Applied Mechanics and Materials Vols 448-453 (2014) pp 2278-2285 *Online: 2013-10-31*
doi:10.4028/www.scientific.net/AMM.448-453.2278

FEM Simulation of PD Acoustic Signal Propagation in Transformers

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Keywords: transformers, partial discharge, ultrasonic wave, propagation property, FEM, numerical calculation

Abstract. In order to study propagation process of partial discharge ultrasonic signal in power transformer, the finite element method is used for simulation modeling and calculation. Ultrasonic waves can be activated by partial discharges (PD) in power transformers. The ultrasonic method is used for evaluating the insulation condition of power transformers by analyzing the partial discharge signals information which is detected by AE sensors. Compared with other diagnostic methods the AE method causes relatively low disturbance, and measuring apparatus is simple and easy to use. This technique is noninvasive and immune to electromagnetic noise. Simulate partial discharge sources of different positions respectively. Achieved results indicate that the space and time distributions of the acoustic pressure depend on the induction position. Furthermore, a greater pressure gradient is observed in domains with higher speed of sound while the signal amplitude decays when it moves away from the PD source.

Introduction

PD measuring and positioning is of key importance to the maintenance and the evaluation of service life to risk. The ultrasonic method detecting PDs depends greatly on the estimation of PD source location, so the research on acoustic signal path is very important. Many academics studied on this topic, among whom A. O. Akumu, etc. created a simplified transformer model, researched on the PDs in the model, then verified the mathematical model with physical experiments. The analysis result was fine [1-3]. Based on previous studies, the partial differential equations describing wave propagation are solved by means of finite element method. A simplified 3D transformer model was established. Further simulation was conducted over the model.

Introduction to the Finite Element Method (FEM)

Time domain finite element method is a numerical algorithm seeking solution in the time domain. The FEM algorithm seeking solution for sound field problems is finite element discretization based on the standard acoustic wave equations. It partitions the solution area into a combination of finite elements and presents an approximate solution to each element, then combines all the elements into a system similar to the original system according to the standard method. The problem is then converted to a system of partial differential equations for solution utilizing the variational principle. The earliest numerical simulation method is Finite Difference Time Domain (FDTD) method. But in comparison with FEM, FDTD has limited properties that are impossible to be overcome:

FDTD cannot deal with geometries with complicated shapes nor boundary problems of different materials. More memory is needed than the FEM. On the numerical calculation aspect, FDTD cannot deal with high order approximations, especially multi-dimensional problems. The approximate solutions of each grid element are of low quality, which lead to unsatisfactory calculation precision. FEM is not only of high precision, but also capable of adopting to all kinds of complicated shapes and coping with complicated boundary conditions. FEM is thus more suitable for solving systems of partial differential equations in numerical analysis.

In-Transformer Ultrasonic Wave Propagation Model for Simulation

The volume of the simplified transformer model shown in Fig. 1 is 2.6m x1.2m x 1.5m. The model is filled with transformer oil and 3 cylinder transformer iron coils, numbered 1, 2 and 3 from left to right, with windings placed in the center of the model. A pedestal is installed to each end of the coils and windings. The material of the coils and pedestals is constructional steel, whose density is 7850 kg/m3 and in which the sonic velocity is 5100 m/s. The material of the windings is copper, whose density is 8700 kg/m3 and in which the sonic velocity is 4760 m/s. Transformer oil's density is 890 kg/m3 and the sonic velocity in it is 1390 m/s.

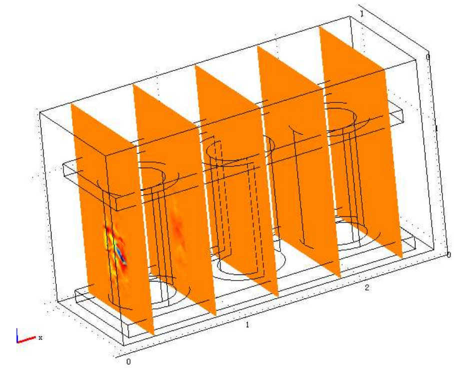


Fig. 1 Simplified Transformer Model

To study the path of propagation and changing process of PDs inside the transformer model, PD sources are placed at different positions inside the coils and windings for simulation. A PD can be seen as a point-type acoustic source, hence the ultrasonic pulse propagates with the wave front in a form of spherical wave. The spherical wave intensity is inversely proportional to the area of wave front, in other words, it is inversely proportional to the square of the distance to the acoustic source[4]. The simulated PD source is given by equation (1):

$$Q(t)=\frac{1}{1+e^{-a(t-b)}}e^{-(t-b)f}\sin((2\pi f(t-b)+\varphi) \tag{1}$$

where a is a dimensionless pulse width ratio, which is 1×108；b is the time offset, which is 3×106; f is the frequency, which is 1 MHz. φ is the supplementary ratio of the mean. The PD supersonic signal in the simulation is shown in Fig. 2.

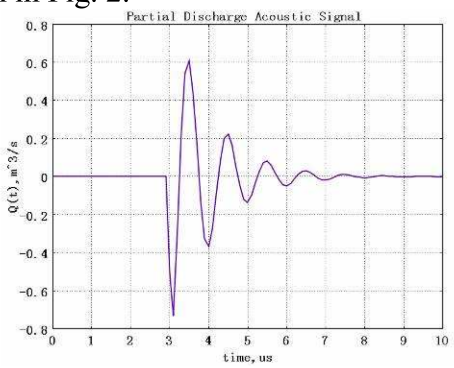


Fig.2 Supersonic Signal of Partial Discharges

This mathematical modal did not take any hydrodynamic or any other acoustic physical problem into consideration. So the flow ability, heat conduction characteristics and electromagnetic field coupling characteristics are not considered either. Besides, we suppose that the mediums are lossless, so the supersonic wave will not attenuate in the coils, windings and transformer oil. As for the configuration of boundary conditions, the outer boundary is firstly set. The transformer's shell is supposed to be an "absolute soft boundary", i.e. the sound pressure p is zero. Then the inner boundaries, the contact surfaces of oil, windings and coils are supposed to be continuous.

The numerical calculation of the sound pressure p in the model is seriously performed according to the partial differential equation

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \qquad (2)$$

In the formulac is the propagation velocity of sound waves inside the medium; the effective value of the sound pressure p is a function of space and time. This equation is a simultaneous system of 3 basic equations describing continuity, conservation of momentum and medium elasticity. For better displaying the process when the sound pressure changes, sound pressure level L[dB] is used instead of sound pressure p for graphic display. Calculation of the sound level is shown in equation (3)

$$L = 20\log(p / p_0) \qquad (3)$$

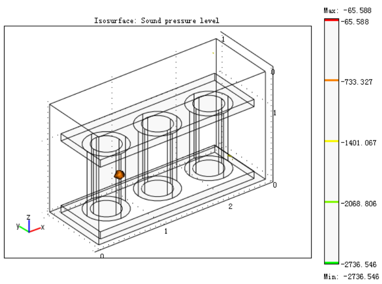
where p stands for the effective value of the sound value, whose unit is Pa. p_0 means the reference sound pressure, which is 20μPa by default.

In the simulation, COMSOL is used for transformer model PD simulation on a dual core 2680 MHz Intel Pentium D805 computer with 1GB RAM. CPU time used was 2696 seconds. Since matrix inversion need to consume a lot of CPU time and computer memory, GMRES (Generalized Minimal Residual Method) linear iterative solver is used with geometric multigrid preprocessor for solution under transient analysis mode. The divided mesh grid was composed of 10765 tetrahedrons, the smallest of which is only 0.2915 in size.

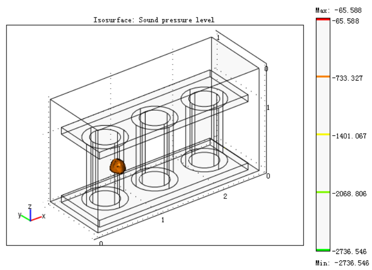
Simulation Result and Analysis

In order to research on the effect of different PD source location on signal propagation characteristics, simulations were performed. The sound pressure's spatial and temporal distribution was studied by varyingstimulating source and observation positions.

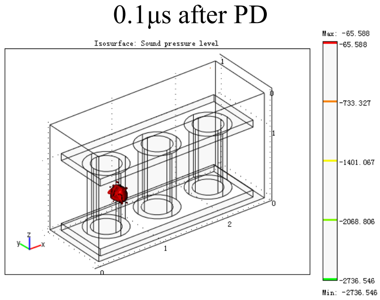
Spatial Distribution of the Sound Pressure. In the simulation, a PD source was placed in a transformer coil and then the middle of the windings. Due to that the results of spatial changes of in-coil PD and in-winding PD are similar, here only the in-winding PD simulation is taken as an example. Fig. 3 shows the spatial distribution of the sound pressure level L caused by in-winding PD in the first 6μs.



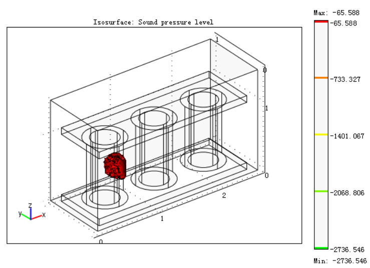
(a) Spatial Distribution of Sound Pressure Level L 0.1μs after PD



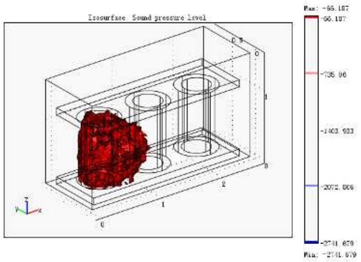
(b) Spatial Distribution of Sound Pressure Level L 0.2μs after PD



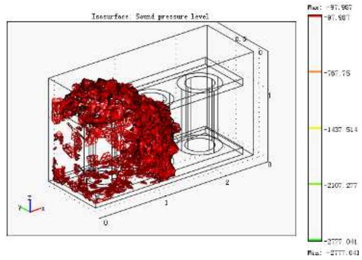
(c) Spatial Distribution of Sound Pressure Level L 0.3μs after PD



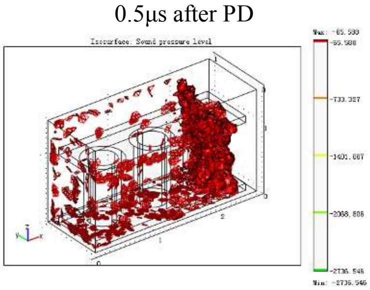
(d) Spatial Distribution of Sound Pressure Level L 0.4μs after PD



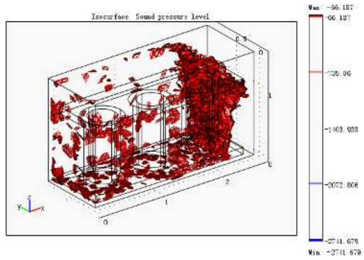
(e) Spatial Distribution of Sound Pressure Level L 0.5μs after PD



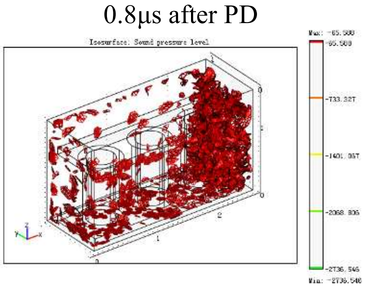
(f) Spatial Distribution of Sound Pressure Level L 0.6μs after PD



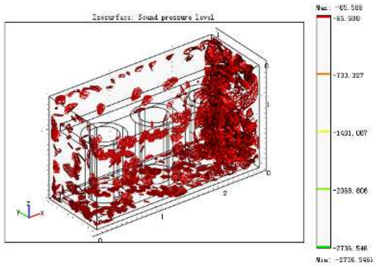
(g) Spatial Distribution of Sound Pressure Level L 0.8μs after PD



(h) Spatial Distribution of Sound Pressure Level L 1μs after PD



(i) Spatial Distribution of Sound Pressure Level L 3μs after PD



(j) Spatial Distribution of Sound Pressure Level L 6μs after PD

Fig. 3 Spatial Distribution of Sound Pressure Level *L* within 6μs after PD

It is obvious in the changing process of the isobaric surface of the sound pressure that the sound pressure distribution inside the transformer has changed rapidly within 1 μs after the PD, while the change was no longer apparent after 1 μs. Meanwhile, it can be found that inside the transformer coils and windings the sound pressure change was steeper than in oil, where the velocity of sound propagation is only 1/4 ~ 1/3 of that in the coils and windings. It is thus known that the faster the sound propagates in a medium, the steeper the sound pressure change gradient is. Besides, it can be seen in Fig. (a) ~ (f) that PD acoustic explosion propagats in the form of spherical wave front [4]. It is consistent with theories.

Temporal Distribution of the Sound Pressure. Fig. 4 is showing a transformer, in which there are 3 points A1(0.9,0.5,0.5), A2(0.9,0.3,0.5) and A3(0.9,0.1,0.5) with common x=0.9. Their distances to the PD source S(0.5,0.5,0.5) located at the center of a coil satisfy d1<d2<d3. Simulation observation point is shown in Figure 4.

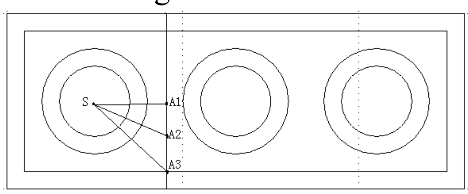


Fig. 4 Sectional View of Model and the Observation Point

Sound pressure signals at each observation points are shown as Fig. 5. It is clear in the figure that due to d1<d2<d3, at every moment the sound pressures satisfy A1>A2>A3, so the attenuation of the signal's amplitude increases with the propagated distance.

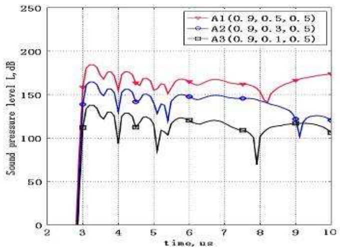


Fig. 5 Sound Pressure Signal at Each Observation Points

In the coil-winding structure of transformer 1, the PD source is moved from the center of the coil to the middle of the winding. Fig. 6 and 7 have respectively shown the sound pressures of 4 points inside the tank with common x=1.3m under two kinds of partial discharge source location.

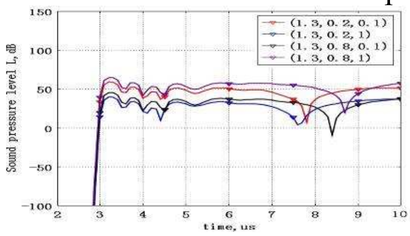


Fig. 6 Sound Pressures of 4 Points with x=1.3 when PD Source in Center of Coil

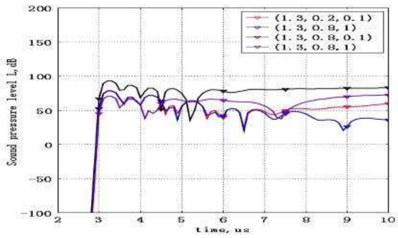


Fig. 7 Sound Pressures of 4 Points with x=1.3 when PD Source in Middle of Winding

Because that the partial discharge starts at approximately 3μs, it is easily observed that within 1μs after 3μs, sound pressure amplitudes had gone through a process of increase, decrease, increase again and then decrease again. But there was no clear pattern after 4μs. Meanwhile, the average of signal amplitude in Fig. 6 is 30dB smaller than that in Fig. 7. It is because that the signal spread from the coil into the winding that the propagation path was increased. Besides, the transformer's coil-winding structure has a relatively big effect on sound wave propagation characteristics.

To further study the effects the PD position on the signal propagation characteristics, the PD source's position was changed in the following simulations: PD sources PD1, PD2 and PD3 were placed at the center of coils number 1, 2 and 3, respectively. 10 observation points B1 ~ B10 were set up where x = 2.5m. The coordinates of them are: B1(2.5,0.1,0.5), B2(2.5,0.2,0.5), B3(2.5,0.3,0.5), B4(2.5,0.4,0.5), B5(2.5,0.5,0.5), B6(2.5,0.6,0.5), B7(2.5,0.7,0.5), B8(2.5,0.8,0.5), B9(2.5,0.9,0.5) and B10(2.5,1.0,0.5). A vertical section is shown as Fig. 8.

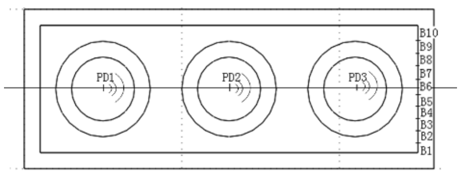


Fig. 8 Vertical View of PD Source and Observation Point Positions

Table 1 shows maximum and statistical average values at the observation points of sound pressures caused by PD sources at 3 different positions.

Table 1. Sound Pressures of Different Observation Points and PD Sources

	Maximum, Average Analysis		
	PD1	PD2	PD3
B1	-59.6,-72.3	-7.7,-20.5	111.2,98.4
B2	-58.1,-67.6	-3.2,-12.7	128.6,115.3
B3	-48.9,-62.5	7.4,-1.9	133.9,119.8
B4	-51.2,-65.7	4.0,-6.6	130.5,120.0
B5	-59.8,-71.8	-4.3,-17.9	133.3,120.5
B6	-66.1,-79.8	-12.1,-21.0	135.4,122.4
B7	-74.0,-84.8	-5.7,-14.4	135.8,125.8
B8	-76.6,-89.5	11.6,-1.5	127.7,114.0
B9	-70.7,-84.8	12.1,-0.5	120.6,108.3
B10	-62.6,-76.9	18.0,6.2	113.6,101.6

From the signal amplitude maximum value and the time average value given in Table 1, the attenuation status with the signal propagation distance is clear. From the horizontal variation of the values, we can see that for one observation point, for PD sources 1 to 3 the maximum values and RMS values have increased. It indicates that the closer the PD source is to the observation point, the larger the received signal amplitude is. From the vertical variation of the values in column 3, Because B6 and B7 are at each side of the center line, the maximum values and RMS values reached their peaks, and decrease progressively to the sides. This indicates that for the same PD source, the closer the observation point is to the PD source, the larger the received signal amplitude is. The vertical values of PD1 and PD2 is incomparable due to the complexity of sound propagation path. In addition, the PD signal's temporal variation at the observation point where x=2.5m during the simulation is shown as Fig. 9. Due to space reasons, only the PD in coil 2 is taken as an example.

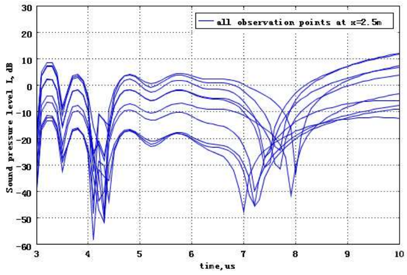


Fig. 9 Signals of PD in Coil 2 at Observation Points at x=2.5m

3.3 Sound Pressure Distribution in Different Directions

The projected view of PD sound wave propagation on xy direction at 3μs and 5μs are shown as Fig. 10 and 11. It can be seen from the figures that with the process the sound wave started from the center of the coil, passed through the winding, then transformer oil, into the transformer tank, the color has turned from red to yellow, then light green and finally blue. It means that the sound pressure value was decreasing. Meanwhile, by comparing the changes in coil 1 in Fig. 6 and Fig. 7, we can see that with the flow of time, PD source started from the coil center, where the sound pressure amplitude was its maximum (shown in darkest red), then the color spread, which means that the PD sound explosion was extending in the area.

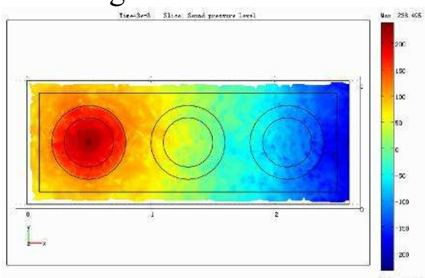


Fig. 10 Projected View of Sound Propagation at 3μs on xy Direction

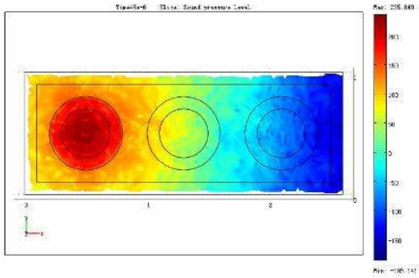


Fig. 11 Projected View of Sound Propagation at 3μs on xy Direction

Fig. 12~14 are the PD sound propagation views at 3 μs on surfaces xy, xz and yz, respectively. The sound pressure distributions in the transformer from different views in x, y and z directions are given. It is even more obvious from the gradual changes of the color, with the sound's propagation in coils, windings and transformer oil, the sound pressure amplitude experienced different attenuation with the increase of propagation distance due to the differences of propagation paths.

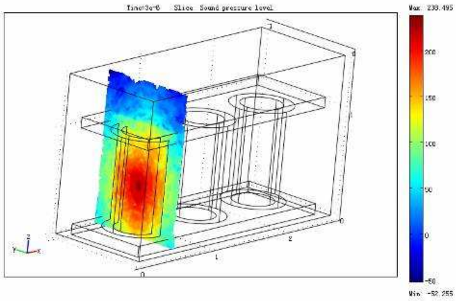


Fig. 12 3D View of PD Sound Propagation on yz Surface at 3μs

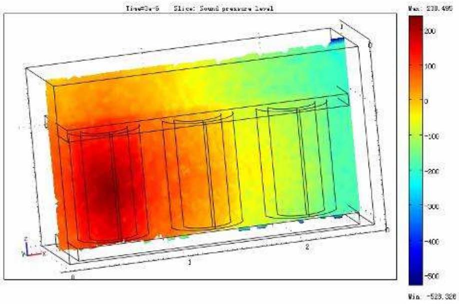


Fig. 13 3D View of PD Sound Propagation on xz Surface at 3μs

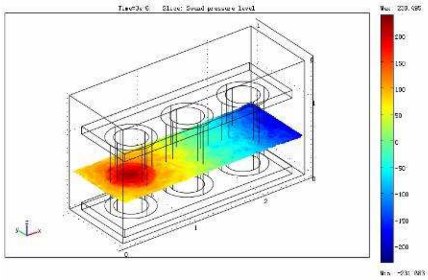


Fig. 14 3D View of PD Sound Propagation on xy Surface at 3μs

Conclusion

1) By numerically calculating wave equation utilizing FEM software COMSOL Multiphysics, the transient distribution of sound pressure at different coordinates in a transformer can be analyzed. Coil and winding structures of the transformer greatly affects sound signals' propagation characteristics.

2) Sound pressure, caused by PDs, at different time has different spatial distribution. The greater the sound velocity, the greater the sound pressure variation gratitude.

3) According to the extent of signal amplitude attenuation at different observation points, the farther the point is from the PD source, the greater the sound pressure attenuation. Meanwhile, for a same observation position, the longer the path of signal propagation, the more severe the signal amplitude attenuation.

4) For further studies, more complicated transformer model should be considered, as well as sound wave attenuation in different mediums. In addition, the effects that kinetics and other physical phenomena have on sound wave propagation characteristics should be taken into consideration.

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10.4028/www.scientific.net/AMM.448-453

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10.4028/www.scientific.net/AMM.448-453.2278