Abstract—Transformers are one of the most important and costly components of any power system. Proper monitoring of the health of a transformer is thus indispensable. Online monitoring of partial discharges (PD) is one of the ways by which the risk of catastrophic failure of a power apparatus can be reduced. The acoustic emission method for PD measurement has numerous decisive advantages over the electrical measurement method. The acoustically emitted (AE) waves due to PD tend to propagate along various paths before being detected by the sensors. This paper analyses the results obtained from theoretical analysis of various propagation paths. It also analyses the experimental signals by applying various filtering techniques. A correlation between the theoretical and experimental results is thus established. Hence, by applying filtering techniques, it is possible to ascertain the peaks of the direct path and indirect path AE signals respectively and this can significantly reduce the error during the application of the PD source location algorithms, as more accurate time difference is now available. In the system under consideration, acoustically emitted signal produced by the PD are detected by the sensors mounted on the tank surface, stored on an oscilloscope and fed to a computer for analysis. For the theoretical analysis, the physical properties & features, of the transformer tank metal (steel) and the transformer oil are taken into consideration.

Index Terms—Acoustic Emission (AE), Digital Filter, Partial Discharge (PD), Propagation path.

I. INTRODUCTION

The deterioration of the insulation of any power apparatus depends upon many factors such as moisture content, temperature, partial discharges etc. Partial discharge is basically an electrical phenomenon that occurs within a transformer, whenever the electric stress is sufficient to produce ionisation and partially bridges the insulation between conductors. Although the magnitude of such discharges is usually small, they cause progressive deterioration and may lead to ultimate failure [1]. Thus, it is evident that online monitoring of the partial discharges occurring in a transformer is of utmost importance, as it can help us reduce the risk of a failure.

Different types of partial discharges are produced depending on the origin or the location and all of these produce acoustic pulses. These acoustic pulses are sensed by the acoustic sensors. Acoustic methods of PD measurement are more advantageous than the electrical methods as they are non-invasive and immune to the electromagnetic noise and interference, their sensitivity does not vary with object capacitance and they can often provide an indication of PD source location within a complex system [2]. In order to theoretically determine the time difference between direct path AE signals and indirect path AE signals, the path of shortest time needs to be computed. This is done, acknowledging the fact, that during the indirect mode of propagation, the AE signals can hit any one of the five tank surfaces (top of the tank is open) and reach the sensor. Thus, general equations for propagation through indirect paths are derived, using which the indirect path propagation time is computed. By comparing the time taken in each path of propagation, to reach the specified sensor location, the indirect path of shortest time for AE signal is determined. The output signatures obtained from the acoustic sensors are stored on a digital storage oscilloscope and are subsequently fed to the computer for the analysis. Analysis of these signatures gives the time difference between the direct path AE signals and the indirect path AE signals. It is also known that while employing the PD source location algorithm, majority of the errors are induced, because the peaks of some of the indirect path AE signals with significant contribution are mistakenly considered as the peaks of the direct path AE signals. Thus this paper also aims at reducing this ambiguity by filtering the signatures in order to conclusively determine the points, where the direct path and the indirect path AE signals appear in the signature.

II. EXPERIMENTAL SETUP

As it is desired to sense the acoustic pulses produced as a result of partial discharge, acoustic sensors are employed. These acoustic sensors are mounted on the outer surface of the transformer tank. The size of the transformer and the perceptible limit of the acoustic sensor determine the maximum propagation distance. For the above experimental purpose a transformer tank of 60 cm X 60 cm X 60 cm is used [3]. This transformer tank is made up of steel. The schematic diagram given in fig. 1 gives the specifications and components present inside the tank.

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Apart from the model experimental tank with acoustic sensors mounted on it, there are other constituents like the voltage source, control unit and the recording device (digital storage oscilloscope) which constitute the whole experimental setup (Fig. 2).

III. THEORY

A. Direct path

It is defined as the path in which the acoustic signals travel along a direct, straight line route from the source to the sensor (Fig. 3). Direct path mainly comprises of the distance traveled in the oil and a relatively very small distance traveled in the tank metal (waves have to travel through the thickness of the metal (0.5 cm) to reach the acoustic sensor mounted on the outer surface of the tank) [4]. The AE waves travels as spherical waves in oil. In a lossless medium, the intensity of a spherical wave decreases inversely to the area of the wave front (i.e., inversely proportional to the distance from the source squared) [2][5]. From the experimental results, it is found that in most of the cases the time taken by the direct path AE signals to reach the sensors is more than the time taken by the indirect path AE signals which can be understood from the fact that the speed of the waves travelling in transformer oil (1415 m/s) [2] is less than one-fourth of the speed of the waves travelling in transformer tank metal or steel (5900 m/s) [2]. However, it should be noted that the contribution of the direct path AE signals in the output signature obtained from the acoustic sensors, is considerably larger than the indirect path AE signals because the attenuation of the AE signal in the oil path is relatively less (Table I) [5][6].

B. Indirect Paths

It can be seen from the Fig. 3 that the acoustic waves hitting the nearby tank wall create an alternate propagation path via the tank walls to the sensor. As the acoustic wave hits the tank wall, its frequency characteristics remain the same [4], but its mode of propagation and propagation speed change. Indirect path comprises of the structure-borne path as well as the path travelled in the oil [4]. In majority of the cases the structure borne path is larger than the oil borne path. As the speed of the wave in the tank metal is greater than that in oil, the wave travelling along the structure-borne path arrives at the sensor earlier than the wave travelling along the direct acoustic path in most of the cases. It is also important to note that the attenuation of the AE signals in the metal is larger than in transformer oil (TABLE I) and therefore the intensity of the wave travelling along the indirect path is lesser than the waves travelling along the direct path. Thus, it is evident that the contribution of the indirect path AE signals in the output signature obtained is of small proportion.

### TABLE I

<table>
<thead>
<tr>
<th>Medium</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>0.02 dB/m</td>
</tr>
<tr>
<td>Steel</td>
<td>0.215 dB/m</td>
</tr>
</tbody>
</table>

C. Transmission coefficient

The transmission coefficient between any two media is determined by the difference in acoustic impedance for the two media.

\[
\alpha_{transmission} = \frac{I_2}{I_1} = 4 \frac{\left( Z_1 \cdot Z_2 \right)}{\left( Z_1 + Z_2 \right)^2}
\]

\(Z_1=\)Acoustic Impedance of oil
\(Z_2=\)Acoustic Impedance of steel

The above formula implies that for large differences in acoustic impedance, only a fraction of the incident wave is transmitted across the interface. The transmission coefficient, \(\alpha\), is defined in terms of the intensity in the two media [2],[6].
Magnitude of transmission coefficient = $\alpha_t = 0.1068$ [2]
Incident medium = Oil
Transmitted medium = Steel (transformer tank).

IV. THEORETICAL CALCULATIONS

A. For direct path
To calculate the time taken by the direct path AE signals the distance travelled by the AE signals in the oil needs to be calculated. The distance travelled in the metal is actually the thickness of the metals (5 mm) which can be neglected.

If the coordinates of the sensor are $(x_s, y_s, z_s)$, the coordinates of the PD source are $(x_1, y_1, z_1)$ and the direct path distance is $dd$; then, from Fig. 4 it is seen that the direct path distance between the sensor and the source of PD is given by

$$dd = \sqrt{(x_s - x_1)^2 + (y_s - y_1)^2 + (z_s - z_1)^2} \text{ cm} \quad (2)$$

Now the time taken by the shortest path AE signals is given by

$$\text{Time taken}, \quad T_{\text{direct}} = \frac{dd}{141500} \text{ s} \quad (3)$$

Where the velocity of the wave in the oil= 141500 cm/s.

![Fig. 4: Illustration of one of the direct paths.](image)

B. For indirect path
To determine the shortest time path for indirect path AE signals it should be understood that the signals can impinge on any one of the tank surfaces and follow the structure borne path as shown in Fig. 5. Thus, five general equations are written with the sensor location known and the coordinate of the z-axis fixed. Now, if the coordinates of the sensor are $(60 \text{ cm}, 30 \text{ cm}, 48 \text{ cm})$ and the coordinates of the PD source are $(x, 30 \text{ cm}, z)$ then, the general equations to determine the path for shortest time are given by Equation Set 1, which consists of 4(a), 4(b), 4(c), 4(d) and 4(e).

**Equation Set 1.**

$$T_1 = (x/141500) + \left(\frac{(180 - y)}{590000}\right) s \quad 4(a)$$
$$T_2 = (y/141500) + \left(\frac{(132 - x)}{590000}\right) s \quad 4(b)$$
$$T_3 = ((60-x)/141500) + \left(\frac{(72 - y)}{590000}\right) s \quad 4(c)$$
$$T_4 = \left(\frac{[(60 - y)/141500] + \left(\frac{\sqrt{(48-x)^2}}{590000}\right)}{s} \quad 4(d)
$$
$$T_5 = \left(30/141500\right) + \left(\frac{(60-x)+\sqrt{(48-y)^2 + (30)^2}}{590000}\right) s \quad 4(e)$$

After the computation of $T_1, T_2, T_3, T_4$ and $T_5$ for a specified coordinate, the smallest value among them is taken as the path for shortest time. The shortest distance need not necessarily be the path for shortest time. This process of computation is repeated by varying x-axis and y-axis from 0 to 60 cm in steps of 2 cm.

In order to calculate indirect path for shortest time, for variation along all the three axes, equation set 2 has been deduced. Again the path for shortest time is computed using the equation set 2 which consists of 5(a), 5(b), 5(c), 5(d), 5(e), 5(f) and 5(g).

If the coordinates of the sensor is $(x_s, y_s, z_s)$ and the coordinates of the PD be $(x_1, y_1, z_1)$, then

**Equation Set 2**

*For Path 1*

For path 1 there will be three different routes to reach the sensor, as shown in Fig. 6(a).

$$T_1 = (y_1/141500) + \left(\frac{x_1 + 60 + \sqrt{(z_1 - z_1)^2 + (x_1 - y_1)^2}}{590000}\right) s \quad 5(a)$$
$$T_2 = (y_1/141500) + \left(\frac{60 - x_1 + 60 + \sqrt{(z_1 - z_1)^2 + (60 - x_1)^2}}{590000}\right) s \quad 5(b)$$
$$T_3 = (y_1/141500) + \left(\frac{z_1 + 60 + \sqrt{(z_1)^2 + (x_1 - x_1)^2}}{590000}\right) s \quad 5(c)$$

*For Path 2*

For, Path 2

$$T_4 = (x_1/141500) + \left(\frac{60 - y_1 + \sqrt{(x_1)^2 + (z_1 - z_1)^2}}{590000}\right) s \quad 5(d)$$

*For, Path 3*

For, Path 3

$$T_5 = ((60 - y_1)/141500) + \left(\frac{\sqrt{(z_1 - z_1)^2 + (x_1 - x_1)^2}}{590000}\right) s \quad 5(e)$$

*For, Path 4*

For, Path 4

$$T_6 = ((60 - x_1)/141500) + \left(\frac{60 - y_1 + \sqrt{(z_1 - z_1)^2 + (60 - x_1)^2}}{590000}\right) s \quad 5(f)$$

*For Path 5*

For Path 5

$$T_7 = (z_1/141500) + \left(\frac{60 - y_1 + \sqrt{(z_1)^2 + (x_1 - x_1)^2}}{590000}\right) s \quad 5(g)$$

C. Method of rotation of planes

For taking into consideration, the diagonal paths which the AE signals can traverse in the structure borne path and thereby improve the accuracy of the results, the method of rotating the planes is applied. Here, the sensor is brought to the same plane as that of the face of the tank which is
hit by the AE signal. Then the distance between the points along that plane is found. If the sensor coordinates are \((x_s, y_s, z_s)\) and the PD source coordinates are \((x_1, y_1, z_1)\) then, it can be seen from the figures 6(a), 6(b) and 6(c) that the sensor and the point on the transformer wall which is hit by the AE signal while propagating through the path of the shortest time, lie on the same plane after rotating. Thus the shortest path travelled in steel is, the distance between those two points on that plane which in this case is given by

\[ d_{13} = \sqrt{(y_1 + 60 + y_s)^2 + (z_1 - z_s)^2} \text{ cm} \quad (6) \]

**Equation Set 3**

**For path 1**

\[ T_1 = \left( y_1/141500 \right) + \left( \sqrt{(x_1 - (60 - x_s))^2 + (z_1 - z_s)^2} / 590000 \right) \text{ s} \quad (7a) \]

\[ T_2 = \left( y_1/141500 \right) + \left( \sqrt{(z_1 - z_s)^2 + (x_1 + x_s + 60)^2} / 590000 \right) \text{ s} \quad (7b) \]

\[ T_3 = \left( y_1/141500 \right) + \left( \sqrt{(x_1 - x_s)^2 + (z_1 + z_s + 60)^2} / 590000 \right) \text{ s} \quad (7c) \]

**For path 2**

\[ T_4 = \left( (60 - y_1)/141500 \right) + \left( \sqrt{(x_1 - x_s)^2 + (z_1 - z_s)^2} / 590000 \right) \text{ s} \quad (7d) \]

**For path 3**

\[ T_5 = \left( (60 - z_1)/141500 \right) + \left( \sqrt{(y_1 - (60 + x_s))^2 + (z_1 - z_s)^2} / 590000 \right) \text{ s} \quad (7e) \]

**For path 4**

\[ T_6 = \left( (y_1 - 120 + x_s)/141500 \right) + \left( \sqrt{(x_1 - z_s)^2 + (z_1 - z_s)^2} / 590000 \right) \text{ s} \quad (7f) \]

**For path 5**

\[ T_i = \left( (60 - 120 + x_s)/141500 \right) + \left( \sqrt{(y_1 - 120 + x_s)^2 + (z_1 - z_s)^2} / 590000 \right) \text{ s} \quad (7g) \]

For \((z_1 = z_s)\), \((x_1 = x_s)\) and \(y_1 > 40\) computation should be done without considering 7(f). It should be noted that these equations give satisfactory results iff the plane opposite to the sensor is \(xz\)-plane and the coordinate axes are taken as shown in the Fig. 6(d) as the above equations are computed according to those coordinates. For any other orientation, the coordinates should be changed such that it is in accordance with the axis shown in the Fig. 6(d) in order to use these equations or alternatively the equations of rotation of planes can be modified and the desired results can be obtained.

Similarly, considering the other paths, the equations for shortest time along each path are given by Equation Set 3 which comprises of 7(a),7(b),7(c),7(d),7(e),7(f) and 7(g).

The acoustic sensor position is fixed at \((12 \text{ cm, } 60 \text{ cm, } 35 \text{ cm})\). The PD source is varied along \((x, y, z)\) coordinates and the corresponding indirect paths for shortest time are computed theoretically from equation sets 2 and 3. They are then tabulated in Table III. It is seen that distance obtained from equation set 3 are smaller in magnitude. Hence it is concluded that the equation set 3 give more accurate path for shortest time for the indirect AE signals as the diagonal paths that can possibly be traversed to reach the acoustic sensor are now taken into consideration. The acoustic sensor position is fixed at (48
cm, 60 cm, 30 cm). The PD source is varied and corresponding time and distances are computed analytically by following the methods mentioned in section IV and are tabulated in Table II. From Table III, it is clear that the results obtained by employing the method of rotation of planes are more accurate. In Table III, ID₁ & TD₁ represent the indirect path distance and the time difference obtained from equation set 2 whereas ID₂ & TD₂ represent the indirect path distance and the time difference obtained from equation set 3 respectively. Fig.7 displays a plot between direct distance between sensor and PD source point and the time difference between the direct and the indirect path. It has been verified that the plot obtained by theoretical calculation in this paper is analogous to the plot obtained by practical experimentation in literature [5].

<table>
<thead>
<tr>
<th>PD point (x₁,y₁,z₁)</th>
<th>Indirect path (m)</th>
<th>Direct path (m)</th>
<th>Indirect path time (s) *E-04</th>
<th>Direct path time (s) *E-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12,10,30)</td>
<td>1.1</td>
<td>0.616</td>
<td>2.51</td>
<td>4.35</td>
</tr>
<tr>
<td>(12,50,30)</td>
<td>0.46</td>
<td>0.373</td>
<td>1.32</td>
<td>2.64</td>
</tr>
<tr>
<td>(20,50,30)</td>
<td>0.38</td>
<td>0.297</td>
<td>1.18</td>
<td>2.10</td>
</tr>
<tr>
<td>(30,40,30)</td>
<td>0.38</td>
<td>0.269</td>
<td>1.72</td>
<td>1.90</td>
</tr>
<tr>
<td>(40,10,30)</td>
<td>1.02</td>
<td>0.506</td>
<td>2.27</td>
<td>3.58</td>
</tr>
<tr>
<td>(48,10,30)</td>
<td>0.74</td>
<td>0.500</td>
<td>1.90</td>
<td>3.53</td>
</tr>
<tr>
<td>(48,50,30)</td>
<td>0.34</td>
<td>0.100</td>
<td>1.22</td>
<td>0.707</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PD point</th>
<th>ID₁ (m)</th>
<th>TD₁ (sec)</th>
<th>ID₂ (m)</th>
<th>TD₂ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(48,10,10)</td>
<td>1.1021</td>
<td>2.29E-04</td>
<td>1.0231</td>
<td>2.43E-04</td>
</tr>
<tr>
<td>(48,10,20)</td>
<td>1.1229</td>
<td>1.93E-04</td>
<td>1.1114</td>
<td>1.95E-04</td>
</tr>
<tr>
<td>(48,20,10)</td>
<td>1.0021</td>
<td>1.96E-04</td>
<td>0.9319</td>
<td>2.08E-04</td>
</tr>
<tr>
<td>(48,30,10)</td>
<td>0.9021</td>
<td>1.69E-04</td>
<td>0.843</td>
<td>1.79E-04</td>
</tr>
<tr>
<td>(48,10,30)</td>
<td>1.1026</td>
<td>1.86E-04</td>
<td>1.1013</td>
<td>1.86E-04</td>
</tr>
<tr>
<td>(20,20,10)</td>
<td>0.9936</td>
<td>5.18E-05</td>
<td>0.9713</td>
<td>5.55E-05</td>
</tr>
<tr>
<td>(30,20,50)</td>
<td>0.9433</td>
<td>1.52E-04</td>
<td>0.8412</td>
<td>2.39E-05</td>
</tr>
<tr>
<td>(20,10,20)</td>
<td>1.0921</td>
<td>1.34E-04</td>
<td>1.0321</td>
<td>1.45E-04</td>
</tr>
<tr>
<td>(15,10,30)</td>
<td>0.7083</td>
<td>1.43E-04</td>
<td>0.772</td>
<td>1.44E-04</td>
</tr>
<tr>
<td>(20,40,30)</td>
<td>0.2943</td>
<td>-1.05E-06</td>
<td>0.2943</td>
<td>-1.05E-06</td>
</tr>
</tbody>
</table>

A typical signature of any AE signal recorded on the digital storage oscilloscope comprises of three major components, the noise, the direct path AE signals and the indirect path AE signals. Thus, there is a need to filter out some of the components present in the signature recorded in order to conclusively ascertain the respective peaks obtained from the direct path and various indirect path AE signals. This, in turn helps us to determine the time difference between the direct path and the shortest indirect path AE signal w.r.t a specific sensor experimentally. It is also known that the attenuation of the signal is less, when the signal propagates through the direct path, and thus the direct path can be easily perceived from the signature. It is seen that the highest peak corresponds to the instant of time at which the waves emitted due to the partial discharge reach the sensor. It should also be noted that peak of the indirect path cannot be distinctly distinguished from the direct path and other major components present in the signature by mere inspection, because of the fact that the intensity of the indirect path AE signal reduces by considerable proportion because of the relatively larger attenuation in steel as well as the overlapping of the various components of the waves in different zones of signal. Thus, to differentiate the indirect peak from the other overlapping components, the signature needs to be filtered so that the unwanted frequency components can be filtered out. As a result of this observation, various filters are designed and the signature is passed through these filters. After due analysis of these filtered signals, in some of the cases, it is possible to conclusively determine the peaks of the indirect path AE signal at various instants.

V. ANALYSIS OF EXPERIMENTAL SIGNALS

Experiments are conducted for a known location of PD source and four acoustic sensors are mounted on two faces of the transformer tank which record the AE pulses for further analysis. Sampling frequency of signal recording is kept at 1 MHz to get signal frequency upto 500 kHz [3]. A typical AE pulse and is shown in Fig. 8.
VI. RESULTS

Noise signal are separated from the original signal in the time domain. The frequency domain spectrums of these two signals are compared and filter is designed to eliminate the noise frequency from the original signal. In the frequency domain analysis, overlapping of the noise frequency spectrum and the frequency spectrum of the actual signal is seen, at a frequency greater than a particular frequency and this frequency is considered to be the cut off frequency while designing the filter. Further the beta parameter is adjusted taking into consideration the main lobe width and the height of the side lobes. Filters are designed using Kaiser’s Window technique [8] and the signature is passed through the various filters. The filtered signals are then critically analysed to ascertain the peaks of the direct path and indirect path AE signals and consequently the time difference. The results thus obtained are compared with the results obtained from the analytical method by tabulating them in the following manner. (Table IV)

<table>
<thead>
<tr>
<th>Sensor position (cm) (x1,y1,z1)</th>
<th>PD position (cm) (x2,y2,z2)</th>
<th>Experimental time-difference</th>
<th>Analytical time-difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12,10,30)</td>
<td>(12,60,30)</td>
<td>154.0 μs</td>
<td>163.47 μs</td>
</tr>
<tr>
<td>(12,10,30)</td>
<td>(48,0,30)</td>
<td>128.0 μs</td>
<td>184.5 μs</td>
</tr>
<tr>
<td>(12,10,30)</td>
<td>(48,60,30)</td>
<td>144.0 μs</td>
<td>132.3 μs</td>
</tr>
<tr>
<td>(12,10,30)</td>
<td>(12,0,30)</td>
<td>-48.0 μs</td>
<td>-51.422 μs</td>
</tr>
</tbody>
</table>

A negative time difference is obtained for channel 4 as the location of sensor is such that the direct path AE signals reach the acoustic sensors, before the indirect path AE signals. The filter type and its specification used for filtering the signals is shown in Table V

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Order</th>
<th>Cut off frequency</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pass</td>
<td>260</td>
<td>Fc=0.4961</td>
<td>12.03</td>
</tr>
</tbody>
</table>

Fc= cut off frequency, β= shape parameter

VII. CONCLUSIONS

This paper highlights the theoretical analysis of the acoustically emitted signals taking into consideration the physical properties of the wave and the different media. The paper also shows that the shortest time path for any mode of propagation can be theoretically determined by following a simple method such as rotating the planes. It is also clear from the filtered signatures that by filtering, the peaks of direct path and indirect path AE signals become prominent which in turn helps to obtain the time difference experimentally. As a result, a direct correlation between the experimentally obtained results and theoretically calculated results is manifested. Improved time differences obtained by using the filtering technique can be used in source location algorithm. It should be noted that the above analysis has been carried out for single source PDAE signal but it can be extended to multiple source PDAE signals by treating multiple source PDAE signals as superposition of various single source PDAE signals. Hence, further investigation is needed for multiple PD sources [9].

ACKNOWLEDGMENT

All the authors gratefully acknowledge the support of Indian Institute of Technology, Kharagpur. Prathamesh Dhole, Tanmoy Sinha and Sumeet Nayak also acknowledge the support of Prof. N. K. ROY who is with Department of Electrical Engineering, National Institute of Technology, Durgapur.

REFERENCES