Simulation of Transformer Oil Effect on PD Source Allocation

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Abstract- Ultra Wide Band (UWB) radio frequency 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. One of the first steps to study UWB method is simulating effect of environment on PD source allocation. In this paper, a three-dimensional simulation is performed using CST software and effect of transformer oil on the PD source allocation is simulated. According to the results, this software is helpful for simulation of PD source allocation and the transformer oil reduces PD source allocation error.

Keywords- CST software, PD location, TDOA, UWB, transformer oil.

I. INTRODUCTION

Power transformers play a major role in electricity distribution and transmission systems. Their reliability affects both the electric energy availability and economic operation of the utility. The power transformer's loss can be extremely expensive for the utilities. Therefore, online monitoring and preventive tests are frequently performed to predict the initial fault conditions [1-3]. The insulating system of a power transformer is a major 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 economic operation and safe, 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 insulation system deterioration that is caused by PD activity can be detected at an early stage. Because of the complex structure of the power transformer, accurate location of PD is difficult and is one of the challenges power utilities are faced with [7-10].

At present, acoustic and electrical methods have been employed to make PD source location in power transformers [11-14]. With the electrical method, it is difficult to make PD source location because of the structure difference 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 PD measurement international standard [15] and is a long-established principle. The PD source location employing electromagnetic signals that emitted from PD source is an attractive research field in the condition monitoring of power transformers for its high sensitivity and excellent noise-immune characteristics.

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 the PD pulses in time domain [16-17].

A three-dimensional simulation of PD allocation through CST software is proposed and performed in [14]. In this paper, the effect of transformer oil on the PD source allocation is simulated. According to the results, the transformer oil reduces PD source allocation error.

II. TIME DIFFERENCE OF ARRIVAL (TDOA)

Depending on sensors location regard to the signal source, sensors receives signals with different time delays. A signal time delays which are sensed by S_1, S_2, S_3 and S_4 are shown in Fig. 1 for a general case.

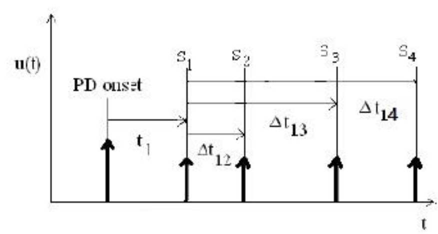


Fig. 1.Visualization of signal arrival times in reference to the unknown PD onset

The TDOA 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 Δt_{12}, Δt_{13} and Δt_{14} are the time delays and 'c' is the velocity of the signal in the medium,. 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 't_1' the PD onset instant and (x,y,z) of the source location.

III. PD Electromagnetic Signal Analysis

The practical measurement and theory analysis show that PD signals have very steep wave front [18]. A typical PD can be numerically simulated by Gauss function as follows [18]:

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

where 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, I_0 is amplitude 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.

The characteristic parameter σ of PD pulse current can help us to understand the PD state. The current frequency components can be obtained by taking the Fourier transform from (5).

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

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

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

The power spectrum density of the radiating signal is written as (9):

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

From (9), we can deduce that the peak value of $P(\omega)$ is at ω=1/σ. For example, 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.

IV. Case Study

The electromagnetic field analysis is based on the Maxwell equations. For this purpose, CST software utilized which is capable to solve transient electromagnetic field in both time and frequency domains using the finite integral technique (FIT). This technique breaks the solution space into small spaces with mesh grading and then solves it [19]. It is known that detecting UWB signals is a practical method for power transformers monitoring, but due to the limitations of hardware and software, simulation of such a structure is not possible. Therefore, the dimensions are multiplied by 0.2. The dimensions of simulated transformer are extracted from [18] and are shown in Table 1. For simplifying 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 without oil in CST software in different directions.

The single-phase transformer is in air condition and the background material of the simulation is set to normal type that mue and epsilon are set to 1.0. The boundary 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. Open Add Space is same as Open, but adds some extra space for far field calculation. This option is recommended for antenna problems.

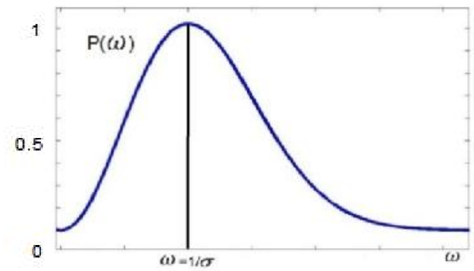


Fig. 2. The function of power spectrum density (normalized)

Table I. 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 material between H.V. and L.V. and between H.V. windings	paper
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
Epsilon of oil	2.33

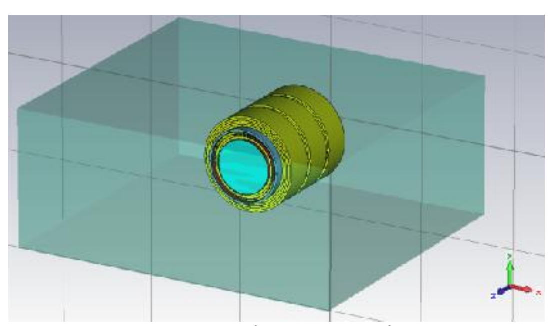


Fig. 3. Schema of simulated transformer

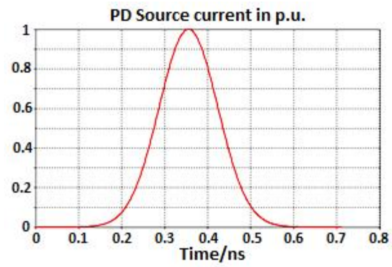


Fig. 4. PD source current (normalized) [14]

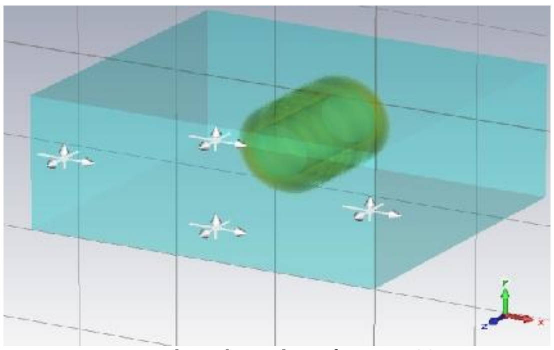


Fig. 5. The probes and transformer in CST

V. Simulation Results

For simulation of PD current in CST software, a discrete port is used as a PD source that its amplitude is 5mA. A typical PD waveform is depicted in Fig. 4.

The simulation is in time domain and for frequency between 0 GHz to 10 GHz. The PD source is located at (0,21.75,78.4) between third and fourth H.V. windings. For detecting 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) and S_4(-74.8,0,137.82). The transformer and probes are illustrated in Fig. 5.

Each probe has three signals in three dimensions. The received signals in three dimensions for first antenna (S_1) and the absolute received signals in the four probes are shown in Fig. 6 and Fig. 7, respectively, in the case of no oil. The time delays between first peak of the received signals of the probes can be found from Fig. 7 (Δt_{12}, Δt_{13} and Δt_{14}). c and (x_i, y_i, z_i) are light velocity in environment (oil or air) and antennas position. Therefore based on (1)-(4), the calculated results for the PD source position and its errors with/without transformer oil are given in Table 2. The light velocity in transformer oil condition is assumed 237 km/s.

As it can be found from table 2 and Fig. 6, S_3 and S_4 are symmetrical to port and their results are same. Worst result is for S_3 and S_4, because the direct path between these probes and PD source is the longest.

The direct path between PD source and antennas has different materials. In addition, the velocity of light in oil is less than no oil condition. So undesirable signals are attenuated more than no oil condition and as shown in table 2, transformer oil lead to decrease PD source allocation error.

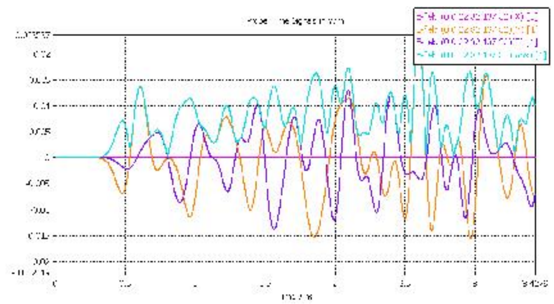
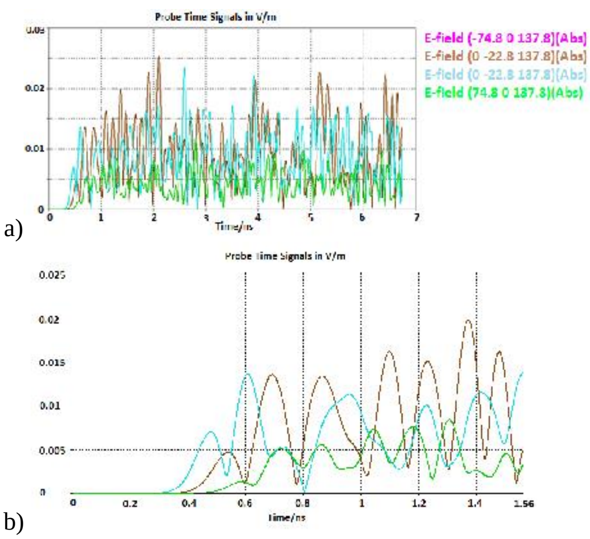


Fig. 6. The received time signals for S_1



a)

b)

Fig. 7. The received time signals in probes
a) time signals from 0 to 7 ns
b) magnified time signals from 0 to 1.56 ns

Table II. Simulation results and PD location estimations

	Time delays (ns)			***calculated PD position error (mm)***	***Calculated PD estimated position***
	Δt_{12}	Δt_{13}	Δt_{14}		
With transformer oil	0.08544	0.17223	0.17223	8.9041	(0,30.58,79.53)
Without transformer oil	0.06009	0.10743	0.10743	14.9065	(0,36.55,80.17)

VI. 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 in three-dimensional scopes. The PD current source with/without transformer oil is localized through TDOA method and the effect of transformer oil is studied. As it is shown in the results, the accuracy of estimated PD position is improved by simulation of the transformer oil in this modeling. This method is greatly helpful to develop an on-line PD diagnostic method, in a real transformer.

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