

*Full Length Research Paper*

# Detection and wavelet analysis of acoustic emission signal from partial discharge captured by multimode optical fiber and piezoelectric sensors in insulation oil

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High-voltage transformer is the most critical and expensive component in a power system network in order to ensure the stability of the system. Partial discharge (PD) detection is a technique widely used for high voltage equipment insulation condition monitoring and assessment. In this paper, the characteristics of two acoustic sensors multimode fiber optical (FO) and piezoelectric (PZT) sensor have been successfully explored and monitor the condition of high voltage equipment insulation. Both the sensors were placed in an oil tank in which optical breakdown was produced by neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (1064 nm) device. The optical signal of light source was linked by a photodetector which was also connected with multimode fiber (MMF) by means of a fiber optical adapter. The data obtained by both sensors were then analyzed in time and frequency domain.

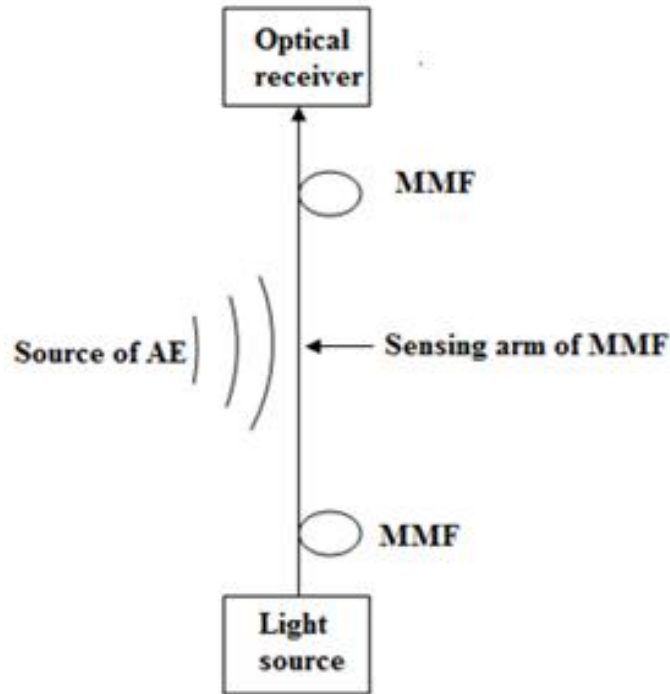
**Key words:** Fiber optical sensor, piezoelectric sensor, acoustic emission, optical breakdown, partial discharge, wavelet analysis.

## INTRODUCTION

The strong electric field has some hidden mysteries that appear as electrochemical and plasma-chemical reactions around the high voltage appliances like cables and transformers. One of the mysterious phenomenon is small electrical sparks that are present in an insulation medium which deteriorates the material as a result insulation becomes weak to sustain that high voltage and causes electrical breakdown. In case of cables, the entrapped gas condition in void spaces of the medium is the root cause of this phenomenon which changes the electro-physical nature of the medium. In case of power

transformers, high non-uniform electric field is present near the vicinity of devices which produce degradation and aging effect for insulators. This micro discharge activity near the high voltage devices is called partial discharge (PD) phenomenon which generates acoustic emission (AE) that can be measured and used for the diagnostic and monitoring study of power transformer before complete failure. In usual cases when electric field exceeds the limit of local ionization threshold of dielectric insulation, the PD phenomenon occurs (Boffi et al., 2006). Generally, insulation of high voltage power

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**Figure 1.** Diagram illustration of proposed multimode FO acting as AE sensor.

equipments remain in a degradation process during working and detection of partial discharge phenomena can predict its severe effect (Lamela-Rivera et al., 2003). It is important to save these costly equipments before failure by choosing a reliable diagnostic sensor to enhance the network reliability (Firoozi and Karami, 2011).

The PD produced AE phenomenon has gotten attention which emit electromagnetic emission as radio waves, light and heat waves. The energy produced by AE is in the audible and ultrasonic ranges and it can be used to detect the intensity and location of PD signal. In some previous studies, the frequency of PD in oil has been found in wideband range (10 to 500 kHz) (Frazao et al., 2010) which was detected by brand a broad band frequency piezoelectric (PZT) ultrasound sensor (model No. SDT1-028K). The fiber optical (FO) sensor has applications in many fields, and also can translate numerous measurands such as pressure, strain, temperature and AE into modulated light. AE are pressure variation in elastic medium (Posada-Roman et al., 2012) also known as stress wave emission. The conventional AE monitoring system was used as PZT sensor. The disadvantage of PZT sensor is low heat resistance due to the curie temperature of PZT, heavy monitoring system for multi-channel monitoring (Cho et al., 2006). Nowadays, AE is picked up by FO sensor due to some advantages such as small size, light weight, large wavelength, immunity to electromagnetic

interference noise, low power consumption, high sensitivity and low cost. These advantages make FO sensor a good candidate for acoustic detection as compared with conventional acoustic sensor.

FO sensor can be classified as intrinsic or extrinsic. In intrinsic FO sensor, the optical signal does not leave the fiber optical while extrinsic FO sensor carries light to and from an external optical device. Recently, optical fiber has been used as single-mode intrinsic FO sensor based on interferometer measurement of AE inside insulation oil (Zhiqiang et al., 2000; Macià et al., 2003). The main advantage of single-mode FO sensor is that it has high sensitivity when using long fiber in sensing arm, its drawback is that the frequency response is not much high. In this work, AE induced by optical breakdown and PD using multimode intrinsic FO sensor and PZT sensor and assessment of the condition of high voltage equipment insulation in insulation oil were monitored. The data of both sensors were analyzed for comparative study which have been discussed in the results.

### Principle of sensing

The simple optical AE detecting system consists of multimode optical fiber MMF linking light source and photo detector was adopted from the literature (Papy et al., 2003; Rippert et al., 2002). The complete strategy of AE detection is shown in Figure 1. This manuscript

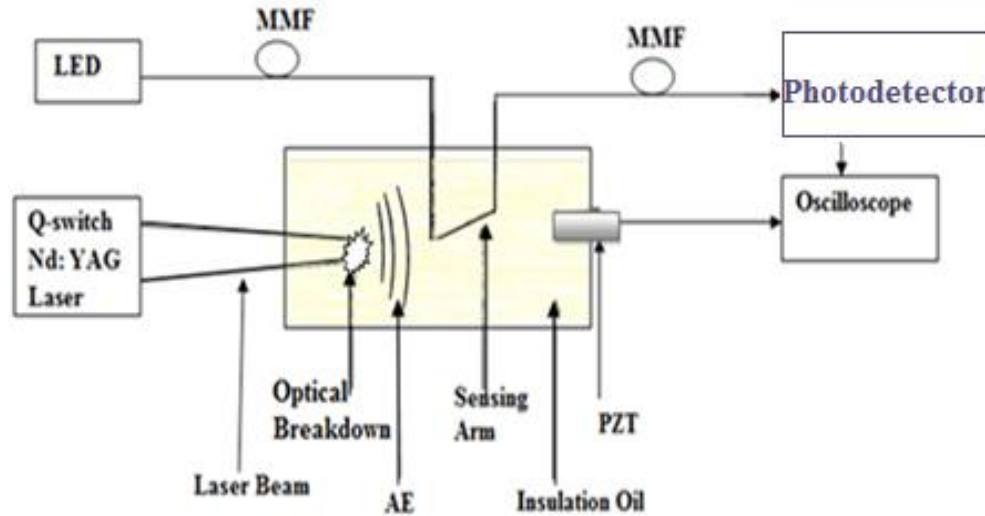


Figure 2. Experimental setup of FO and PZT sensors dipped in an oil tank.

describes a scheme for capturing partial discharge by multimode optical fiber in insulation oil. In the scheme, acoustic emission (AE) is induced by a neodymium-doped yttrium aluminum garnet; Nd:Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> (Nd:YAG) laser optical breakdown. The strong power density of laser plume approximately  $6 \times 10^{10} \text{ Wcm}^{-2}$  at the focal point is responsible to ionize the medium in plasma formation which is associated with a shock wave phenomenon. This shock wave propagation generates acoustic sound in the interacting medium and it disturbs the multimode mode fiber (MMF). In this experiment, two sensors consisting of multimode optical fiber and PZT sensor were used to capture AE induced by optical breakdown produced by Nd:YAG laser (1064 nm) in oil tank. The optical detection system consists of a light source 850 nm, optical receiver as photo detector (PD1) and MMF in which photo detector converts optical signal to electrical signal while MMF produces a link between light source and optical receiver unit.

The multimode mode fiber (MMF) is disturbed by AE and this induces the change in the refractive index of the MMF which causes polarization and phase shift of the laser beam. Phase modulation of the laser beam from MMF has to be converted into amplitude modulation, and only then the photo detector can read the effect of disturbances applied to the MMF. Therefore, it appears that the photo detector in the scheme might detect amplitude modulation of the laser beam due to some other effects. The change in refractive index is read according to the equation given (Bucaro and Hichman, 1979):

$$\Delta n = n_2 p_e P/2E \quad (1)$$

Where  $\Delta n$  is change in refractive index,  $p_e$  is effective photoelastic constant,  $P$  is applied pressure and  $E$  is

Young's Modulus.

The change in refractive will produce a phase change given by relationship:

$$\Delta \Phi = 2\pi \Delta n l/\lambda \quad (2)$$

Where  $l$  is interaction length,  $\lambda$  is optical wavelength,  $\Delta \Phi$  is phase change and  $\Delta n$  is change in refractive index.

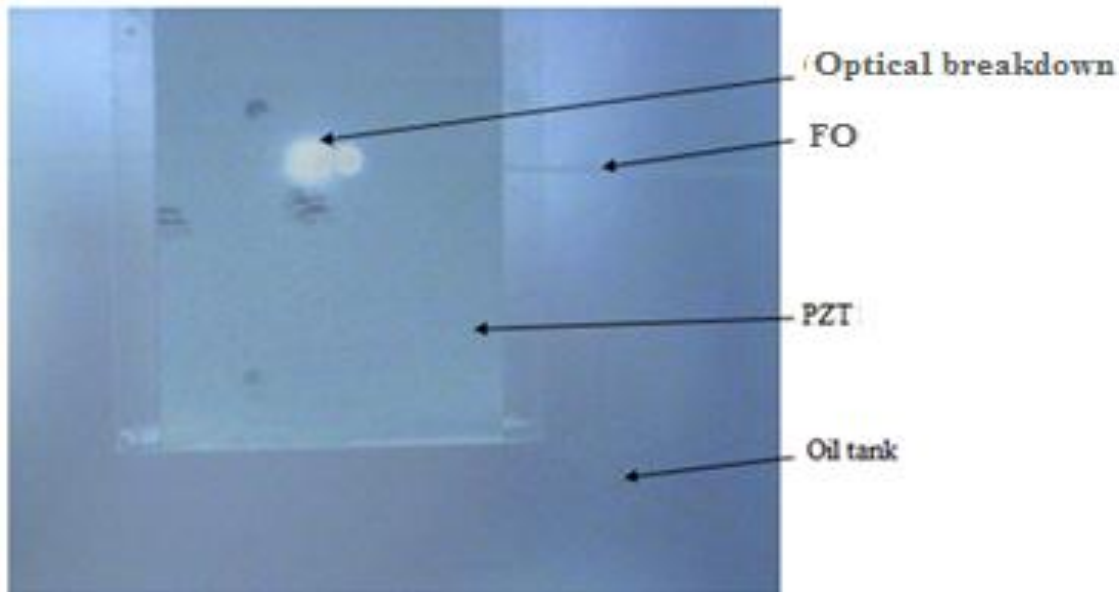
## METHODOLOGY

### Simulation of PD conditions

The schematic illustration of the experimental setup is described in Figure 2 in which light source consisting of a LED type OV-LS (850 nm) with output power 0.01 mW. The light is sent through MMF and the optical signal of light source is received by a photodetector (PD1) which is also connected with MMF by means of a fiber coupling adapter. The MMF is a graded index fiber with core diameter (50  $\mu\text{m}$ ) and its cladding diameter with acrylate coating layer is 125  $\mu\text{m}$ . The acrylate material has narrow band pass sensitivity to an ultrasound of AE which can give good results in oil insulation. Both sensors FO and PZT sensors were dipped in an oil tank (20  $\times$  15  $\times$  10 cm) for the detection of AE in insulation oil. The distance of FO was 3 cm from the AE source (optical breakdown of laser) while the distance of PZT sensor was 4 cm. The AE was induced by optical breakdown of Nd:YAG laser having 600 V is the Xe lamp voltage and 55 mJ average energy of one pulse. The outputs of optical signal of light for both sensors were recorded by a digital oscilloscope (TDS 3052C Digital phosphor Oscilloscope (500 MHz) which is shown in Figure 3.

### PD detection under insulation oil by two sensors FO and PZT

The schematic diagram of complete experimental setup to generate PD and its AE is described in Figure 9. The tank was filled with insulation oil so that the steel electrodes remain completely immersed in the middle of the tank. Two sensors, multimode optical fiber and PZT were mounted on the top with the same distance 8 cm from PD source. The optical fiber used is a multimode graded



**Figure 3.** Image of optical breakdown along with FO and PZT sensor in an oil tank.

index fiber having core diameter of 50  $\mu\text{m}$ . The cladding diameter of multimode fiber is 125  $\mu\text{m}$  with coating layer plus soft coating such as acrylate based elastomers. Length of FO sensor inside oil tank was 6 cm. The electrodes having 5 mm gaps were connected to 2.5 kV high voltage source to produce PD under insulation oil. The acoustic emission produced by PD was then sensed by two sensors. The partial discharge generated an electromagnetic emission between two electrodes which created an interference in the light passing through the OF connected to the oscilloscope.

## RESULTS AND DISCUSSION

### Simulation of PD conditions

The graph of acoustic signals was detected by two acoustic sensors, FO and PZT sensors shown in Figure 4. The output of acoustic signals of both sensors in time domain analysis indicates that, the acoustic signal comprises of sinusoidal pulses with gradual decrease in intensity. Two acoustic signals have the same time period (1  $\mu\text{s}$ ) with voltage (5 mV) with frequency 180 kHz of AE generated by optical breakdown of laser, which is considered a perfect value for detection of AE (Lundgaard, 1992a; Lundgaard, 1992b; Kawada et al., 1984; Howells and Norton, 1981; Eleftherion, 1999). An analysis of detected acoustic signals depicted in Figure 4 dictates that both sensors are eligible to provide interesting information of acoustic signal induced by optical breakdown of Nd: YAG laser in oil. A typical shape of acoustic signal of both sensors is shown in Figure 5 which gives information of peak values of signals. The peak value of FO sensor has a high 0.015 V, while PZT sensor has a low peak signal of 0.002 V. It was also observed that acoustic signal of PZT sensor has a multi

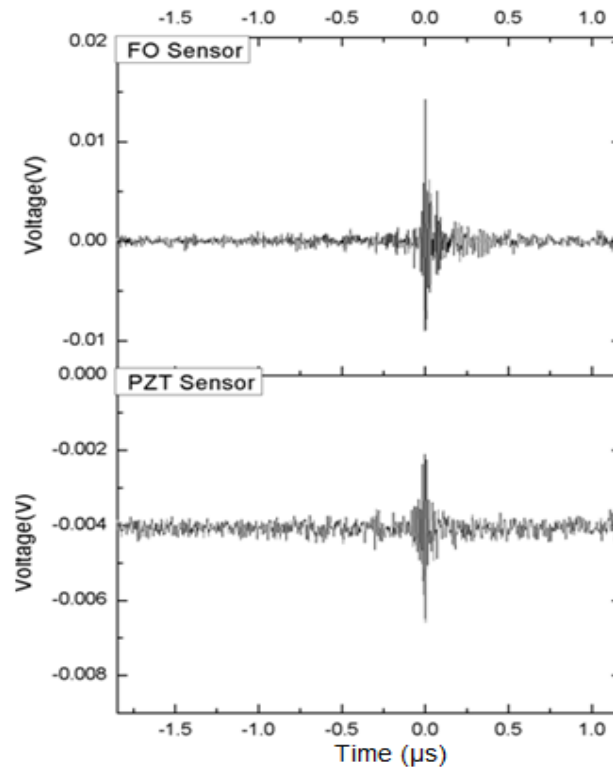
reflection due to degeneration of received signal while FO sensor has detected a clear acoustic signal.

In frequency domain analysis, Figures 6 to 8 shows the fast fourier transform (FFT) analysis of stored data of time domain signals of photodetector which was performed for both sensors. Figure 6 shows FFT of amplitude spectrum of both sensors (a) spectrum of FO sensor (b) spectrum of PZT sensor. Figure 6(a) shows acoustic wave of FO sensor with range (10 to 450 kHz); it can observe the frequency response of FO sensor consisting of a series of peaks which have maximum amplitude (0.1 mV/Hz) at frequency 180 kHz while PZT sensor has one peak which has maximum amplitude (0.4 mV/Hz) at frequency 180 kHz. Figure 7 shows the histogram of amplitude with the distance of FO sensor. It was observed that FO sensor has higher amplitude at distance (3 cm) between AE source and FO sensor.

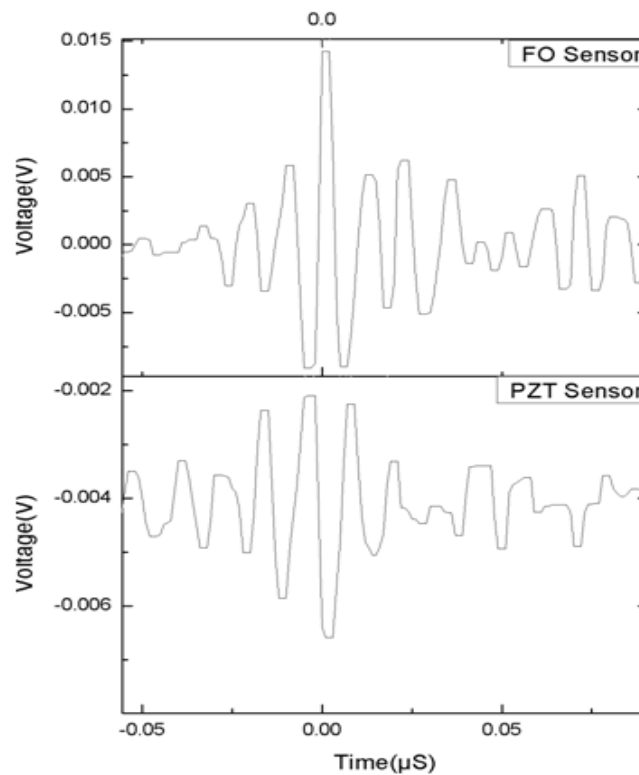
Figure 8(a and b) show FFT spectrum of both sensors in oil. Figure 8(a) shows frequency response of FO sensor, which shows that the level of signal at 180 kHz was -20 dB with noise floor -55 dB which shows FO sensor has a resolution of 35 dB above noise floor. Figure 8(b) shows FFT spectrum of PZT, which has the signal level at 180 kHz was -35 dB with noise level -50 dB, which has resolution 15 dB above noise floor. It is clear that the FO sensor has better resolution than PZT sensor.

### PD detection under insulation oil by two sensors FO and PZT

The data of AE signal output of both sensors were



**Figure 4.** The graph of acoustic signal detected by FO and PZT sensors.



**Figure 5.** Typical shape of acoustic signal of FO and PZT sensors.

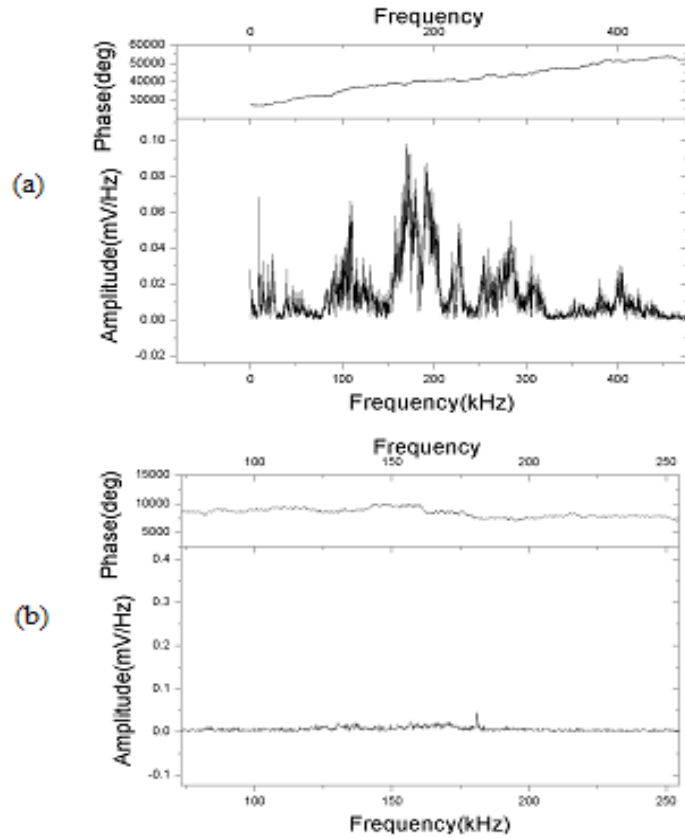


Figure 6. FFT spectrum of acoustic signal at frequency 180 kHz in oil (a) amplitude of FO sensor (b) amplitude of PZT sensor.

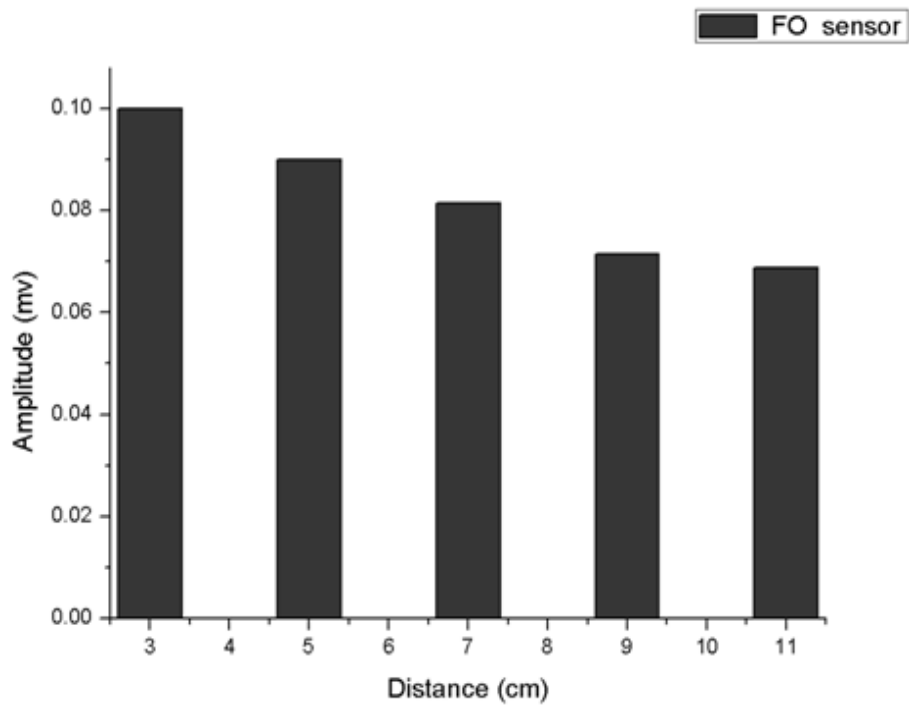
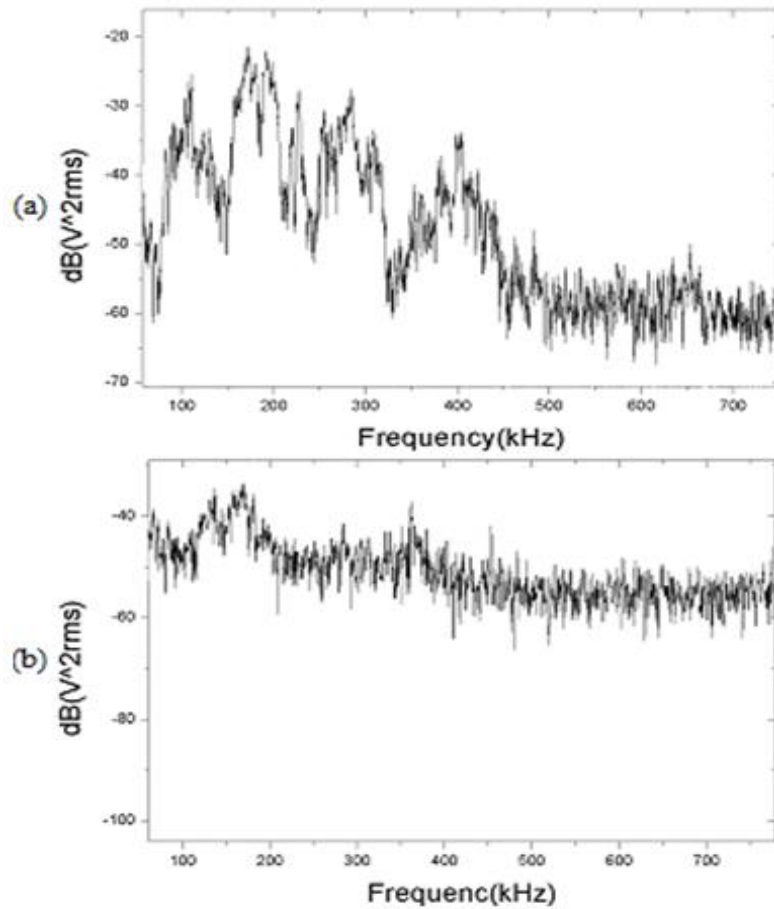
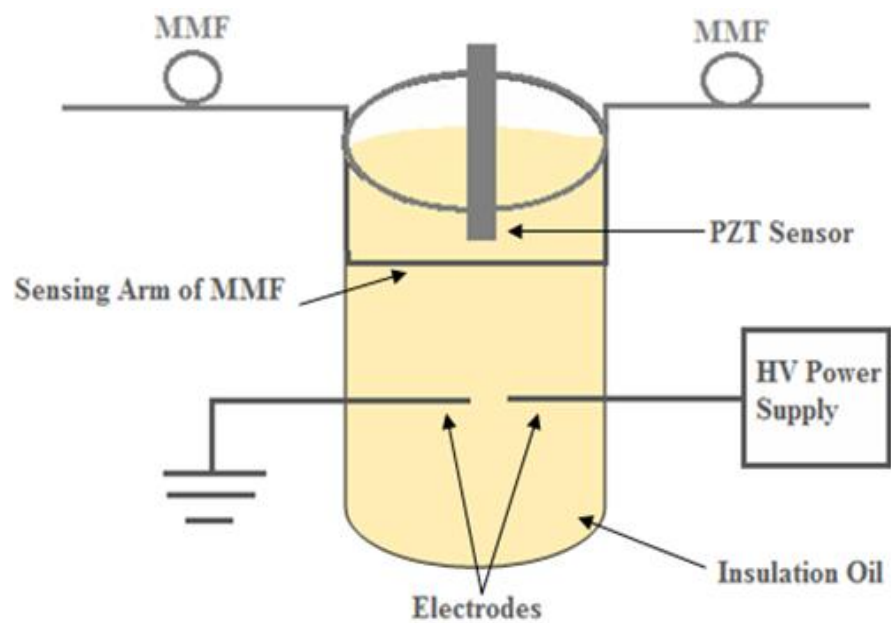


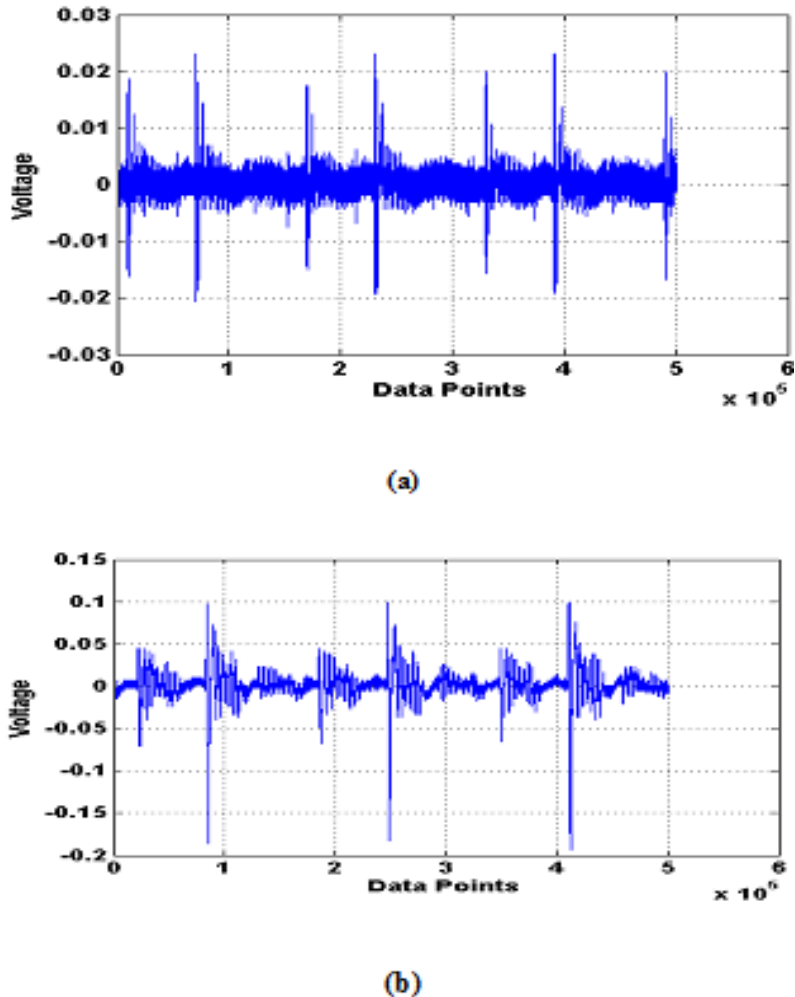
Figure 7. Histogram of amplitude with distance for FO sensor.



**Figure 8.** (a) Frequency response of FO. (b) Frequency response of PZT sensors in oil.



**Figure 9.** High voltage produced PD and AE signal insulation oil.



**Figure 10.** (a) The captured partial discharge signal from the piezoelectric sensor. (b) The captured partial discharge signal from the fibre optical sensor.

recorded by four channels digital Lecory oscilloscope. The typical spectra of acoustic signals detected by both sensors PZT and FOS are shown in Figure 10. These results show that acoustic signal generated by PD comprises sinusoidal pulses which have gradual decreasing trends in their intensity. Although, the shapes and peaks of the signal output of both sensors follow the same oscillatory pattern; it was also observed that PZT sensor has a noisy signal due to multi reflections which cause degeneration of the received signals. In case of PZT, it is difficult to determine exactly how long a PD will last while FOS gives a clear picture of acoustic wave.

#### WAVELET TRANSFORM ANALYSIS OF PD SIGNAL

The acoustic signals have some non-linear characteristics due to the PD and that make somewhat difficult to deal with because of nonlinear and the random like behavior of the system. The problem of non-linearity

of the acoustic signal is overcome by using wavelet transform (WT) which is a strong tool for feature picking-up. It is equivalent to filters. Details (dn or hn) are produced by high pass filters and approximations (an or ln) are produced by low-pass filters. Due to the multidimensional characters which the wavelets possess, they are able to adjust their scale to the nature of the signal features (James, 1999). It can zoom in or zoom out the required details just like a microscope. Furthermore, wavelets can decompose a signal to give dilations and translations parameters, so the information in the signal is presented by these parameters in the form of frequencies. The Matlab wavelet toolbox is used to verify the algorithm where discrete wavelet transforms (DWT) is used to analyze the signals. The coefficients are generated and the features from the signal are extracted. Wavelet is a good tool to analyze the non-linear signals as it represents the features both in time and frequency domains (Ming and Birlasekaran, 2002; Gulski and Kreuger, 1992; Ma et al., 1992). The WT analyses the



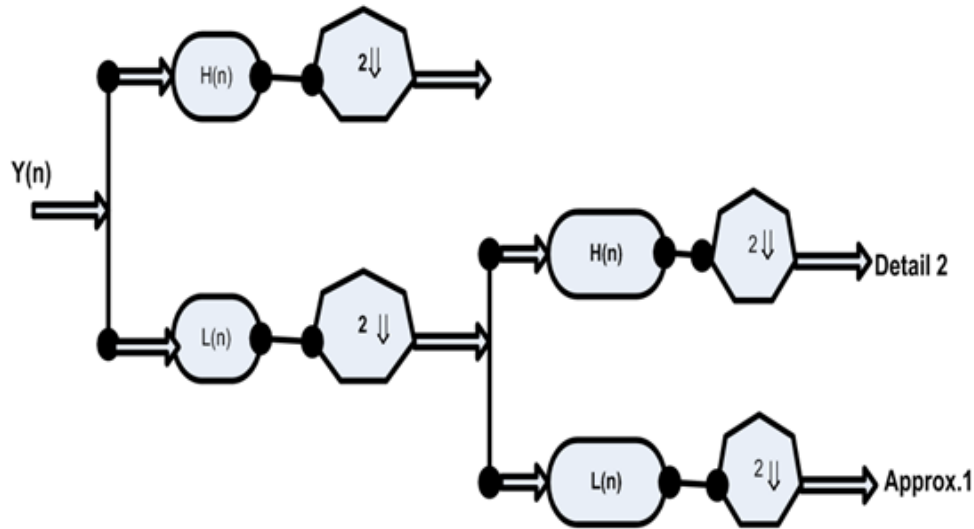


Figure 11. The filtering process in the DWT.

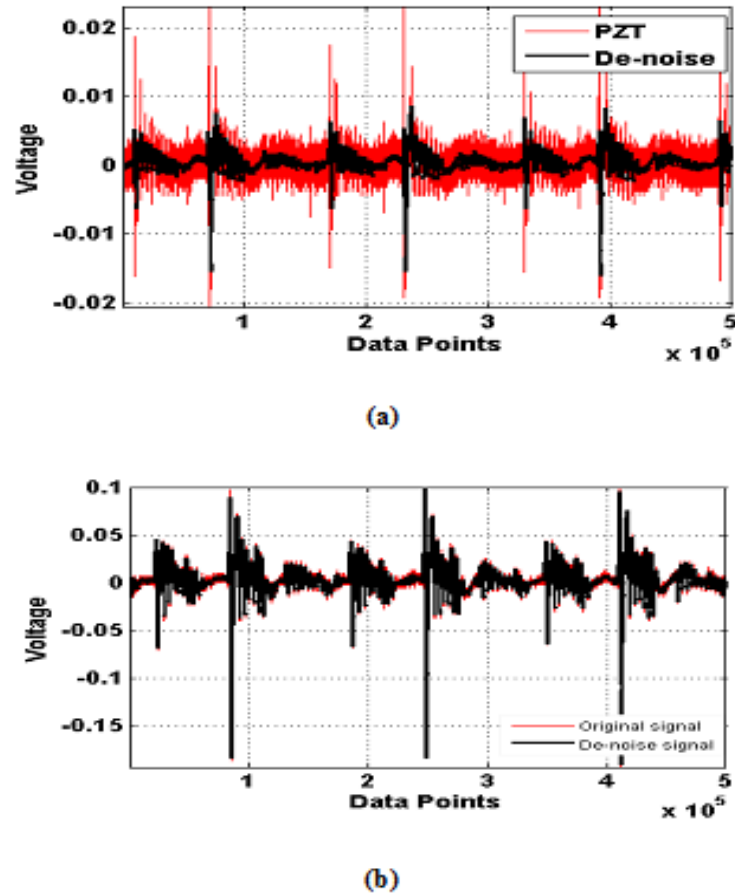
non-periodic partial discharge signal and adopts the principle of linking of frequency scales. Generally, the DWT is used for this mission (Suresh, 2005; Ma et al., 2005).

One of the capabilities of DWT is that, it produces details to show high frequency information and approximations to show low frequency information. The most suitable mother wavelet for detecting PD acoustic signals is the Daubechies (Db) wavelets transform, which is capable of detecting short duration, fast decaying, high frequency and low amplitude signals. The decomposition process in the WT consists of many numbers of filters from (Db2 to Db44), so the most promising number depends upon how they minimize the aliasing. Basically, in the first stage, the captured signal is divided into two of the frequency bandwidth, which is then passed to high pass and low pass filters (Lalitha and Satish, 2000). After that, the output signal from the low pass filter is further subdivided into two of the frequency bandwidth and sent to the following stage (Geethanjali et al., 2005). This procedure continues until the predetermined number of levels is reached. The output of the final stage represents the same captured signal but at different frequency bands (Pihler et al., 1997; Mao and Aggarawal, 2000), which was realized in Figure 11. The suitable selection of mother wavelet depends on this application. Among the various de-noising techniques, from the point of view of the de-noising effect and the computing time, the DWT method is the most suitable. Finally, the Daubechies wavelet is most appropriate for treating PD (Zhou et al., 2006; Coifman et al., 1992).

In this study, the adaptability of the Daubechies wavelets of orders 2 has been evaluated, and results have shown its superiority. It is befitting to select a suitable number of breakup levels based on the nature of

the signal. Based on acoustic signal features, it is seen that four levels of decomposition is the best choice, because it described the PD acoustic signal in a more mindful and symptomatic way. This decision is mainly due to the low frequency band (approximation), which is the most valuable part of the acoustic signal (Daubechies, 1992; Al-geelani, 2012). The detected signal due to the partial discharge using a piezoelectric sensor is shown in Figure 10(a) where the high spikes in addition to the background noise mixed-up with the PD signal can be seen. Thus, the Daubechies 2 wavelet transform has been used, at level 4 of decomposition for the wavelet analysis applied to the signals obtained in this analysis. Selection of mother wavelet is a core question often asked, but a generalized answer seems to be still elusive even to signal processing experts. Also, no direct answers are available in the literature. As per this fact, the present work was based on a trial-and error and guided by hints published in literature on similar types of work. Being well aware of this issue, the authors have examined many wavelets and found Daubechies' wavelet to be the most suitable. Thus, the wavelet technique has successfully de-noised the captured piezoelectric PD signal as can be seen in Figure 12(a) without compromising the unique feature of the signal which can be realized by the peaks and the values. This is the strength of wavelet analysis.

Figure 10(b) shows the captured partial discharge signal using a fibre optical sensor, this signal is more accurate than the one detected using the piezoelectric sensor, since the amplitude is higher and very sharp in terms of peaks and valleys. The process of de-noising is shown in Figure 12(b) where the original signal or the captured partial discharge signal using the optical fibre and the de-noise signal are approximately the same, overlapping in a



**Figure 12.** (a) The captured and the de-noise signal from the piezoelectric sensor. (b) The captured the de-noise partial discharge signal from the fibre optical sensor.

very good manner. This means that the signal detected by optical fibre cable is a noise free signal. Figure 13 shows that there is some similarity between the original and approximation (a1, a2, a3 and a4) signals more than details signals (d1, d2, d3 and d4). For the aforementioned reason, the approximation (a4) is a very good representation of the original signal. The levels of detail d1, d2, d3 and d4 contain useful higher frequency information. These subseries exhibit some regularities, similar shapes and compare mean values. Irregularities in those levels of detail are due to signal random variations and measurement errors. For the aforementioned reason, the approximation (a4) is a very good representation of the original signal. The most essential information can be found at this level. The accuracy of the approximation can be explained by the fact that there remains only a low-frequency signal corrupted by noises which was removed.

Figure 14 shows that As can be seen from the levels of approximations (a1, a2, a3 and a4) that no much difference occurred between the different levels; this is because the fiber optical sensor has detected the partial

discharge signal with a very low level of noise. The details (d1, d2, d3 and d4) show the high frequency content where the level d4 is the best representation for the signal.

## Conclusion

A comparative study of FO and PZT sensors for AE has successfully been done. The data of both sensors were analyzed in time and frequency domain. The time domain analysis showed that the acoustic signal of FO sensor has big peak signal (0.015 V), while peak signal of PZT was (0.002 V). The FO sensor could capture acoustic signal with less noise. The FFT analysis of time domain signal of store data of both sensors showed FO sensor within the range (10 to 450 kHz), it can be observed that the frequency response of FO sensor consisted of a series of peaks which have maximum amplitude (0.1 mV/Hz) at frequency 180 kHz whereas, PZT sensor has one peak which has maximum amplitude of 0.4 mV/Hz at frequency 180 kHz. This means that the amplitude of FO

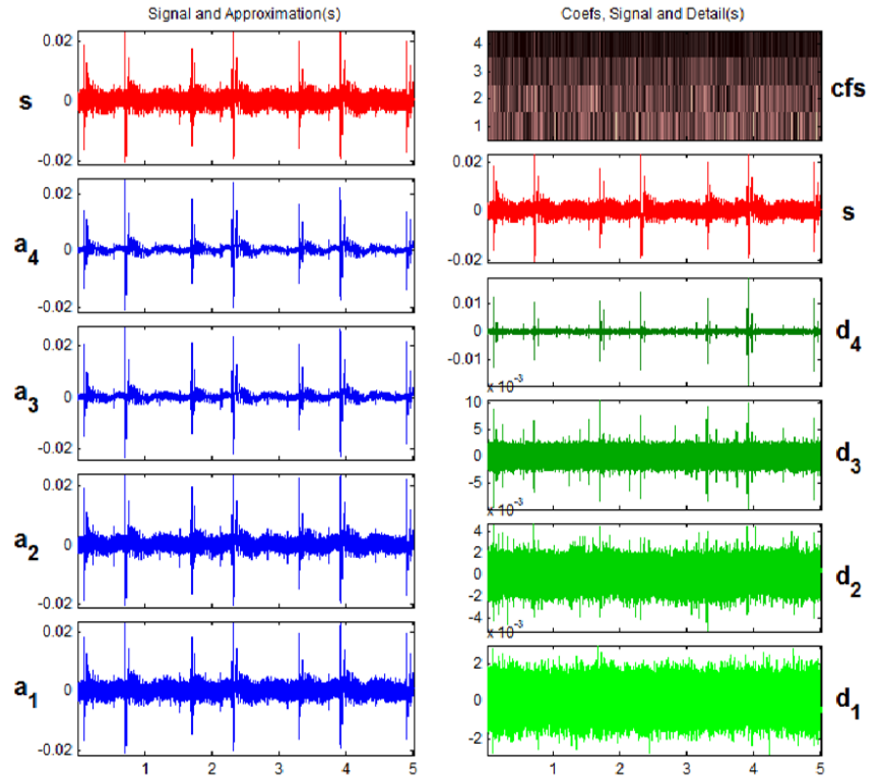


Figure 13. The 4 decomposition levels of DWT of the PZT PD signal.

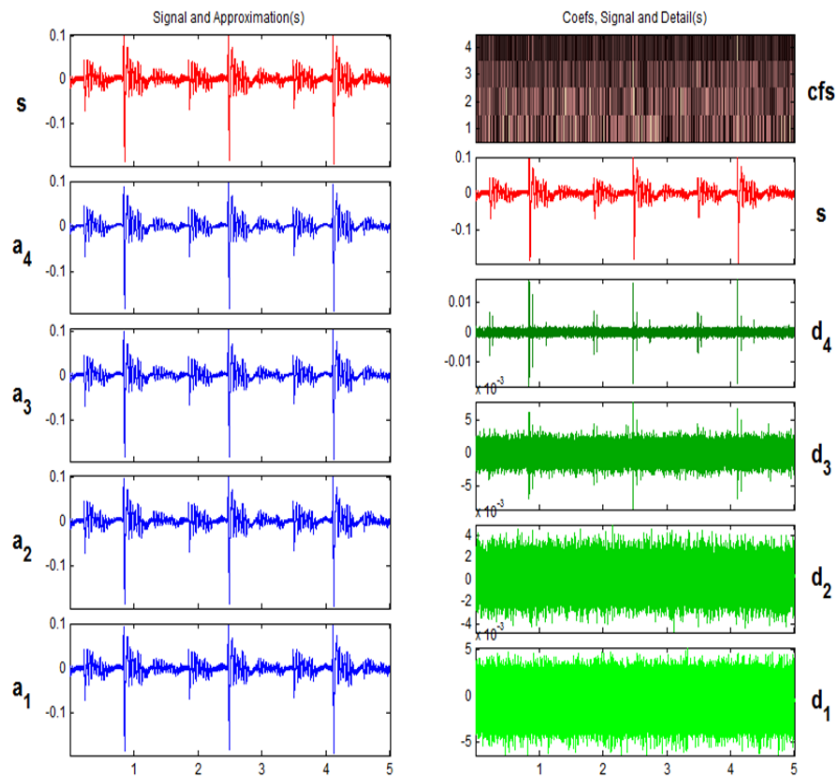


Figure 14. The 4 decomposition levels of DWT of the optical PD signal.

sensor is much higher than the PZT sensor. Also, FFT analysis showed a frequency response of FO and PZT sensors, which shows that FO sensor has signal level -20 dB at 180 kHz with noise floor -55 dB, while PZT sensor has signal level -35 dB at 180 kHz with noise floor -50 dB. It is clear that the resolution of FO sensor was very high (35 dB) above noise floor as compared with resolution of PZT sensor (15 dB) above noise floor. These experimental results are interesting and suggest that both sensors have peculiar characteristics for the detection of AE and can be used for any PD detection requirements. Wavelet analysis of PD signals shows that the signal detected by optical fibre cable is a noise free signal.

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