Evaluation of Partial Discharge in Power Transformers by Acoustic Emission Method and Propagation Modeling of Acoustic Signal

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***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 inevitable. 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. Common insulation in power transformers are pressboard and oil. Unconventional PD measurement was developed for several decades ago as a form of PD detection system. In these PD measurement systems that are named unconventional method PD is analyzed by indirect features of this phenomenon, which includes electrical, acoustic, UHF, optical, and chemical methods. The main advantage of unconventional method is the ability of this method in order to decrease the amount of signal to noise ratio for on-site or on-line measurement. A study of the correlation between acoustic emission signals generated by PD and electrical PD charges is inevitable. By developing the speed of measuring devices like digital signal processor (DSP) the possibility of evaluation and calculation of acoustic signals in very short time have been increased. The aim of this paper is evaluation of acoustic signals for two different kind of pressboard (new and aged) with two types of sensors (75 kHz and 150 kHz peak frequency) and simulation of Acoustic Emission (AE) signals propagation which are produced due to PD inside a sample transformer tank by using Finite Element Method (FEM).**

***Index Terms*—partial discharge, transformer, acoustic emission sensor, finite element analysis tools**

I. Introduction

Power transformers are one of the major capital items, and the cost due to a failure, is high in both direct costs and downtime. The early detection of problems is essential in order to reduce losses due to failure. For this reason transformers are monitored frequently by using a variety of methods. An important way for monitoring conditions of high voltage equipment is Partial Discharge (PD) evaluation for these devices. Electrical, mechanical and thermal stresses can be caused for occurring breakdown on aged insulation and high voltage devices and it can be led to failure on the device. Occurring PD has some effects that can be used in order to indicate the problems such as electromagnetic waves, acoustic waves, local heating and chemical reactions.

The acoustic method is one of the nondestructive diagnostic methods used to measure, detect and localize PD in insulation systems of power facilities. Another advantage of this method is immunity to electromagnetic interference [1].

For diagnosing whether an acoustic wave is produced by a PD source or not it is sufficient to review some characteristics of this acoustic signal such as rise time of first oscillation or length of wave.

In electrical PD method in order to consider the severity of PD signal a specific threshold about 300 pC to 500 pC is used, but in acoustic method because of attenuation of acoustic signals that are traveled from PD source to sensor and therefore decreasing amount of amplitude while interfere with material inside the transformer tank, sensors should detect the weakened signals. Each type of acoustic waveform is representative the specific path that signals traveled.

The features of two electrical and acoustic methods depend on the type of coupling path and the location of PD source between the detector and event which can be done by electric and acoustic signal, also in order to face noise signal both methods have different ways.

Acoustic signals that are produced by PD source have a specific range that can measure by acoustic sensors but this property decreases the amount of noise.

II. Acoustic Signals

AE signals have frequencies between 50 kHz and 350 kHz, the main frequency for 150 pC PD is about 100 kHz and this frequency will decrease when the discharge become larger [2].

The characteristics of AE signals such as amplitude and time domain depend on some factors that the most important of them are the size of transformer tank and the location of the sensors.

In the Fig. 1, one signal in two different domains is shown, the upper one is in the time domain while below is in the frequency domain; the x axis is in Hertz (Hz). In this figure, the main sensitivity of sensor is from 20 kHz to 180 kHz and the second oscillation at 700 μs illustrates the reflection of the AE signal.

Manuscript received June 20, 2013; revised September 13, 2013.

doi: 10.12720/ijoee.1.4.182-187

Fig. 2 shows another phenomenon, if the waveform is considered carefully, it is understood that this signal consists of two-step, at first the longitudinal wave that has lower amplitude is sensed by sensor then the transversal wave arrive to the sensor [3] and [4].

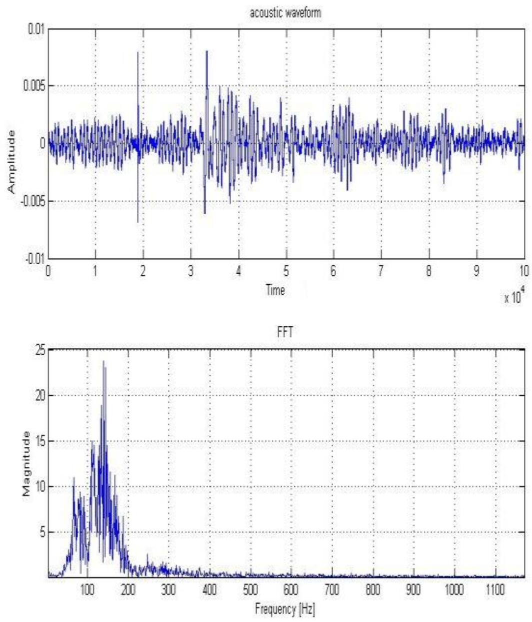


Figure 1. A laboratory recorded direct PD signal (top) and its power spectrum (bottom).

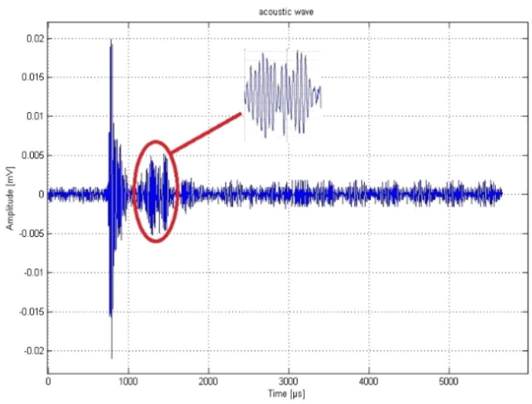


Figure 2. The burst envelope of a sample signal.

III. Test Set Up

A. Test Container

The size of this sample container is 80 cm×40 cm×30 cm which is made of steel Fig. 3.

B. Instrumentation and Test Set Up for Acoustic Tests

A μSAMOS Digital AE System (DSP) © Physical Acoustic measuring system was used to diagnosis and evaluation of PD occurring inside the oil. The integral sensors are completely enclosed in a stainless steel case and coated to minimize RFI/EMI interference. The 40dB pre-amplifier is situated inside the sensors. In addition, the critical input stage of the pre-amplifier is provided in such a way to have excellent temperature stability over the range of -45 ℃ to +80 ℃. For ease of use, the integral sensors utilize a standard coaxial cable with BNC connector to power the pre-amp and carry the output signal.

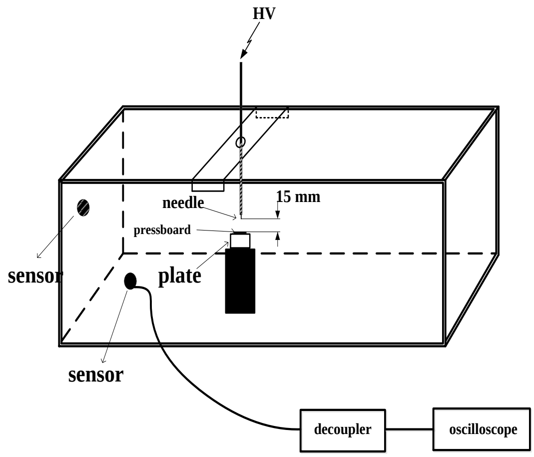


Figure 3. Dimension of sample container.

IV. Experimental Results

In this Section some experiment results and the comparison between them is presented. The aim of these experiments is evaluation of different situation in occurring PD such as with pressboard, without pressboard and with aged pressboard at different distances and analysis of results that are obtained from these experiments Fig. 4 and Fig. 5.

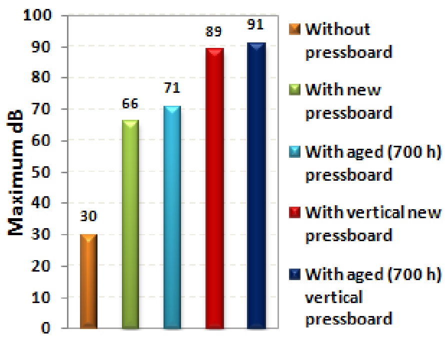


Figure 4. Comparison between maximum dB and different situations at 40 cm and 100 pC average PD via 150 kHz peak frequency sensor.

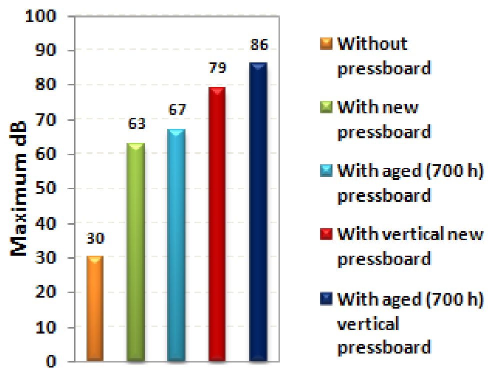


Figure 5. Comparison between maximum dB and different situations at 40 cm and 100 pC average PD via 75 kHz peak frequency sensor.

A. AE Inception PD

AE inception PD is one the most important factors which means the amounts of minimum pC needed to get acoustic signal, in this case this phenomenon is analyzed for 150 kHz sensor at different situations. Fig. 6 indicates the results for this experiment.

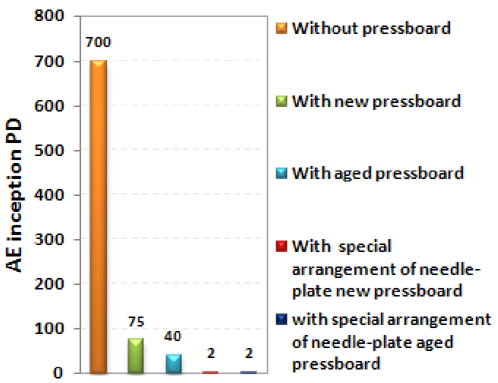


Figure 6. AE inception PD at different situations and some distance to the measuring point (40 cm).

As it can be resulted from the bar charts, minimum necessary apparent charge is much higher in situation without pressboard. There is an obvious reason for this difference. When PD occurred within pressboard, acoustic signals are much higher in lower apparent charge than without pressboard.

B. Comparison between AE Signal and PD Apparent Charge

In this Section two different types of pressboard (aged and new) in vertical and horizontal situations are compared.

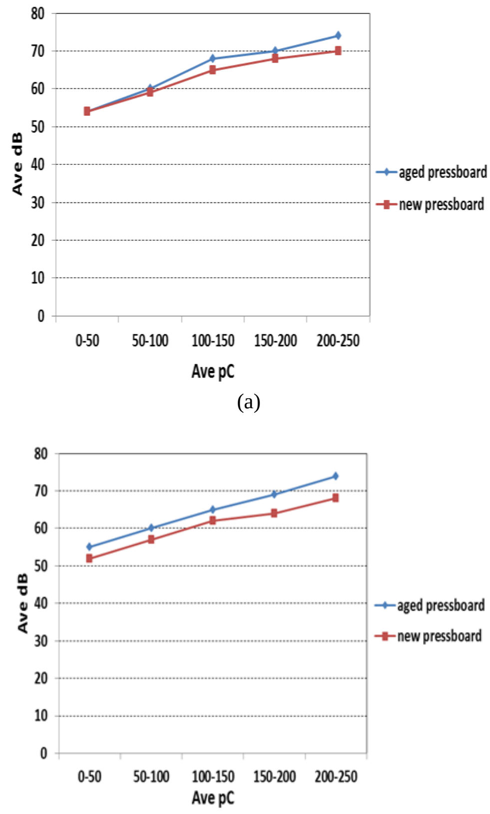
TABLE I. COMPARISON OF RESULTS OBTAINED FROM 75 KHZ

Average pC	Average dB	
	Aged pressboard	New pressboard
0-50	53	53
50-100	60	58
100-150	68	65
150-200	70	68
200-250	74	70

TABLE II. COMPARISON OF RESULTS OBTAINED FROM 150 KHZ

Average pC	Average dB	
	Aged pressboard	New pressboard
0-50	55	52
50-100	60	58
100-150	65	62
150-200	69	64
200-250	75	68

As is illustrated, the amount of magnitude which is sensed by sensors is higher for aged pressboard than new pressboard which can be seen in Table I and Table II. Personal viewing of this fact is because of this reason that through broken structure of pressboard acoustic wave can transmit with higher amplitude Fig. 7. When a pressboard is getting aged the molecular structures of the pressboard are broken, it gets softer than new pressboard and because of this reason the acoustic wave can go through the pressboard with higher amplitude.



(b)

Figure 7. Comparison between average dB of AE signal for aged and new pressboard and PD apparent charges at 40 cm via a) 75 kHz and b) 150 kHz peak frequency sensor.

V. TWO-DIMENSIONAL SIMULATION MODELS

The following two-dimensional model investigates the occurrence of a partial discharge within various geometries containing dielectric liquid.

A. Model 1

Sound propagates through a medium by means of wave motion [5]. In order to model the system, the wave equation was selected. The wave equation is a type of classical partial differential equation.

Next, the geometry of the model had to be constructed. Fig. 8 shows the first model that was constructed.

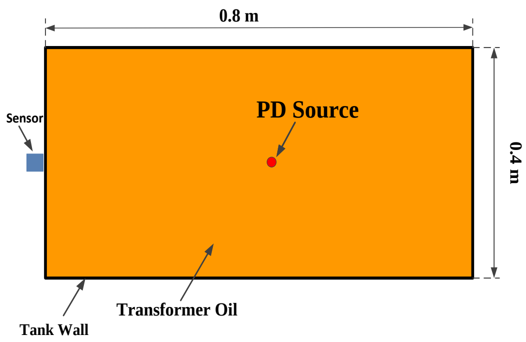


Figure 8. 2D geometry of model 1.

Note that the dimensions are arbitrary. The PD source was placed at co-ordinates:

$$(x , y) = (0.4, 0.2).$$

The first simulation was done as Fig. 8. The tank was set to be reflective, i.e. not permit any energy to pass through the tank walls. Consequently, the tank walls were set with the Neumann boundary condition with g = q = 0. Next, the PD source was set to emit a pulse of constant magnitude. It was therefore set with Dirichlet boundary conditions, with r =100, which specifies that the function would have a value of 100 on the boundary of the source of the partial discharge. The speed of sound in transformer oil was set at 1400 m/s (assuming factory conditions). The mass coefficient for the domain, da, was set to be 1 .The source term was set to zero. The model was then meshed. When acoustic waves are being modeled, it is important to ensure that there are enough mesh points in order to resolve the waveform accurately. This also ensures that effects such as interference are modeled correctly. In order to achieve this, it is recommended that there be 8 mesh points per wavelength. The system was then simulated for 20 milliseconds, in steps of 10 microseconds.

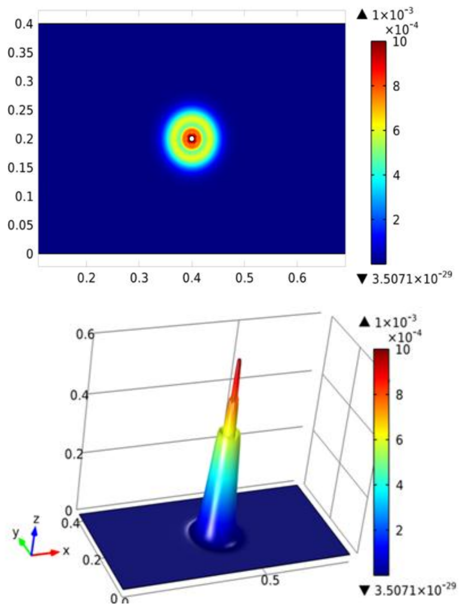
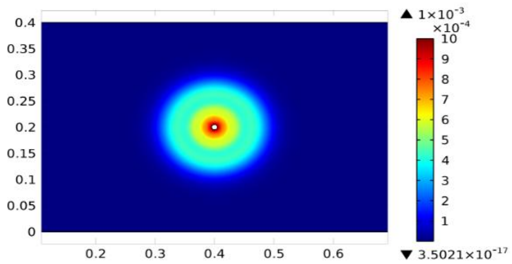
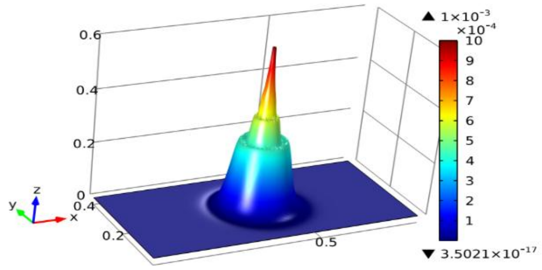


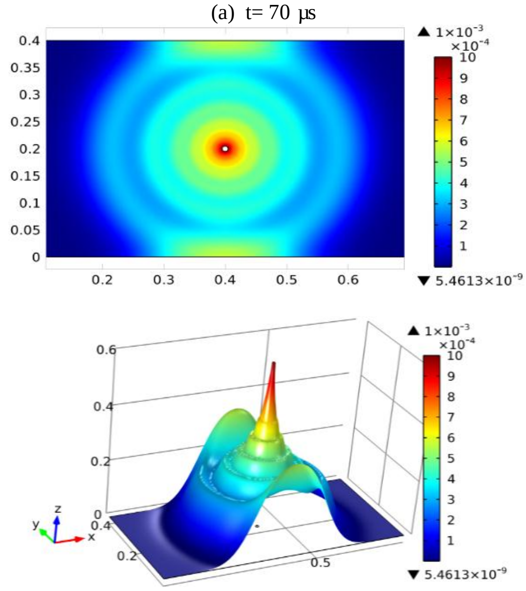
Figure 9. Initial propagation of the acoustic wave.

Fig. 9 represents the initial propagation of the acoustic wave from the PD source. The intensity of the PD was set to 100 N/m^2 under the boundary conditions tab. The intensity of the PD was specified to be constant for all time.

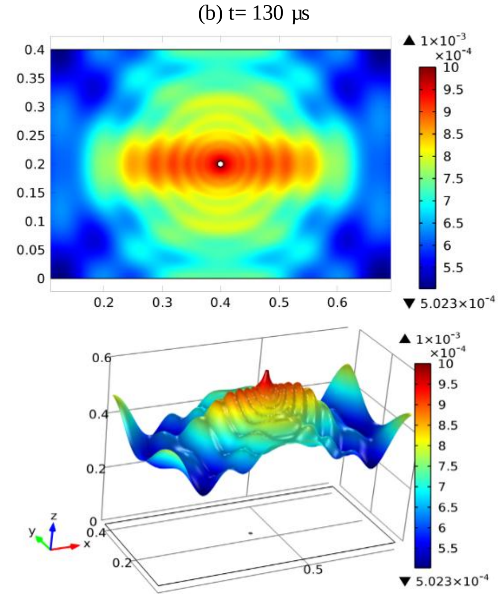




(a) t= 70 µs



(b) t= 130 µs



(c) t= 270 µs

Figure 10. Propagation of acoustic wave at various times, (a) 70 µs, (b) 130 µs, (c) 270 µs.

Note that at times 130 µs and 270 µs reflections at the transformer tank wall can be observed Fig. 10.

B. Model 2

In this model three sensors are placed on the tank wall and the PD location is assumed at the specified coordinates (x=0.3, y = 0.2). The main goal of this simulation is comparing the result of experimental tests with simulation. By comparing the result from simulation and experiment, it can be possible to determine the accuracy of acoustic arrival time with the electrical reference method and, also, be sure that localizing is accurate. Fig. 11 reveals the acoustic waves that are detected by AE sensors and the time difference between electrical trigger.

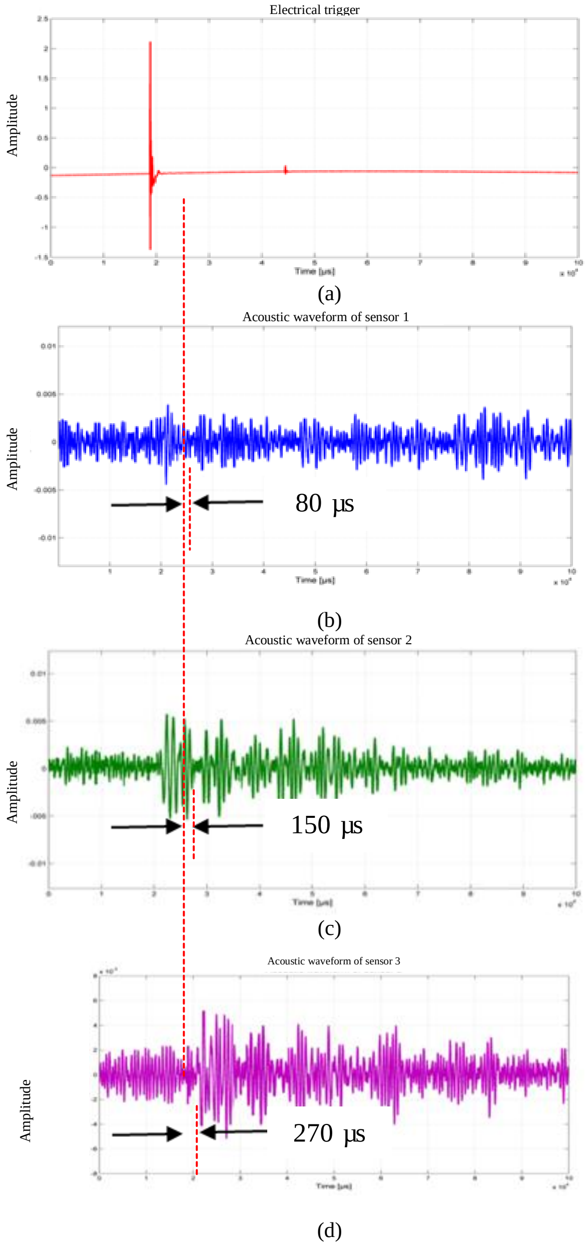


Figure 11. (a) Electrical trigger and acoustic waveform of (b) sensor 1, (c) sensor 2, (d) sensor 3.

The calculation for localizing PD can be mentioned by "Eq. (1) ~ (3)" [6].

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_s \cdot T_{s1})^2 \quad (1)$$

$$(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 = (v_s \cdot T_{s2})^2 \quad (2)$$

$$(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 = (v_s \cdot T_{s3})^2 \quad (3)$$

where, T_{si} is the measured arrival times, is v_s the measured arrival sound velocity and (x_{si}, y_{si}, z_{si}) are the Cartesian sensor coordinates.

We can derive from the above equations:

$$(x - 30)^2 + (y)^2 = 441 \quad (4)$$

$$(x - 20)^2 + (y - 20)^2 = 501.76 \quad (5)$$

$$(x - 50)^2 + (y)^2 = 1225 \quad (6)$$

The coordinates calculated by the "Eq. (4) ~ (6)" are x = 23 cm, y = 21 cm. According to this coordinates, the model that is used in simulation is shown in Fig. 12.

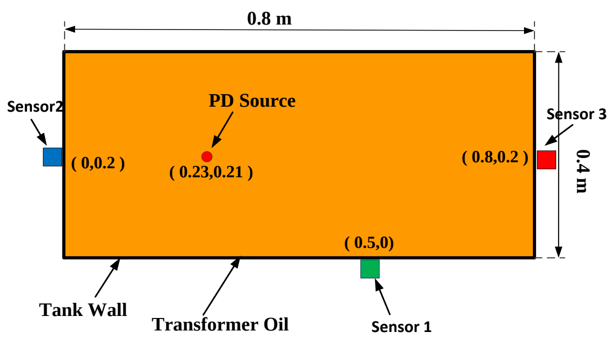


Figure 12. 2D geometry of model 2.

The system was simulated and the result of sensing the pressure of acoustic wave that was produced by PD source is presented in Fig. 13.

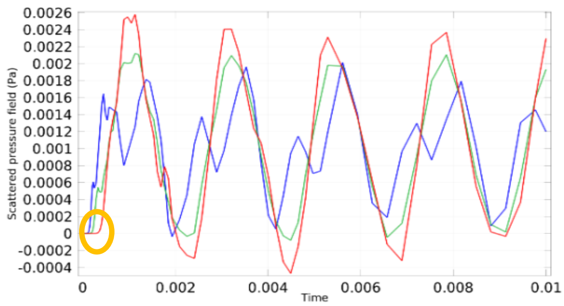


Figure 13. The result of simulation for model 2(scattered pressure field vs. time).

Fig. 14 shows the pressure during 0.01 second, as it can be seen in this figure the primary time that sensors start to detect the pressure is specified.

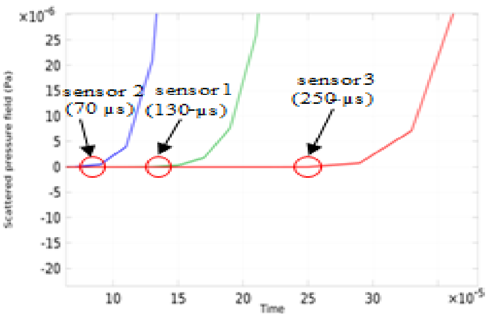


Figure 14. Time of sensing pressure by sensors (model 2).

By comparison between experimental and simulation results it can be confirmed that the value of error is acceptable.

Experimental results are given $t_1 = 150\,\mu s$, $t_2 = 80\,\mu s$ and $t_3 = 270\,\mu s$. On the other hand, simulation results are given $t_1 = 150\,\mu s$, $t_2 = 80\,\mu s$ and $t_3 = 270\,\mu s$.

These results show that the error value of this method is less than 10%.

VI. Conclusion

Experimental tests has been shown that the amount of maximum dB detected by sensors is much larger in creepage discharge than other situations, because of displacements of needle that amplifies the acoustic signal and, also, for aged pressboard (vertical and horizontal) the amplitude of all signals detected by sensors were higher than the other case with the new pressboard. Another subject that was evaluated is comparing the number of acoustic emission hits for different situations which were discussed above as specific PD apparent charge. All of the results can be seen more clearly as a signal waveforms in time and frequency domain.

One more important results that were evaluated is AE inception PD, the result of this experiment confirms this phenomenon that in without pressboard situation until 700 pC apparent charge no AE signal could be detected but for other situations the amount of AE inception PD decreases by a fix rate approximately for new, aged, new and aged creepage discharge respectively. Furthermore, the comparison between the amplitude of two sensors confirms that low PD apparent charges have higher AE frequency (up to 150 kHz) than high PD apparent charges.

The results obtained from this study confirm the combination of acoustic emission and electrical PD measuring method offers an excellent and real time solution for the detection as well as the localization of partial discharges.

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List of Symbols and Abbreviations

Symbol	Meaning	Symbol	Meaning
AE	acoustic emission	μs	microsecond
cm	centimeter	pC	picocoulomb
EMI	electromagnetic interference	PD	partial discharge
HV	high voltage	RFI	Radio frequency interference
kHz	kilohertz	UHF	ultra high frequency
FEM	Finite element method		

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