $I_0 = 3\,mA$, $\sigma = 3\,ns$ and $t_0 = 18\,ns$.

Table 1: Transformer data which is used in simulation

Phase number	3
Core material	Steel
Core diameter	135 mm
Internal height of window (H_w)	300 mm
Internal width of window (W_w)	120 mm
External height of window (H)	536 mm
External width of window (W)	624 mm
Yoke diameter	118 mm
Tank height	950 mm
Tank width	840 mm
Tank length	350 mm
Dielectric constant of oil	2.2

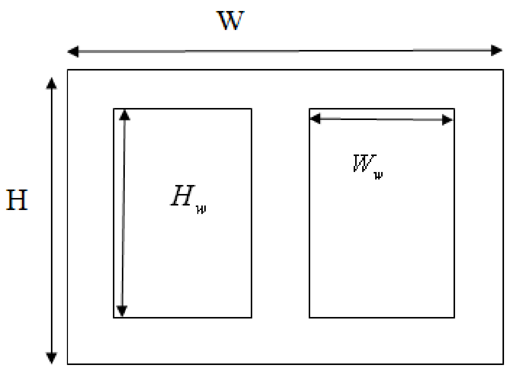

Fig.6: Core dimensions

Fig. 8 shows the resulted UHF signal in (175, 420, 700) space coordination. It is clear that by variation of the oil duct, only the peak value of the signal is affected and no change in arrival time could be observed. In Fig. 9, the energy of the signal with respect to oil duct in five different space positions is shown. The energy of the signal in all positions has greater value when the breadth is bigger. But as it is shown in Fig. 10, the peak value of the signal in different acquiring positions does not show regular behavior with respect to distance between coils.

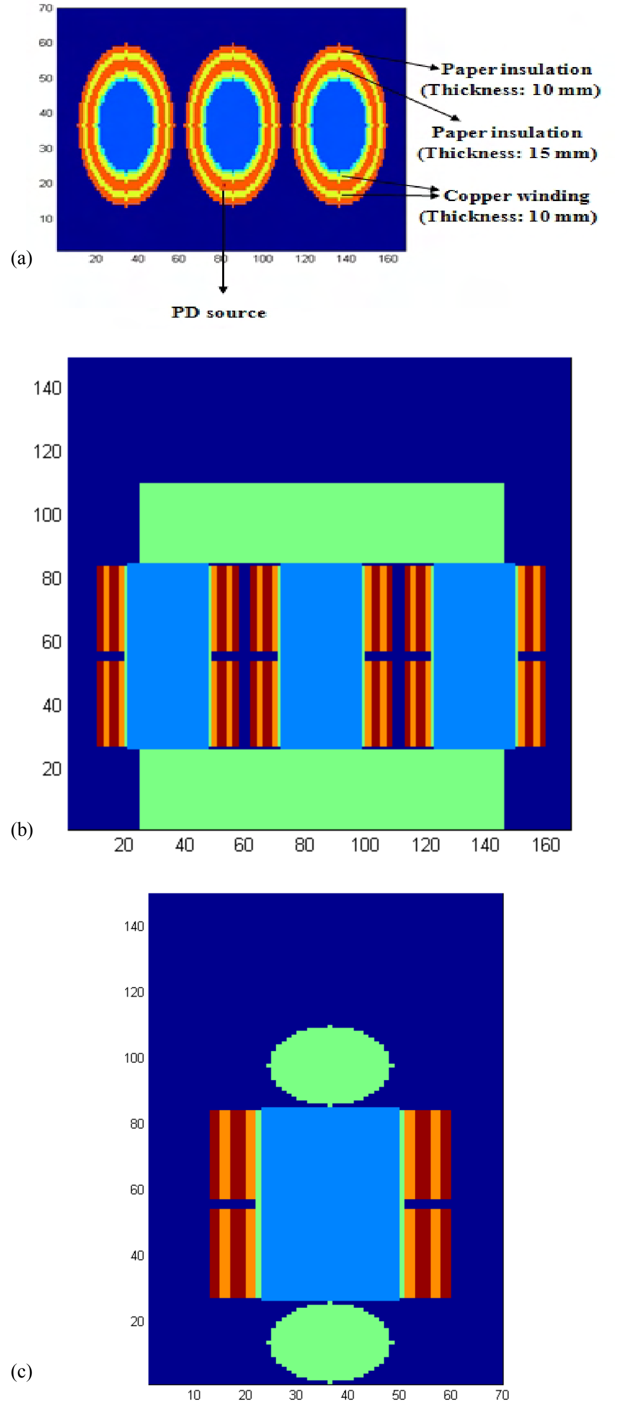

Fig.7: Schema of simulated transformer in different coordinate directions a) z direction b) x direction c) y direction and oil the gap in the windings.

VI. Investigating the Effects of Defect Type in Acquired UHF Signal

It was mentioned in section III that the parameter σ is related to the physics and dimension of the void. Therefore by changing this parameter it is possible to simulate the current waveform of different PD defects.

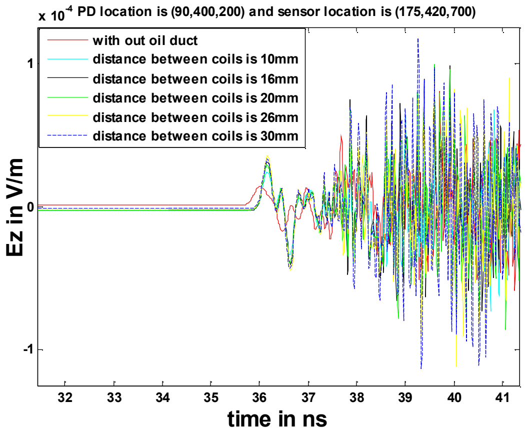

Fig.8: Received UHF signal for different modes of distance between coil

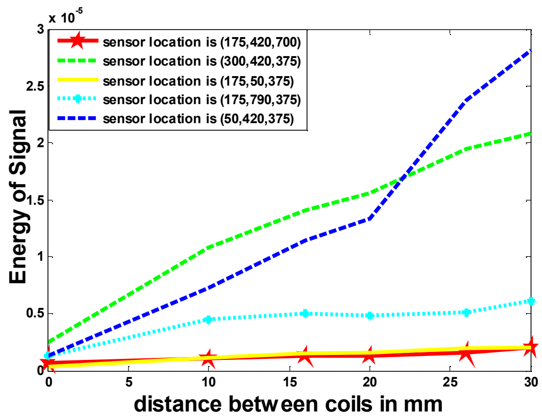

Fig.9: UHF signal energy with respect to coil distance in different position

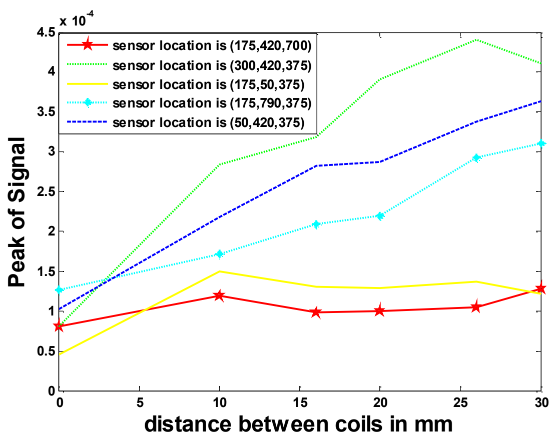

Fig 10: UHF signal peak with respect to coil distance in different position

In this section, different values for parameter σ are tried to investigate the type of PD defect in electromagnetic waves propagation inside transformer. Fig. 11 shows that the arrival time and UHF signal peak depends on the radiating source current waveform. In Fig. 12 the energy of the signals are shown with respect to σ. It is evident that energy of the signal is increasing by σ in all acquiring space positions. In Fig. 12 the peak value of the signals are shown too. It could be seen that although the stimulating current peak value of radiating source are equal, but the peak value of acquired signals in all positions are increasing by σ.

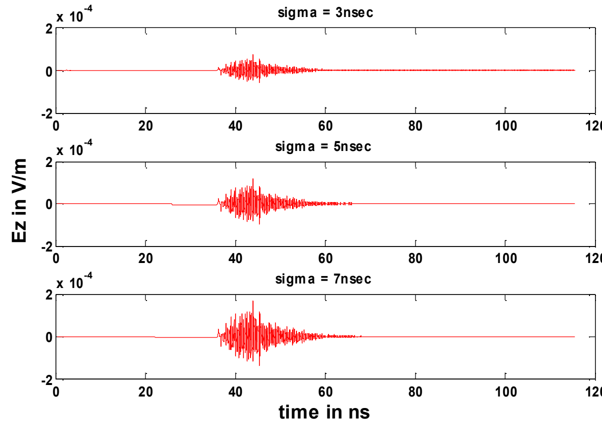

Fig 11: Comparison of received UHF signal for different defects in same space position for $\sigma = 3ns$, $5ns$ and $7ns$ (PD location is (90,400,200) and sensor location is (175,420,700))

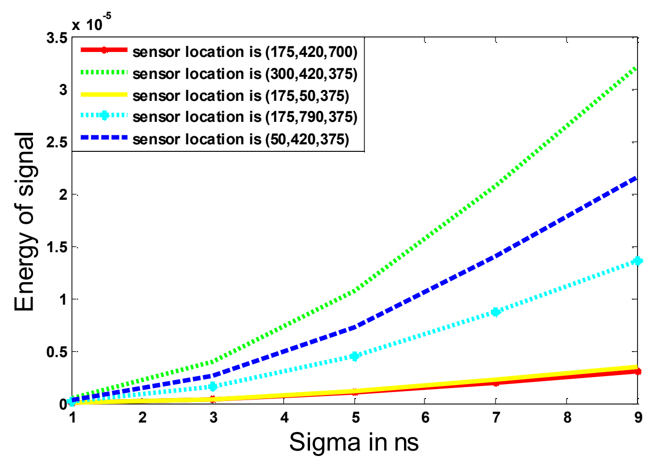

Fig.12: UHF signal energy with respect to σ parameter in different position

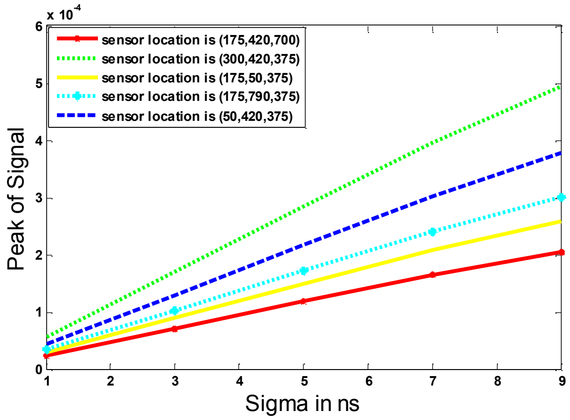

Fig.13: UHF signal peak with respect to σ parameter in different position

VII. CONCLUSION

In this paper some simulations have done to investigate the effects of transformer active part in UHF electromagnetic propagation. For this purpose, a FDTD base method was proposed and validated using CST software. The simulations which were made by this method show that UHF waves could penetrate from the gaps between adjacent disks of the winding. It was observed that wider gap breadth results in stronger acquired UHF signal. Also it was resulted that PD pulses with steeper front time cause to smaller energy and peak values of the acquired UHF signals.

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