Localisation of Single and Multiple Partial Discharge Sources based on Sequence of Arrival and Levels of Peak Amplitude of Acoustic Emissions

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***Abstract*— Partial Discharge (PD) is one of the most critical electrical phenomena affecting the life of electrical equipment. Repetitive PD can lead to gradual deterioration of the insulation, which may further lead to complete failure of the electrical insulation. Hence, detection and localization of PD inside electrical equipment is necessary for early detection of impending failure. Keeping this in mind, this paper proposes a methodology to localize single and multiple PD sources based on acoustic signals emanated from such sources. The localization has been done based on sequence of arrival and levels of peak amplitude of acoustic waves. The proposed approach makes use of a low complexity methodology for PD localization without the use of complex classification tools. The results show that this developed methodology is able to localize the single and multiple PD events with considerable accuracy.**

Keywords—Partial Discharge; Acoustic emission based partial discharge detection; sequence of arrival; levels of peak amplitudes.

I. Introduction

Partial Discharge (PD) phenomena is a localized electrical discharge within any insulation system, as applied in electrical apparatus, components or systems, that only partially links the insulation between conductors which may or may not occur adjacent to a conductor [1,2]. Generally partial discharges take place due to local electrical stress concentrations appearing within voids or bubbles inside the insulation or on the surface of the insulation. Every discharge event causes chemical transformations of many types due to impact of short-time avalanche of high energy electrons or accelerated ions. This in turn results into gradual deterioration of the material and may further lead to ultimate failure of the apparatus involved, if unchecked [1-4]. Hence presence of partial discharge in an apparatus is an indication to transpiring dielectric defects in the insulation of the apparatus. Early detection and localization of such discharges may prevent the impending apparatus outage and the resulting inconvenience or revenue loss.

There are several popular methods of PD detection such as - conventional method based on coupling capacitor [1,3] or UHF Radio waves emitted by PD sources [6], chemical methods [7], acoustic emissions (AE) [8-11,13], optical methods [12], or any combination of these alongwith modern classification tools [11]. Among these methods, the AE based monitoring of oil-filled equipments, such as transformers, possesses certain advantages such as less prone to electrical and electromagnetic interference, non-invasive to the equipment and provides better flexibility because the positions of sensors can be reconfigured as necessary to get clearer acoustic signals [5]. However, main disadvantage of externally mounted acoustic sensors is that they are more susceptible to mechanical noise.

The main contribution of the present work is the localization of single and multiple PD sources based on sequence of arrival and levels of peak amplitude of acoustic waves captured using strategically placed acoustic sensors. The proposed method offers a much simpler approach as compared to other computationally intensive methods such as estimation of time difference of arrival between different sensors followed by localisation employing triangulation [5] or localisation employing classification tools.

II. Experimental Test Setup

A. Partial Discharge Simulator (PDS) Tank

For PD data acquisition, a cubical steel box with insulated top lid has been constructed. This steel box emulates the metallic tank of any electrical equipment and has been labelled as Partial Discharge Simulator (PDS) tank. It has side length of 0.32 m or 32 cm. The details of the PDS tank has been schematically shown Figure 1.

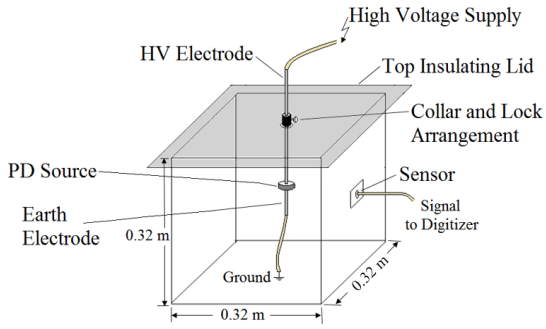

Fig. 1. Partial Discharge Simulator (PDS) Tank

The insulated top lid of the box has a hole through which the live conductor of High Voltage supply for the PD source is made to pass. A fixing collar and a lock arrangement hold this conductor tightly. The PDS tank has been filled with transformer oil.

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B. Partial Discharge Source

The PD source comprises of an acrylic disc having thickness of 3 mm and a diameter of 10 mm, placed between a set of brass made point-plane electrodes. The pointed top electrode is connected to HV supply and the bottom electrode is kept at earth potential by connecting a flexible copper wire as earth conductor. Figure 2 schematically shows the PD source with point-plane electrode system.

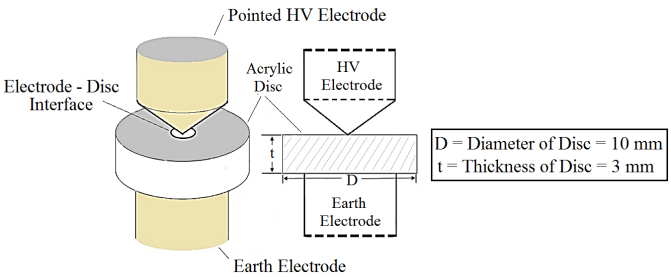

Fig. 2. Partial Discharge Source

The voltage applied to HV electrode was kept at 30 kV. The frequency of PD generated acoustic waves lie in the range of ultrasonic spectrum (20 kHz – 500 kHz).

C. Placement of PD source inside PDS Tank

The PD source has been placed inside the PDS tank at strategically chosen locations by maneuvering the HV electrode fixed with it. Once desired vertical and horizontal position is obtained, the HV electrode is fixed with the top insulating lid tightly by collar and lock arrangement. Figure 3 given below shows the nomenclature of marked locations for placement of PD source.

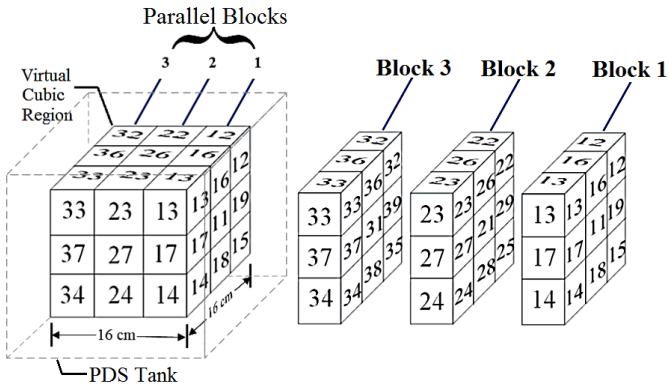

Fig. 3. Locations for placement of PD source inside PDS tank

The PD locations collectively form a virtual cubic region of 16 cm side and 8 cm apart from all the walls of the PDS tank. The cubic region has been subdivided into 27 small cubic sub-regions having equal volume and uniformly distributed into three parallel blocks, as shown in Figure 3. The small cubic sub-regions have been marked as follows – three parallel blocks have been numerically marked as 1, 2 and 3. Now the cubic sub-region at the middle of block 1 has been marked '11'. Next the corner sub-regions are progressively marked as '12', '13', '14' and '15'. Lastly the regions at the middles of the four sides have been progressively marked as '16', '17', '18' and '19'. Sub-regions in the blocks 2 and 3 have been marked similarly.

When a single PD source has been placed inside PDS tank, the event is termed as a Single Partial Discharge (SPD) event. On the other hand, to emulate multiple PD case, two such PD sources have been placed at two locations of the virtual cubic region and PD is made to occur simultaneously in both the locations. Such events are termed as Double Partial Discharge (DPD) events. In the present work, 27 SPD events and 20 DPD events have been considered. Also a well-defined notation system has been developed to identify the PD events. All the SPD and DPD events and their corresponding notations have been shown in Table 1. The notation for SPD events is same as the position of PD source at the corresponding grid point of Figure 3. For example, notation '11' denotes set of signals captured when the PD source is placed at location '11'. For DPD events, the notations are of the form '11_31', '11_32' etc. where notation '11_31' implies that two PD sources have been placed at locations '11' and '31' respectively and so on.

TABLE 1. PD EVENTS AND CORREPONDING NOTATIONS

Type of PD Event	PD locations or sub-regions and corresponding notations
SPD Events	11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39
DPD Events	11_31, 11_32, 11_37, 31_12, 31_17, 12_13, 12_14, 13_15, 15_14, 19_17, 22_23, 22_24, 23_25, 25_24, 29_27, 32_33, 32_34, 33_35, 35_34, 39_37

D. Placement of Acoustic Sensors

In order to detect the acoustic signals from the PD source, five acoustic sensors have been placed on the center points of outside walls of PDS tank except the top lid. No sensor has been placed on top lid because it has been kept free for insertion of HV electrode and other adjustments of PD source inside PDS tank. The placement of five acoustic sensors on five walls of the PDS tank has been schematically depicted in Figure 4.

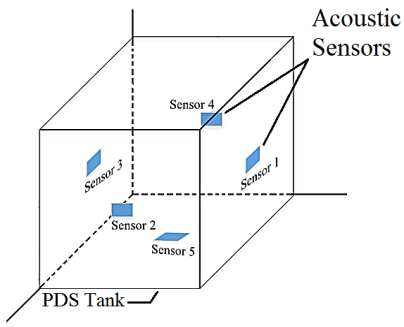

Fig. 4. Placement of Acoustic Sensors in PDS tank

Throughout this paper, the five sensors have been denoted as S1, S2, S3, S4 and S5, as shown in Figure 4. It is worthwhile to mention here that, considering practical situations, the PD source localisation methodology becomes more accurate and less complex when triangulation method using five sensors is employed. This type of sensor placement is as per the IEEE standard C57.127 – 2007 [5]. The acoustic sensors used in the present work are transmitter/receiver type sensors having sensitivity of 67 dB at center frequency 40.0 ± 1.0 kHz.

E. PD Data Acquisition

The schematic of the experimental setup used in the laboratory for PD data acquisition has been shown in Figure 5. The test voltage has been kept at 30kV such that sustained discharge can occur in oil.

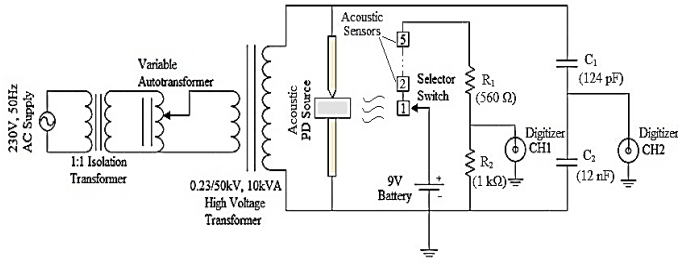

Fig. 5. Schematic circuit diagram of experimental procedure for PD data acquisition

A two channel digitizer from National Instrument™ with sampling rate of 100MS/s has been used in the present work to digitize the analog signals captured by the sensors and to facilitate data acquisition in a computer. To ensure fixed starting point of data capture, the digitizer starts recording the signals from zero crossing of positive half cycle of the supply voltage applied to the PD source. The time duration of each data capture is 500µs. During data capture, first the PD sources are placed at particular locations of Figure 3 and five sensors capture acoustic signals. This is a single data set of five data from five sensors. This process is repeated five times with an interval of 1 hr between two consecutive data capture. Therefore, five data sets are obtained for each of the SPD and DPD events. These data sets will be utilised to evaluate the performance of the proposed method.

III. Methodology for PD Source Localisation

A. Sequence of Arrival

The acoustic emissions from the PD source give rise to two types of elastic waves – 1. **Longitudinal Wave or Pressure Wave** which exists both in transformer oil and wall of the PDS tank. 2. **Transverse Wave or Shear Wave** which only exists in the tank wall and not inside the oil [5]. The phenomenon of wave propagation inside and in the walls the PDS tank has been schematically illustrated in Figure 6. In the present analysis, the pressure and shear waves generated due to acoustic emissions have been assumed to be ideal.

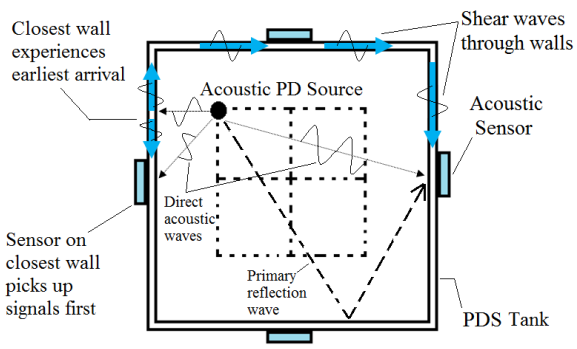

Fig. 6. Wave Propagation in PDS tank

First, let us consider the pressure waves from the PD location which reach the walls directly through oil. Assuming that the acoustic waves travel at constant speed inside the oil, the distance travelled by the acoustic wave through the oil D, speed of acoustic waves in oil v_{oil} and time of travel of acoustic wave T are related to each other by the relation,

$$D = v_{oil} \times T \tag{1}$$

In Figure 6, the wall which is closest to the PD location, experiences earliest arrival of direct acoustic waves. The acoustic sensor mounted on the closest wall will pick up the signals first. For other distant walls the arrival times are proportional to their distance from the PD location.

Upon reaching the closest walls, the acoustic emissions give rise to shear waves that travel through the walls only. As the speed of acoustic wave is more in the steel than in the transformer oil, the shear waves through the walls travel faster than the direct waves travelling through oil and may arrive at sensors before the direct waves do.

Typical nature of one acoustic emission burst from a PD source and recorded by an acoustic sensor has been shown in Figure 7. The sharp rise in amplitude up to positive global peak marks the time instant when the direct acoustic wave arrives and impinges on the wall where the sensor is placed. Several secondary peaks can occur due to a number shear wave arriving at different times. If sufficiently strong shear wave arrives a sensor before the direct wave, then two distinct positive peaks having comparable amplitudes may occur and it will be very hard to ascertain which peak has been created by which type of wave. However, shear waves are generated only when direct waves impinge on wall. As the direct waves undergo energy dissipation while travelling through oil, the resultant shear waves comprise lower energy than direct waves. Due to travel through the steel walls of PDS tank, the energy of the shear waves is further lowered. Therefore, the peaks generated by shear waves are generally of low amplitude than those generated by direct waves.

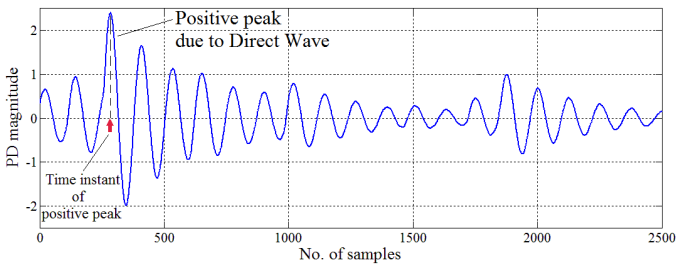

Fig. 7. Acoustic Emission burst

From equation (1) it can be inferred that, all the sensors do not experience simultaneous arrival of direct acoustic waves from the PD location. For sensors which are at same distance from a PD location, the direct acoustic wave travels to them in equal time. On the other hand, for the sensors which are at different distances, the arrival times will be different. Therefore depending upon the distance from the PD location, each sensor is associated with unique time of arrival of direct acoustic waves from a particular location, which is proportional to the

distance between the PD location and sensor location. This fact can be utilised to identify the locations of the PD source.

Let us consider the SPD event '11'. The waveforms of captured acoustic signals by five sensors when PD source is placed at '11' have been shown in Figure 8. From Figure 3 and Figure 4, it can be seen that this location is closest to sensor S1 which is placed outside the wall just in front of it. The sensor S3 is farthest from this sub-region. The rest of the sensors S2, S4 and S5 are equidistant from this sub-region. These sensors are more distant than S1 but are closer than S3. Hence, direct acoustic waves emanated from PD source will reach sensor S1 first. Then the wave reaches S2, S4 and S5 simultaneously. Lastly the wave reaches sensor S3. From Figure 8, this sequence of arrival can be readily ascertained by observing the time instants of occurrence of peaks. This reasoning can be extended for every location of Figure 3. For example, if we consider the location '21', it can be seen from Figure 3 that this location is equidistant from all the sensors. Therefore acoustic emissions from this PD location reach each of the sensors simultaneously.

The sequence of arrival of direct acoustic wave at five sensors corresponding to each PD location of Figure 3 can be considered as a qualitative feature uniquely associated with each location. The sequence of arrival associated with each location can be more systematically presented by utilising the notation scheme of Table 2.

TABLE 2. NOTATIONS TO IDENTIFY SEQUENCE OF ARRIVAL OF DIRECT WAVES

Notation	Interpretation
I	Sensor is first in order of distance from PD location
II	Sensor is second in order of distance from PD location
III	Sensor is third in order of distance from PD location

The sensors which are closest to PD location, direct wave arrives earliest at those sensors. Those sensors have been marked as 'I'. The sensors which are second in order of distance from PD location experience the next arrival. Therefore those sensors have been marked as 'II'. The sensors which are third in order of distance from PD location experience last arrival of direct wave are marked as 'III'. Utilising this notation, sequences of arrival of direct wave at five sensors for all the PD events can be marked. The sequences of arrival for PD events '11' and '21' has been presented in Table 3.

TABLE 3. SEQUENCE OF ARRIVAL FOR SPD EVENTS '11' AND '21'

PD Event	S1	S2	S3	S4	S5
11	I	II	III	II	II
21	I	I	I	I	I

B. Levels of Amplitude

Localisation of PD locations based on unique sequence of arrival works excellently for SPD events. But when DPD events are considered, the situation becomes quite complex. When two PD sources are placed inside the PDS tank and made to discharge simultaneously, acoustic waves are generated from both the sources.

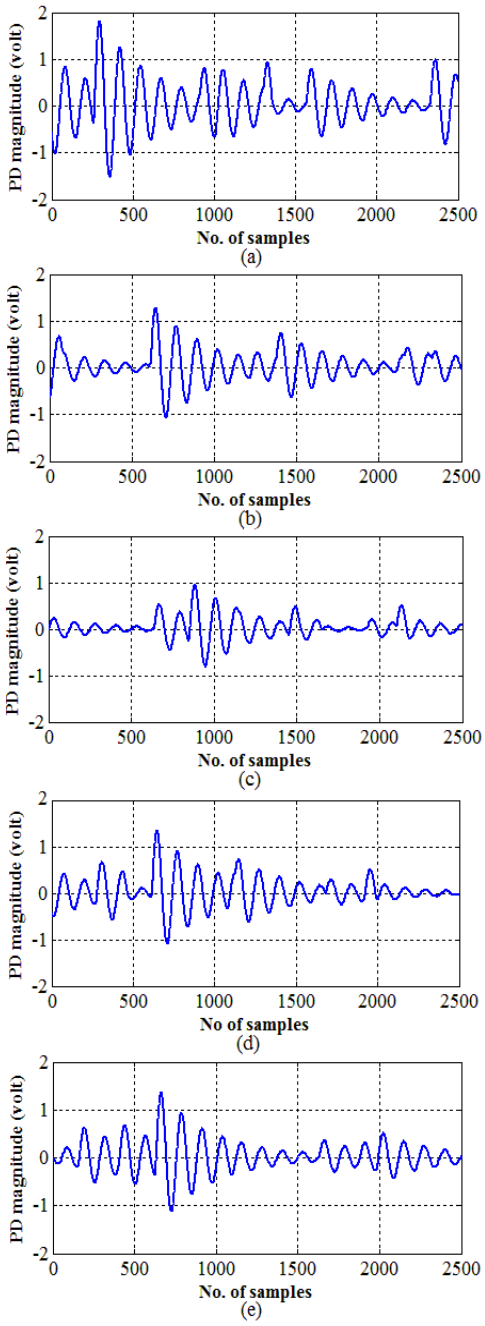

Fig. 8. Acoustic signals captured by different sensors when acoustic PD source is placed at '11' a) Sensor, S1 (b) Sensor, S2 (c) Sensor, S3 (d) Sensor, S4 (e) Sensor, S5.

The direct acoustic waves from the PD sources reach the sensors at different times which are at different distances from these sources. Therefore, the waves get unevenly mixed up due to superposition during capture. In that mixed wave, the peaks cannot be marked clearly and there can be multiple peaks. But if it happens that a sensor is equidistant from both the locations, then it can be assumed that acoustic waves reach that sensor simultaneously. The acoustic waves from two PD sources get superimposed in phase with each other. Therefore peaks of both the waves become concurrent so that the peak in the mixed wave can be identified.

Let us take the example of DPD event '12_14'. The waveforms captured by five sensors have been depicted in Figure 9. It is evident from Figure 3 that both these locations are individually equidistant from sensors S1 and S3. S1 is the closest sensor and S3 is the farthest sensor.

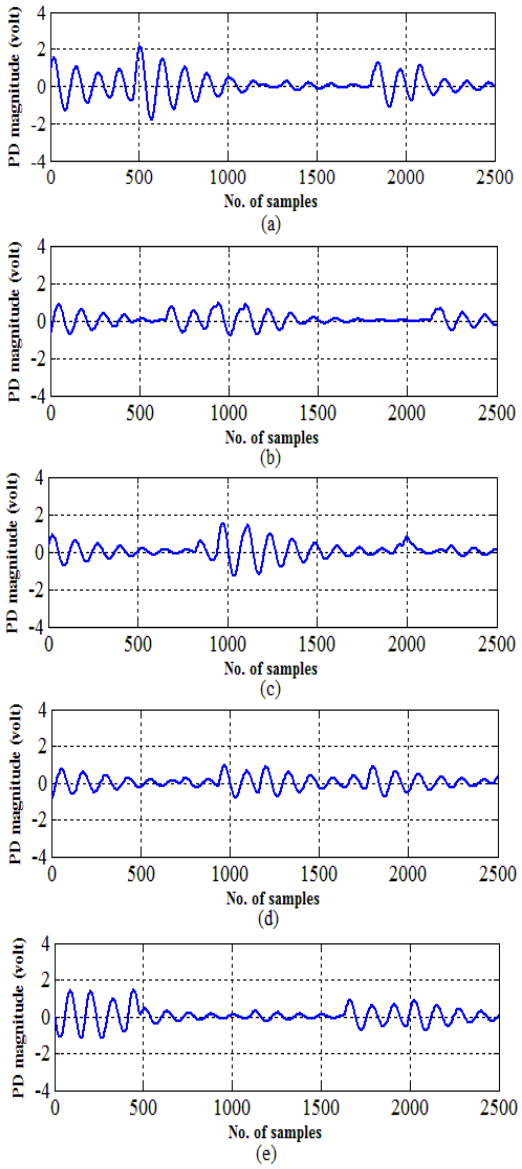

Fig. 9. Acoustic signals captured by different sensors when two acoustic PD sources are placed at '12' and '14' a) Sensor, S1 (b) Sensor, S2 (c) Sensor, S3 (d) Sensor, S4 (e) Sensor, S5

It can be seen in the waveforms of Figure 9(a) and 9(c), pertaining to signals captured by sensors S1 and S3, that the peaks can be easily marked. This happens because for each of these sensors, the direct acoustic waves from the PD locations reach simultaneously and get superimposed in phase. Therefore the peaks of individual direct waves are approximately concurrent. But in the waveforms captured by other sensors, the peaks cannot be easily marked. This is because the rest of the sensors are at different distances from these PD locations.

Hence for DPD event '12_14', the sequence of arrival of direct waves can only be ascertained for sensors S1 and S3. For rest of the sensors sequence cannot be obtained. It may so happen that the sequence pertaining to '12_14' matches with any other DPD event. For example, consider the DPD event '13_15'. Referring to Figure 3 and Figure 4, it can be seen that for this event also the sensors S1 and S3 are individually equidistant from locations of PD sources while rest of the sensors are at different distances. In terms of notation introduced in Table 2, the sequence of arrival for DPD events '12_14' and '13_15' will be as given in Table 4. Note that for S2, S4 and S5, the time of arrival cannot be evaluated and hence no sequence can be assigned.

TABLE 4. SEQUENCE OF ARRIVAL FOR DPD EVENTS '12_14' AND '13_15'

PD Event	S1	S2	S3	S4	S5
12_14	I	-	III	-	-
13_15	I	-	III	-	-

Therefore DPD events '12_14' and '13_15' are indistinguishable with respect to sequence of arrival. Hence, information of the sequence of arrival is not sufficient for identification of DPD events.

The other parameter that is associated with the PD waves is the peak amplitude of acoustic signals. It has been already discussed that the peak amplitude of direct acoustic wave vary inversely with respect to the square of distance between PD location and the sensor. If sensor is more distant from the PD location then, due to energy dissipation in transit, the peak amplitude of the direct wave decreases. Hence the peak amplitude in the signal captured by a sensor is also an indication of the distance of this sensor from the PD location. The sensors which are closest to PD location capture signals comprising highest peaks. For the sensors which are farthest the reverse happen. Rest of the sensors capture signals whose peak amplitude varies within these maximum and minimum value.

For example, refer Figure 8. As sensor S1 is closest to location '11', the signal captured by S1 has highest peak. Whereas, for signals captured by sensors S2, S4 and S5, the peak amplitudes are approximately same because these sensors are equidistant. But these peak amplitudes are lower than that of the signal captured by S1 because these sensors are more distant than S1. Lastly, the signal captured by S3 has least peak amplitude as it is farthest from the PD location '11'.

This reasoning can also be extended for DPD events. However, in DPD events there may be several local peaks of comparable amplitudes in the signals captured by some of the sensors. In those cases, amplitude of the first peak which has occurred due to arrival of direct wave from the PD source closest to that sensor will only be considered. For example in Figure 8(d), pertaining to signal captured by sensor S4, there are several local peaks which have comparable amplitudes. But the first peak corresponds to PD source placed at '12' and amplitude of that peak will only be considered. Therefore, peak amplitudes of captured acoustic signals is another unique numerical feature associated with all the SPD and DPD events.

IV. Identification of PD Events

From the foregoing analysis, it can be inferred that the acoustic PD events can be completely characterised based on two parameters – sequence of arrival of direct waves at different sensors and levels of amplitudes of the acoustic signals captured by those sensors. Recall that corresponding to each PD event, there are five data sets, each containing five data corresponding to five signals captured by five sensors. For three out of five data sets, sequence of arrival and peak values of the signals captured by five sensors have been obtained. The peak values have been normalised with respect to maximum and minimum values in the range. Employing the concepts of Rough Set Theory, all the numerical values pertaining to normalised peak amplitudes have been discretized for increased flexibility. The ranges of numerical values and corresponding class values have been provided in Table 5. More details about discretization can be found in [14, 15]. The complete information about the sequence of arrival and levels of peak amplitudes corresponding to PD events for one set of data have been provided in Table 6.

Table 5. Different ranges of numerical values pertaining to normalised peak amplitudes and corresponding assigned classes

Range	**0 to 0.25**	**0.25 to 0.35**	**0.35 to 0.45**	**0.45 to 0.55**	**0.55 to 0.65**	**0.65 to 0.75**	**0.75 to 0.85**	**0.85 to 0.95**	**0.95 to 1.00**
Class	0	1	2	3	4	5	6	7	8

Table 6. Sequence of arrival and levels of peak amplitudes pertaining to different SPD and DPD events

SPD Events	**Sequences of arrival**					**Levels of peak amplitudes**				
	S1	***S2***	***S3***	***S4***	***S5***	***S1***	***S2***	***S3***	***S4***	***S5***
11	I	II	III	II	II	4	2	1	3	4
12	I	II	II	I	II	3	1	1	4	2
13	I	I	II	II	II	3	4	1	1	2
14	I	I	II	II	I	3	3	1	2	5
15	I	II	II	I	I	3	1	1	5	4
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
37	III	I	I	III	II	1	4	2	0	4
38	III	II	I	II	I	1	2	5	2	4
39	III	III	I	I	I	1	1	8	5	2
DPD Events	**Sequences of arrival**					**Levels of peak amplitudes**				
	S1	***S2***	***S3***	***S4***	***S5***	***S1***	***S2***	***S3***	***S4***	***S5***
11_31	-	I	-	I	I	1	2	8	3	4
11_32	-	-	-	-	-	1	4	1	4	6
11_37	-	-	-	-	-	4	8	1	3	4
31_12	-	-	-	-	-	2	1	4	4	2
31_17	-	-	-	-	-	8	3	1	1	3
12_13	I	-	II	-	II	3	4	1	3	2
12_14	I	-	II	-	-	5	4	2	1	4
13_15	I	-	II	-	-	5	3	2	1	6
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
33_35	II	-	I	-	-	1	3	3	5	3
35_34	II	-	I	-	-	1	1	4	4	5
39_37	II	-	I	-	II	3	1	4	4	5

Any unknown PD event can be easily identified by matching the sequences and levels with the rows of Table 6. Out of the five data sets, the rest two data set has be used to validate identification accuracy. It has been observed that using information given in Table 6, 25 out of 27 SPD events and 17 out of 20 DPD events can be successfully identified in each of these sets.

V. Conclusions

The present work is aimed at localisation of single and multiple PD sources based on acoustic signals measured in emulated PDS tank. The locations were recognised based on two parameters - sequence of arrival of PD generated acoustic waves at different acoustic sensors mounted on outside walls of the cubical box and levels of peak amplitudes of the captured acoustic signals by those sensors. The results show that this combined methodology can effectively identify the locations of single as well as double PD sources with very good accuracy.

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