PARTIAL DISCHARGE LOCALIZATION IN POWER TRANSFORMERS

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Abstract: This acoustic emission technique is gaining important due to advantages like it is non-destructive, the placement of several sensors on the outside of the tank allows a localization of Partial Discharges, and measurements can be performed on-line and on-site. The objective of this work is to study PD sound detection and measurement procedures, concerning the evaluation of position of PD inside the transformer. The present paper describes a combination of acoustic method triggered by Ultra High Frequency or electrical method according to IEC 60270. The combination of methods is increased the plausibility of PD activity than pure acoustic method. Furthermore the combination of methods can find PD source with higher sensitivity especially for hidden PD defects. In this paper, an experimental validation has been done on the transformer insulation model. The study was complemented with measurements on transformers in the field. By means of measurement in a test field, two transformers are investigated by electric/UHF-acoustic method because gas-in-oil diagnosis indicated PD. With the combined-acoustic measurement, single-shot impulse and averaging method were used to determine the time-of-flight information at each sensor. This paper shows the comparison between single-shot and averaging method for the localization of more than one PD sources.

1 INTRODUCTION

The application of acoustic emission techniques for localization of partial discharges (PD) in power transformers is now well established.

A partial discharge is a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor [1]. PDs occur within a transformer when the electric field exceeds the dielectric strength of the insulation within a localized volume. Possible causes include a temporary over voltage, an incipient weakness in the insulation introduced during manufacturing, or deterioration due to aging effects over the plant's lifetime. Although the PD may be quite small in its early stages of development, it is by nature a damaging process, causing the chemical decomposition and erosion of materials. Left unchecked, the damaged area may grow and eventually cause complete failure. Unanticipated plant failure can result in large financial penalties for utilities. In addition to the damage to the environment, it may pose a serious hazard to employees or the public in the worst case.

The acoustic method is non-invasive and immune to electromagnetic noise [1, 2]. A sound wave produced by a partial discharge inside a transformer propagates through various materials on its way to an acoustic sensor attached at the outside of the tank wall. After receiving the sound signal, localization of PD can be calculated by using the time-of-flight (arrival time) between the sensors and the PD event. However the complicated internal configuration and the diversification of materials of the transformer make the propagation paths of the acoustic wave complex. This fact is unfavorable to the acoustic measurements. All-acoustic method, UHF-acoustic method and electric-acoustic method were used for the localization of PD sources in the transformer.

2 DETECTION AND LOCALIZATION OF PD

At the occurrence of discharges, PD causes; creation and movement of charges (resulting in electrical currents)**,** electromagnetic radiation**,** emission of sound wave (the rapid flow of electrons and ions create a gas pressure wave)**,** light emission (from excited molecules, which lose their energy after the initial discharge), formation of chemical reaction (hot spots or local breakdown inside the transformer occur, several gases are produced and dissolved in the oil). Based on different phenomenon, there are various methods for the detection of partial discharges. There are electrical methods according to IEC 60270, chemical method with dissolved gas in oil analysis (DGA), ultra high frequency (UHF) method by emission of electromagnetic wave, acoustic method related to ultrasonic wave.

2.1 Electric method for PD detection

Electrical PD measurements base on the detection of movement of charges. The actual charge transferred at the location of a partial discharge cannot be measured directly. The preferred measure of the intensity of a partial discharge is the apparent charge 'q' as defined in [3, 4]**.** The apparent charge measured in picocoulombs (pC), which is the integrated current pulse generated by PD. The amplitude of the apparent charge of PD measurements is used as a criterion for the judgement of the PD activity in the insulation of power transformers for a long time. PD test circuits by IEC 60270 are illustrated in Figure 1 [1].

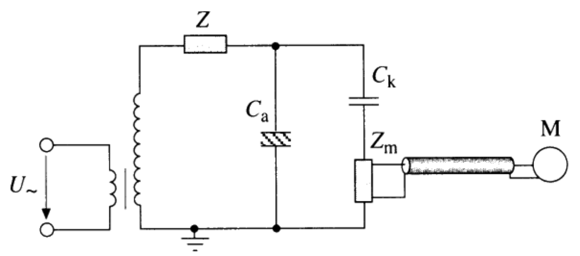

Figure 1. PD Test Circuit Coupling Device in Series with the Coupling Capacitor [1]

This electric method allows a precise calibration but requires a sufficient signal-to-noise ratio. Calibration of the measuring circuit is carried out by injecting a series of known charges at the calibration terminals from a calibration signal generator [3]. Some signal processing methods have been used to suppress unwanted noise [1]. Knowledge of typical PD (PRPD) patterns representing specific PD sources is therefore an important basis for a correct analysis of PD measurements [5]. The discharge pattern produced by individual discharge events is generally recognised as comprising the amplitude of individual discharge events, the number of discharge pulses per power cycle and distribution of these pulses within the power cycle, i.e., their phase relationship.

2.2 UHF Method for PD detection

When a discharge occurs, an electromagnetic wave is produced which propagates away from the PD site. The amplitude of the detected signal is normally in the millivolts to volts range. UHF PD measurement cannot be calibrated like the electrical method according to IEC 60270.

Electromagnetic waves are detectable with UHF probes. The probes can be inserted into the transformer during full operation using the oil filling valve. The probes are normally threaded and screwed into the clamps until it is flush with the earthed enclosure or the probes could be connected by separate channels to (typically) an event recorder. PD under oil is a very fast electrical process and emits electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz). One sensor can detect signals over relatively large area as compared to the acoustic sensor. PD magnitude of less than 10 pC can be detected with good sensitivity. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, normally a clear decision can be made concerning the PD activity of the test object [6]. Figure 2 illustrates the UHF PD measurement setup.

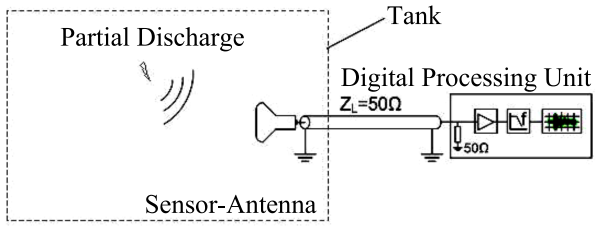

Figure 2. UHF PD Measurement Setup [6]

UHF PD detection sensitivity fairs better and is seen unaffected by barriers and further, even small level of discharges could be recorded with good sensitivity [7].

2.3 Acoustic Method for PD localization

The principle of this method is the detection of the pressure waves generated by the discharge within the insulation. The discharge appears as a small explosion, which excites a mechanical wave, and propagates through the insulation. The propagation speed of the acoustic wave depends on the surrounding medium. Because of the short duration of the PD impulses, the resulting compression wave has frequencies in the ultrasonic region. The frequency range is between 10 Hz and 300 kHz [8]. Figure 3 shows the configuration of the experimental setup of acoustic method.

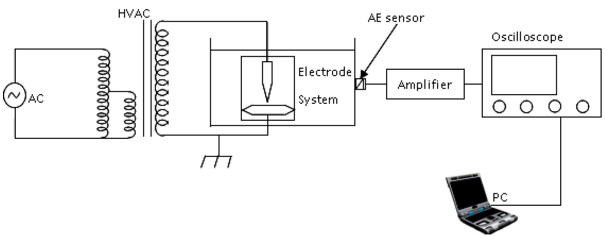

Figure 3. Experimental Setup of Acoustic Method

2.3.1 Single-shot Impulse

Single shot impulse is a situation in which one press of the trigger gets one signal. Sometimes PD cannot be localized by single-shot method because of high noise.

2.3.2. Averaging Method

Averaging is normally used to eliminate noise. Many disturbances in an industrial environment are random whereas partial discharges often recur at approximately the same phase in each cycle of applied voltage. It is therefore possible to greatly reduce the relative level of randomly occurring disturbances by using signal averaging techniques. To be successful a stable trigger is required, signal and noise should be uncorrelated and the noise is supposed to be white (i.e. has a constant spectral density in the investigated frequency range).

2.3.3. Time of flight of signals

As this method is depend on the time of flight from the PD source to the tank wall, determination of a correct objective time of flight, similar the true beginning of a transient signal, is an absolutely necessary part of the localization process [9].

In combined electric-acoustic system, the electric signal is usually considered as detected instantaneously. When using this assumption, the time of flight of electric signal is used as time zero for PD event. The difference in times of flight of electric and acoustic signal is the propagation time between PD and that sensor location. PD localization is then based on absolute time of flight at each sensor shown in Figure 4 [2].

The distance D travelled in a particular medium is the multiplication of sound velocity in oil and the time that it takes for an acoustic signal to complete this journey and as shown below:

$$D = v_s \times t \quad (1)$$

In these non-linear equations, (x,y,z) are the three unknown PD coordinates in space, T_{si} is the propagation time of acoustic.

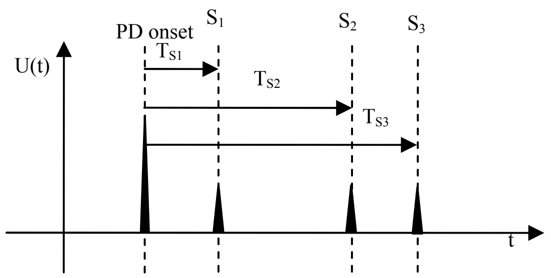

Figure 4. Schematic configuration of the absolute acoustic arrival time T_{si} with the known PD onset

(x_{si}, y_{si}, z_{si}) is the Cartesian coordinates of the sensors and v_s is the assumed sound velocity in oil.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = (v_s T_{s1})^2 \quad (2)$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = (v_s T_{s2})^2 \quad (3)$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = (v_s T_{s3})^2 \quad (4)$$

In these measurements, MATLAB is used to receive the time signal. The automatic determination of time of flight is managed by energy criterion detail in [2].

3 LABORATORY INVESTIGATION

The essential components of the acoustic systems are the acoustic sensors, amplifier, cables, digital processing unit, a personal computer to analyse the signal and to use the signal processing software. For the trigger source, UHF antenna or Electric method is used. PD has been simulated by applying high voltage to an electrode system. Therefore PD signals can be detected by acoustic sensors mounted on the tank and transmitted to the oscilloscope through the amplifier. Another oscilloscope is used for generation of trigger signal by means of the UHF or electrical signal. By using this trigger signal, acoustic signals can be obtained and stored on the computer. By using MATLAB, PD can be localized within the transformer.

The experiment was set up using a steel tank without the core and windings. Tank with the Cartesian space coordinate (1.00 m length×0.50 m width×0.50 m height) was used. A needle-sphere electrode under the oil was used as the discharge source. Figure 5 shows the position of sensor 3 attached at the tank. Figure 6 presents the screen-shot of acoustic signals on LeCroy LT 224. In this figure, trigger point from the UHF antenna (white arrow) can be seen clearly. Therefore time of flight of the sensor can be obtained from trigger point (PD onset) to the starting point of transient signal of the sensor.

Figure 5. Position of Sensor 3 attached on the Tank

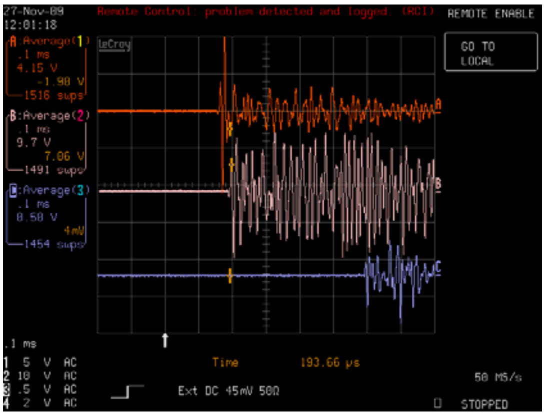

Figure 6. Screen-shot of Acoustic Signals on the Oscilloscope (100µs/div)

After collecting the time of flight of sensors, PD can be calculated in MATLAB and located in transformer.

In some measurements by UHF-acoustic method, estimated PD locations at various positions of sensors are presented in Figure 7. Although there is a different time picking method (single-shot or average), the location of PDs is not so much different in the laboratory because there is not much noise from the environment.

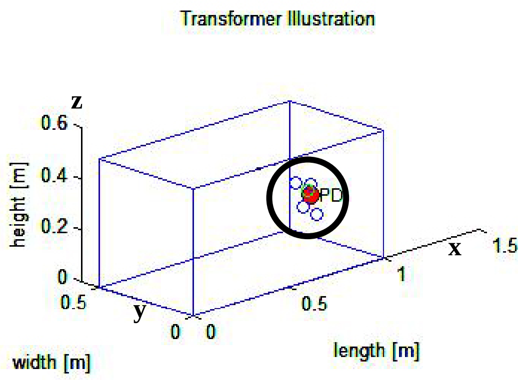

Figure 7. Localization of PD in the Tank

The restore view of transformer in 3D dimension with PD sources is presented in Figure 7. Each circle represents the estimated PD location of each measurement. It can be seen that there is not much difference between actual and estimated PD location in each measurement (see in black circle). Figure 8 shows the spatial deviation of estimated PD location.

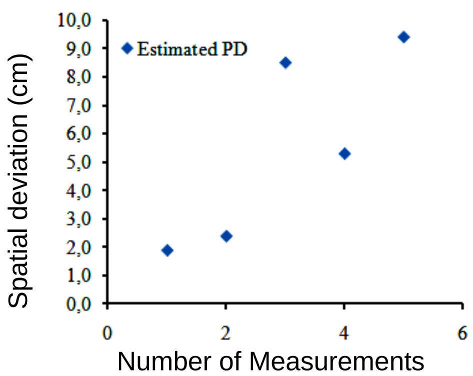

Figure 8. Spatial Deviation of Estimated PD

4 CASE STUDIES

The reliability of electrical networks depends on the quality and availability of primary electrical equipment such as the power transformer. Partial discharges can occur not only due to aging transformer but also due to design-errors.

4.1 Case Study 1 (Electric-Acoustic)

In this case study several transformers have been produced for application in wind energy generation. All of these transformers have partial discharges. Therefore one of these three-phase transformers was tested as an example. After finding too much gas within these transformers, partial discharge test was carried out in the test field. Rated power and voltage of the transformer was 2.5 MVA and 400V/30 kV.

Because this transformer had no oil valve for the UHF probe, the PD measurements were performed by the combination of electric and acoustic method. The calibration of the measurement set-up in terms of apparent charge was also done separately for all three measurement devices with a defined calibrator impulse. The multi-terminal measurements were carried out with MPD 540 from Omicron, Austria. The electrical results show that Phase L_1 has highest level of apparent charge, approximately 20 nC. The result shows that PD level is also high between the phases L1and L2.

After confirmation of PD activity by the electrical method, the next step is the localization of PD by acoustic method. First of all, 4 acoustic sensors were installed roughly at the tank wall. If the absolute time is much greater, the sensors had to be repositioned and the acoustic measurement is repeated until the best closeness between the PD onset and the sensor is obtained.

During the averaging process the noise contained in the acoustic signal tends towards its statistic mean value which is zero if white noise is assumed. Sometimes a single shot acoustic impulse has no clear observable information. In contrast a clear impulse in signals is acquired by averaging. The disadvantage of the averaging is that only one of the time-of -arrival for each one sensor can be obtained. As there may be more than one PD source in the transformer, collecting of the only one time-of-flight for each sensor cannot be sufficient. Because of possibly interfering acoustic signals of different sources which did not overlay constructively. So in these measurements, 100 times of single-shot signals were collected for one position of sensor-array.

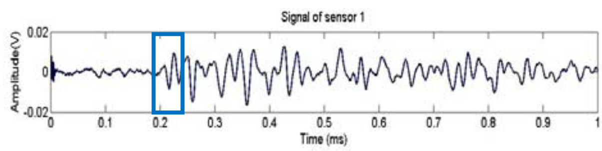

Figure 9. Acoustic PD Signal of Sensor 1 (Averaging Mode)

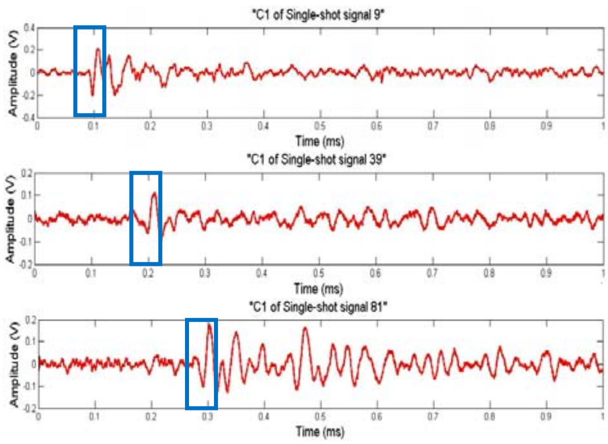

Figure 10. Acoustic PD Signals of Sensor 1 (Single-shot)

Although all of the single-shot signals are not observable to determine the arrival time, some signals reached to get the time of flight and location of PD sources can be calculated. Collecting of time of flight of sensors between average and single-shot signals can be seen clearly in Figure 9 and 10.

By using average method, the time of flight of sensor 1 is 220 µs. By using some usable single-shot signals, there are three different times of flight; 100 µs, 200µs and 300µs in only sensor 1. By using times of flight of the sensors, three groups of PD can be localized. Depending on the results of estimated-PDs, Groups (Gp.) I, II, III can be classified according to similar results. Therefore three PD sources were investigated in the transformer by using both single-shot and averaging methods. By using the averaging method, only PD group I was found. By using single-shot method, three PD sources were found. The various sources of PD in front view are presented in Figure 11.

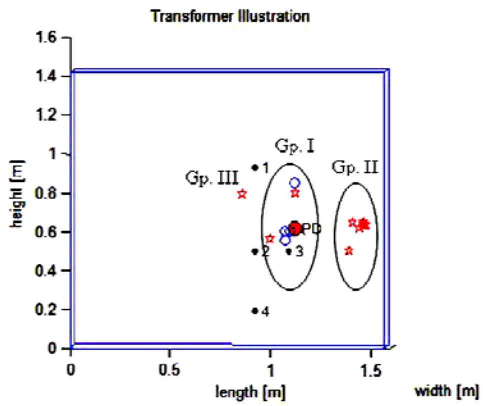

Figure 11. Estimated PD Sources in Transformer

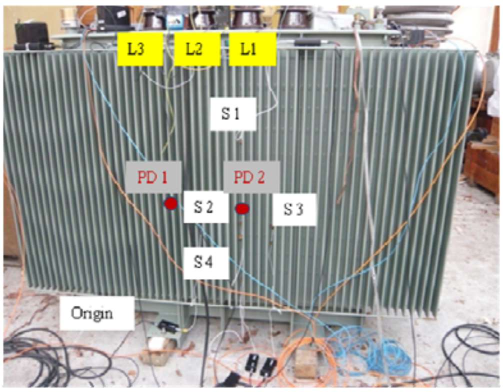

Figure 12. Positions of Sensors and Two PD Sources in the Tank

The measurement setup showing position of sensors and PDs can be seen clearly in Figure 12. Although three groups were found within the transformer, many PDs could be found in group I and II. Therefore only one PD in group III may be a measurement error. It shows that the PD sources are located in between phases L1 and L2, and between phase L2 and L3. That result was confirmed by analysis of the electrical PD measurement.

4.2 Case Study 2 (UHF-Acoustic)

In this measurement, a 40 MVA three-phase transformer was tested on PD in the test field. The rated voltage is 220/63 - 31.5/10.5 kV. During the entire measurement, the tap changer position was 14. The transformer was excited on the low voltage side with 150 Hz electrical frequency. An electrical PD measurement by MTRONIX system was used to determine the actual PD level. Because of the high value of the apparent charge (pC) by the electric PRPD pattern, this transformer was measured. As there was only one oil valve for the UHF probe, localization of PD was investigated by a combined UHF-acoustic measurement. To trigger the acoustic signals, a UHF probe was installed at the DN 125 oil using an adapter DN 125 to DN 80. The antenna of the UHF Probe was placed in the flange 5 cm ahead to the tank wall. Acoustic signals are measured with sensors on the tank surface and recorded with a second storage oscilloscope, using the external trigger signal of the UHF oscilloscope. For a better signal to noise ratio the built in averaging method was used. PD sources were localized with two measurement setups. In setup 1, the sensors are placed all over the tank surface to detect signals from the entire active part. The PD localization of the first general measurement was used to optimize sensor positions. By investigating the signals from the first general measurement, PD location can be estimated. In setup 2 the sensors were arranged near to the estimated PD source.

Oil temperature was 32°C. So the speed of the oil in transformer was 1370 m/s. By using absolute time method with iterative algorithm, PD source could be located within this transformer. In Table 1 the location results are summarized by appropriate combination of sensors in arrangement of sensor-array. This table lists the estimated PD sources by applying electric-acoustic method.

Table1.Estimated PDs by Electric-acoustic Method

Used sensors	PD source		
	x(length)	y(width)	z(height)
$S_1 S_6 S_4 S_2$	2.52	0.79	0.45
$S_1 S_3 S_4 S_2$	2.44	0.10	0.47
$S_1 S_5 S_4 S_2$	2.59	0.85	0.44
$S_4 S_1 S_5 S_3$	2.20	0.25	0.52
averaging	2.44	0.40	0.48

The calculated value for the source in x direction varies between 2.20 m and 2.50 m. The z direction varies between 0.40 m and 0.55 m. For the y direction the algorithm did not work properly, therefore this value is uncertain and varies between 0.25 m and 0.80 m. PD source inside the transformer can be clearly seen in this Figure 13. The x and z direction indicate a PD source at the lead exit or at the first disk of the winding of phase "W".

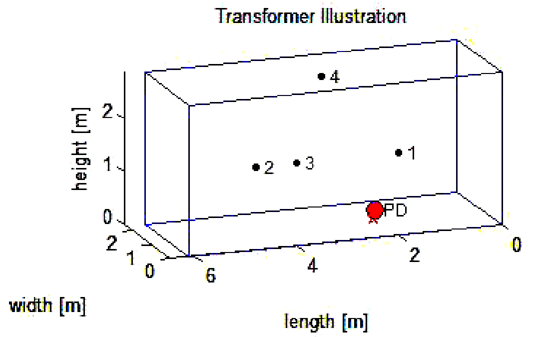

Figure 13. Estimated PD Source in Transformer

5 CONCLUSION

The spatial deviation is for all measurements under 10 cm for the steel tank dimension in (100cm $\times$ 50cm $\times$ 50 cm). The result is satisfactory in the laboratory because there is no winding, core and other insulation system. Normally in a large power transformer, the spatial deviation is about 40 cm. The localization results of estimated PD are almost similar with the actual PD source in laboratory. For the measurements both in laboratory and in test field, an objective time of flight can be obtained by using the energy criterion. The estimated PD location in case studies transformer was approved by the manufacturer in test field measurement.

In the on-site measurement, averaging method should be used because of the noise from outside environment. During the averaging process the noise contained in the acoustic signal tends towards its statistic mean value which is zero if white noise is assumed. Sometimes a single shot acoustic impulse has no clearly observable information. In contrast a clear impulse is visible by averaging method. The disadvantage of the averaging method is that only one time-of -arrival for each one sensor can be obtained. As there may be more than one PD source in the transformer, collecting of only one time-of-flight for each sensor cannot be sufficient because of possible interfering acoustic signals of different sources which do not overlay constructively.

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