Three-dimensional Simulation of PD Source Allocation Through TDOA Method

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Abstract: *Ultra Wide Band (UWB) radio frequency method for allocating partial discharge (PD) is a new method for PD source localization on power transformers which is based on diamond shape multi-antenna PD detection and Huygens-Fresnel principle. Preparing a simulation environment is the first step to achieve this goal. In this paper, a three-dimensional simulation is performed using CST software and the PD source current is simulated. According to the results, this software is helpful for simulation of PD allocation using UWB signals with time difference of arrival (TDOA) method.*

Keywords: CST software, PD location, TDOA, UWB

1. Introduction

Power transformers play a major role in electricity distribution and transmission systems. Their reliability affects both the economic operation and electric energy availability of the utility. The power transformer's loss can be extremely expensive for the utilities. So, online monitoring and preventive tests are frequently performed to predict the initial fault conditions [1-3]. The insulating system of a power transformer is an important part and for the safe operation of the unit its integrity has a significant role. Weaknesses of the insulating systems may lead predisposition to failures triggered from external stresses such as transients in switching operations, lightning strikes or short circuits. For safe and economic operation, accurate assessment of the transformer insulation condition is essential [4]. Experimental experiences prove that in power transformers partial discharges (PD) are an important symptom and major source of insulation failure [5-7]. Preventive maintenance measures may be taken if the deterioration of the insulation system that is caused by PD activity can be detected at an early stage. Because of the complex structure of the power transformer, accurate PD location is difficult and is one of the challenges power utilities are faced with [7-10].

At present, electrical and acoustic methods have been employed to make PD source location in power transformers [11-13]. With the electrical method it is difficult to make PD source location because of the difference of structure between several transformers and the complicated work to make out propagation characteristics of the transformer windings.

Radio Frequency (RF) detection of PD, being described in the international standard of PD measurement [14] and is a long-established principle. The PD source location employing electromagnetic signals that emitted from PD source is a very attractive research field in the condition monitoring of power transformers for its high sensitivity and excellent noise-immune characteristics.

It is known that the shape of PD source signals in the time domain contains so much information about the location and type of the PD defects in these equipments. Using UWB measuring systems, it is possible to acquire the shape of PD pulses in time domain [15-16].

Therefore in this paper three-dimensional simulation of PD allocation through CST software is performed for the first time. The PD source current is simulated and PD location is calculated with emitted signals. According to the results, this software is helpful for simulation and allocating of PD source in transformer windings using UWB signals through time difference of arrival (TDOA) method.

2. Time Difference Of Arrival (TDOA)

Depending on sensors location regard to the signal source, sensors receives signals with different time delays. The time delays for a signal which are sensed by S_1, S_2,$S_3$and S_4areshown in Fig. 1for a general case.

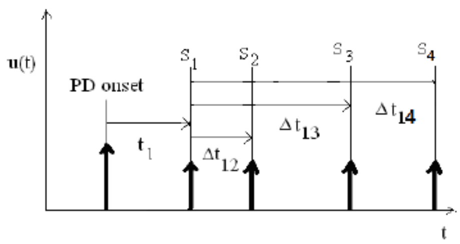

Fig. 1:Visualization of signal arrival times in reference to the unknown PD onset

The TDOA method equations are defined as follows:

$$(c * t_1)^2 = (x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 \quad (1)$$

$$(c*(t_1+\Delta t_{12}))^2 = (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 \quad (2)$$

$$(c*(t_1+\Delta t_{13}))^2 = (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 \quad (3)$$

$$(c*(t_1+\Delta t_{14}))^2 = (x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2 \quad (4)$$

which 'c' is the velocity of the signal in the medium, Δt_{12},Δt_{13} andΔt_{14} are the time delays. The first and second subscripts in the parameter Δt denotes wave time differences of arrival with respect to the first hit sensor and the other respective sensors. The locations of sensors S_1, S_2, S_3 and S_4 are known and is shown by (x_1,y_1,z_1), (x_2,y_2,z_2), (x_3,y_3,z_3) and (x_4,y_4,z_4) respectively. The unknowns are (x,y,z) of the source location and't_1' the PD onset instant.

3. PD Electromagnetic Signal Analysis

The practical measurement and theory analysis show that PD signals have a very steep wave front [17]. A typical PD can be numerically simulated by Gauss function as follows [17]:

$$i(t) = I_0 \ \exp[-\frac{(t-t_0)^2}{2\sigma^2}] \quad (5)$$

where I_0 is amplitude, σ is characteristic waveform parameter and describes the pulse width at half maximum value (PWHM), the PWHM of PD pulse is equal to 2.36σ, and t_0 is the initial time. PWHM has been proved that is closely correlated to the insulation intensity and geometric shape of PD gap. Generally, the smaller the defect geometry dimension is, the steeper the PD pulse wave front would be and PD current waveform parameter (σ) is also smaller, accordingly. Hence, the characteristic parameter σ of PD pulse current can help us to understand the PD state. The frequency components can be obtained by taking the Fourier transform from (5) [17].

$$I(j\omega) = \sqrt{2\pi}\ I_0\sigma \ \exp(-\frac{\sigma^2\omega^2}{2}) \ \exp(-j\omega t_0) \quad (6)$$

where ω is angular frequency. We can consider PD pulse current as an infinite sine series. The radiated EM signal can be simulated by short dipole antenna. The length of short dipole antenna (l) is corresponding to the geometry dimension ofinsulation defect. A time-varying current in a radiating current element can be written as follows:

$$I = I(j\omega)\ \cos\omega t \quad (7)$$

The far radiating field's amplitude can be described in terms of the theory of antenna, as follows [17]:

$$e_k \ \alpha \ I_0\omega\sigma \exp(-\frac{\sigma^2\omega^2}{2}) \quad (8)$$

Also the power spectrum density of the radiating signal is written as (9) [17]:

$$P(\omega) \ \alpha \ (\frac{I_0\sigma\omega l}{c})^2 \exp(-\sigma^2\omega^2) \quad (9)$$

From (9), we can deduce that the peak value of $P(\omega)$is at ω=1/σ. Namely, the spectrum of the radiating signal mainly distributes at ω =1/σ, is shown in Fig. 2. Therefore, PD pulse width can be estimate through spectrum analysis of PD electromagnetic signal.

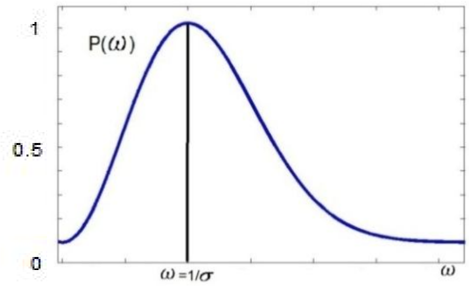

Fig. 2: the function of power spectrum density (normalized)

4. Case Study

The analysis of the electromagnetic field is based on the Maxwell equations. For this purpose, CST software utilized. This software is capable to solve transient electromagnetic field in both time and frequency domains using the finite integral technique. This technique breaks the solution space into small spaces with mesh grading and then solves it. It is known that detecting UWB signal is a practical method for power transformers monitoring, but due to the limitations of software and hardware, simulation of such a structure is not possible. So, the dimensions are multiplied by 0.2.In this paper a transformer is simulated. The dimensions of this transformer are extracted from [18] and are shown in Table 1. To simplify the model, the number of layers is considered 5, the number of coils 3 and the space between coils 15 mm. Fig. 3 demonstrates schema of simulated transformer in CST software in different directions.

Table 1: Transformer data which is used in simulation

Phase number	1
Core material	Steel
Tank body material	Steel
Core diameter	135 mm
Tank height	750 mm
Tank width	840 mm
Tank length	350 mm
Insulation width between H.V. and L.V.	1.5 mm
Duct width between H.V. and L.V.	5 mm
H.V. height	221 mm
H.V outer diameter	239 mm
H.V inner diameter	186.2 mm
Space between coils	5 mm
Insulation width between H.V. layers	0.3 mm
Number of H.V. coils	8
Number of H.V. layers	24
L.V. height	285 mm
L.V. outer diameter	156.2 mm
L.V. inner diameter	138 mm
Insulation material between L.V. layers	Pressboard
Insulation width between L.V. layers	0.5 mm
Insulation material between L.V. and core	Pressboard
Insulation width between L.V. and core	1.5 mm

(a)

(b)

(c)

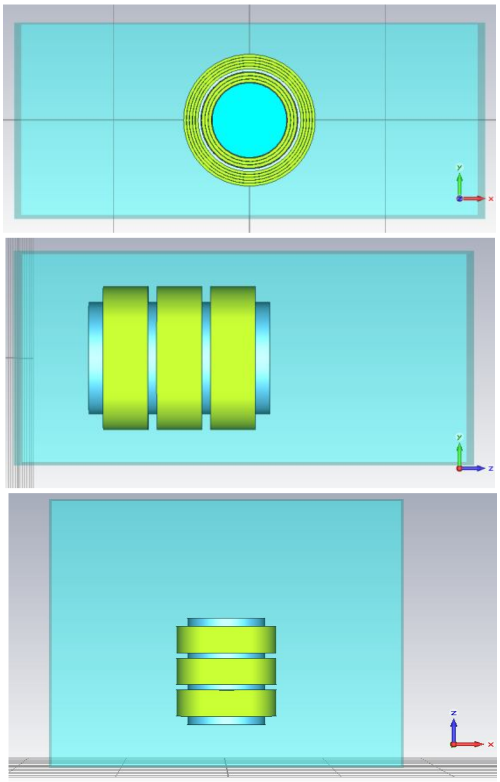

Fig. 3: Schema of simulated transformer in different coordinate directions. a) x-y b) y-z c) x-z.

The single phase transformer is in air condition and the background material of the simulation is set to normal type that epsilon and mue are set to 1.0.theboundary condition set to Open Add Space. CST has two open boundary conditions. Open boundary operates like free space: waves can pass this boundary with minimal reflections. But Open Add Space is same as Open, but adds some extra space for farfield calculation. This option is recommended for antenna problems.

5. Simulation Results

For simulation of PD current in CST software, a discrete port is used as a PD source with the amplitude of 5mA. The rise time of the Gaussian function is set to 0.12 ns. A typical PD waveform is depicted in Fig. 5.

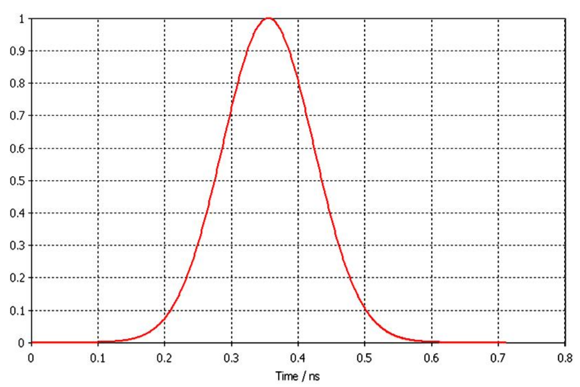

Fig. 5: PD source current (normalized)

The simulation is in time domain and for 0-10GHz. The PD source is located at (0,21.75,78.4) between third and forth H.V. windings. To detect the emitted signals from source, four probes are used as four diamond shape antennas in top of the transformer tank at positions S_1(0,22.82,137.82), S_2(0,-22.82,137.82), S_3(74.8,0,137.82) andS_4(-74.8,0,137.82).These probes and transformer are illustrated in Fig. 6.

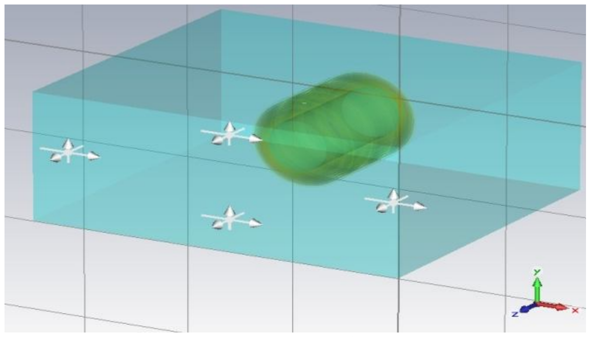

Fig. 6: the probes and transformer in CST

Each probes has three signals in three dimensions. The received signals in three dimension for S_1 and the absolute received signals in four probes are shown in Fig. 7 and Fig. 8, respectively. The different between four signals is time delay, in generally. The calculated results for time delays and position including errors of PD locating source are given in Table 2.

Table 2: simulation results and PD location estimations

Rise time (ns)	*Time delays (ns)*			*calculated PD position error (mm)*	*Calculated PD position*
	Δt_{12}	*Δt_{13}*	*Δt_{14}*		
0.12	0.061	0.108	0.108	15.228	(0,37,80)

As it can be found from table 2 and Fig. 8, S_3 and S_4 are symmetrical to port and their results are same. After calculating PD source location based on (1)-(4), worst result is for S_3 and S_4, because the direct path between PD source and these probes is the longest, also this distance has different materials. So the errors are bigger.

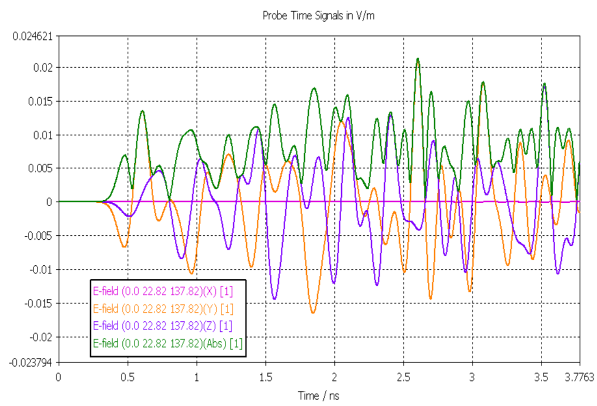

Fig. 7: The received time signals for S_1

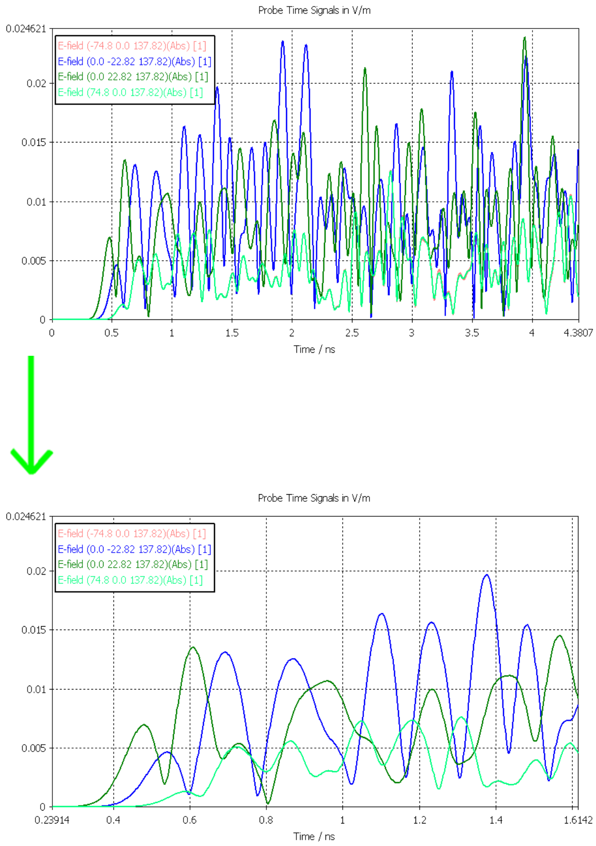

Fig. 8:The received time signals in probes

Fig. 9 shows a typical probe magnitude for S_1 at 0.12 ns rise time in dBV/m for 0-10 GHz.

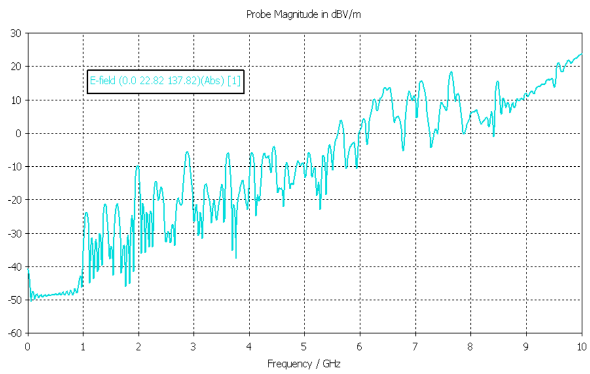

Fig. 9:typical probe magnitude for different frequencies in dBV/m

6. Conclusion

In this paper a novel approach is proposed to localize (detect) a PD source in a transformer. In the proposed method, a power transformer is simulated three dimensional scopes. The PD current source is localized with TDOA method is utilized to estimate PD position and the estimated position error is calculated. The proposed method is greatly helpful for developing on-line PD diagnostic detect in the real transformer.

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