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Detection and Monitoring of Partial Discharge in Palm Oil Using Capacitive and PZT Sensors: A Comparative Study

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ABSTRACT

Background: Precise detection and monitoring of partial discharge (PD) in electric transformer oil for permanent protection avoiding expensive maintenance remain challenging. The insulation quality of high power transformer decides its endurance and the PD assisted sudden failure often results hazard and high economic loss. PD phenomena is the presence of small electrical spark inside the insulating oil originating due to the electrical breakdown of interior air or from the emergence of giant non-uniform electric field can cause transformers power outage. **Objective:** Oil insulation quality in high voltage transformer can be evaluated via efficient detection and screening of PD. Conventionally, the acoustic emission (AE) that appears in the proximity of discharge region is exploited for examining PD. PD activities that give rise to electric field emission are measured to monitor the possibility of potential failures. Truly, acoustical sensors due to their attractive features such as small size, light weight, reliable, accurate, clear, and louder measurement with superior signal-to-noise ratio are promising for detecting and locating PD. **Results:** We measure and analyze the PD activities in natural palm-oil using acoustic piezoelectric transducer (PZT) and capacitive sensor (CS) to compare their sensitivities. Both sensors are immersed in an oil tank fitted with two steel electrodes to apply high-voltages. High-pass filters are used to eliminate the noise below the frequency range of 100 kHz. The resolution of PD peaks is determined in time and frequency domain via FFT. Yet, the achieved higher resolution of PZT (~ 16 dB) compare to that of CS (~ 12 dB) for voltages greater than 10 kV demonstrates that the former one with enhanced signal band-width is superior. **Conclusion:** The impressive features of the results suggest that both the sensors are potential for monitoring PD and assessing transformers oil insulation quality as preventive measure from breakdown.

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INTRODUCTION

Absolutely, high-voltage (HV) equipment are the most important and integrated component in power transmission grid system. Their performance efficiency is critically decided by the stability and insulation qualities. Any part of these apparatus suffering from a slight failure leads to decreased reliability of the network. Consequently, the expenses rise exponentially because of the action of refurbish, maintenance, and service. The life-long function of the HV power transformers in particular, is highly associated with the oil insulation and materials characteristics. Thus, the fault diagnostics and the evaluation of oil quality are the major significant steps to safeguard such transformers from operational failures. After long-time usage the transformers insulation weakens due to the occurrence of various stresses, temperature variations, and increased moisture and oxygen contents. Certainly, the HV transformers are exceptionally expensive and the emergence of PD mediated insulation breakage results major financial loss (Tenbohlen, Denissov, Hoek, & Markalous, 2008).

Generally, to protect the equipment from major setback the operations of all the dielectric are disabled soon after the occurrence PD activities. Nevertheless, this action not only degrades the insulation configuration but creates certain problems and irreparable damage including breakdown . Furthermore, the deterioration of oil insulation system is believed to be one of the possible reasons for transformer failure and related breakdown if undetected. Despite many efforts, the quest for achieving different kinds of highly reliable insulation

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oil system compatible with source exhaustion and leakage sites due to environmental damage is ever-increasing (Lemke, Strehl, Markalous, & Weissenberg, 2008). This continual development forced researchers to identify and quantify the PD signal in many types of vegetable oils for their future use in the transformers. It is acknowledged that palm oil could potentially replace the costly mineral oil presently used in the HV power transformers. Palm oil possesses several advantages such as high cooling ability, excellent insulating performance, decent bio-degradability, and stable oxidation (Kato *et al*., 2009; Li, Zhang, Zou, Grzybowski, & Zahn, 2012). The PD detection is considered as a precautionary measure and widely used parameter in the HV insulation equipment to certify their reliability against extreme threat. Designers and engineers dealing with HV power systems network who are responsible for their installation and maintenance must have thorough understanding of PD mechanisms. It is very essential to monitor and inspect regularly the dielectric features and its development processes in HV transformers (Park, Jo, Kim, & Kil, 2013). The striking features of PD signal in palm oil are examined via its state of insulation using PZT and CS. Responses are measures in the time and frequency domain. The resolutions of PD peaks for both the sensors are determined and their sensitivities are compared.

1. *Overview of PD Detection:*

In the past, PD monitoring and measurement techniques are widely practiced as an identification mode for new HV apparatus to uncover possible construction problems such as design faults, insulation materials defects or even poor workmanship. They are also exploited for detecting the deteriorated parts of equipment insulation under normal operation (Kamata, 1986). Lately, several methods are introduced to monitor and assess the condition of the dielectric attitude, especially the transformers oil insulation. Methods based on the measurements including the resistivity of insulation, response of PD, gas analysis and the dielectric loss are successfully demonstrated. The dielectric loss and insulation resistance determinations are performed off-line. They are applicable for interval accuracy identification and not for the on-line diagnosis (Phung, James, Blackburn, & Su, 1991; Santosh Kumar, Gupta, Udayakumar, & Venkatasami, 2008). Conversely, PD detection and gas analysis are employed as on-line diagnostic technique. Electric measurement and acoustic signal detection are the two main methods for PD diagnostic. The former one possesses many advantages such as measurement precision and high sensitivity. Alternatively, vulnerability to noise is considered as major problem (Saha, 2003). Furthermore, installing the coupling network throughout the process for ultra-high voltage transformers is intricate. PD measurement via acoustical signal detection commonly uses acoustic sensors. Their electrical insulation strongly protects them from environmental electromagnetic noise and makes them superior than electric sensors (Judd, Yang, & Hunter, 2005). Despite several studies the method for precise detection and monitoring of PD signal is far from being achieved.

We used electrical (capacitive) and acoustic (PZT) sensors to capture and analyze the PD signal by immersing them in a palm oil tank containing two steel electrodes connected to the high-voltage source. PD signal is recorded using four channels oscilloscope. A comparison between these sensors is made by analyzing the time and frequency spectrum of PD signal.

A. *Electrical Detection:*

Precise measurement in the variations of PD signals in transformers through electrical quantities is suitable and convenient under laboratory conditions. Nonetheless, it provides incorrect readings for on-site circumstances such as monitoring transformers in-service. This inaccuracy in the observations is due the interference and disturbance that appear at high environmental noise level of transformers (Meunier & Vaillancourt, 1996). Recently, electrical signal measurement using Pulse Capacitive Coupler (PCC) and the Ultra-High Frequency (UHF) methods became attractive. Figure 1 displays the working of a non-conventional UHF sensor. The resistance against external noise makes it suitable for connecting inside the transformer. Electrical resonance emanating from the PD activity is the most measured quantity in UHF technique, especially in the frequency range up to 1.5 GHz (Boltze, Markalous, Bolliger, Ciprietti, & Chiu, 2009). In addition to detection, this method is capable of locating the origin of PD. This technique is beneficial because of very low signal attenuation and low noise levels. Susceptibility to noise is considers as the primary limitation of UHF method due to the presence of transformer’s surrounding electrical noise at high levels (McArthur, Strachan, & Jahn, 2004). Sometimes, the appearance of incorrect detection in the on-line state of transformer arises from the difficulty to distinguish PD from the noise signal due to short PD pulse width(Rubio-Serrano *et al*., 2012). The CS also called PCC that is used for PD measurement picks up the electric field energy of the PD pulses with a metallic electrode structure or additional metallic foil layers placed inside the medium. This is sometimes realized as a dual capacitive sensor working in differential mode to discriminate noise from critical PD(Hikita, Okabe, Murase, & Okubo, 2008).

B. *Acoustic Detection:*

Acoustic technique is meritorious due to its instantaneous energy release from PD activity, where the source points of AE produce an explosion effect.

The wave propagation in all directions allows this activity to be detected by sensors following the same mechanism as piezoelectric sensors (Bengtsson, Leijon, Ming, & Jonsson, 1995). This method can be used for both on-line and off-line performances. This sensor is capable of localizing the PD source position via the observation of phase delay or the amplitude attenuation of acoustic waves while propagating in the transformer oil. These acoustic (mechanical) waves are transmitted in radial direction from the PD source. This explosion of mechanical energy vaporizes some fluid material and thereby develops a pressure field inside the transformer tank. The PZT sensor (Figure 2) placed inside the oil tank can reduce the received signal attenuation and minimize the interference noise in AE (Dukes & Culpan, 1984). By calculating the acoustic wave arrival time this method identifies the PD source location with the aid of multiple location sensors. The surrounding noise leading to some complication in detection of the PD signal can easily be eliminated (Boczar, 2001; Ramírez-Niño & Pascacio, 2009). The implementation of PZT is limited for outside (on the wall) mounting of the transformer because it captures interferences from noisy environment.

2. *Experimental Setup:*

Figure 3 illustrates the detail experimental setting for PD detection using CS and PZT sensor placed inside a cylindrical palm oil tank modeled as transformer. The transformer is further connected to metallic electrode using high-voltage cables to generate electrical sparks mimicking as PD. The applied voltages are monitored via a digital oscilloscope. These electrodes separated by a gap of 5 mm are connected to the HV power supply ranges between 5-15 kV to produce PD in the insulating oil. The acoustic PZT sensor and the CS are placed within the palm-oil tank at variable positions. High-voltage probes are used to capture the source signal for indicating any possible alteration in the wave shape during discharge. Both the sensors are connected to a high-pass filter to eliminate the undesirable low frequency noises.

Multi-channel oscilloscope (Lecroy 300A) provides the banner specifications, feature set and user interface to simplify the data acquisitions and shorten debug time. It possesses a wide (7.5”) and bright display, long 500 kpts/Ch memories up to 2 GS/s you useful for easy capture and observing every detail of the waveform. Furthermore, using the USB ports waveforms can quickly be saved, stored or printed screen captures in a computer. Mathematical and measurement tools are helpful in understanding the waveforms pattern and replay mode allows one to look at the history of capture. This oscilloscope is used to record the PD signal by reducing the effects of noise.

High Voltage Probe (Tektronix) having attenuation ratio of 1000:1, High Voltage (20 kV DC/40 kV), Peak (100 ms Pulse Width), High Bandwidth (75 MHz), Silicone Dielectric, Optional 1000X Coding, Wide Compensation Range (7 to 49 pF) and Heavy Duty Versatile Ground Lead and Clip are utilized. High Pass Filter with pass range above 150 kHz connected to the both sensors to eliminate the unwanted signals below 150 kHz such as noise. Other instruments including 15 KVA, 20/22kV transformer, 0-220 V variac12, grounded tank (for the PD generation process) with 10 cm diameter, sharp edge metallic steel electrode, digital oscilloscope, and high voltage cables (25 kV) are employed. Figure 3 depicts a foil capacitor which comprised of two layers of metal foil sheets separated by dielectric and insulating polymer sheets. CS is alike a flexible card which can easily be mounted on the high voltage cable. Generally, in CS two sheets of aluminium foils are separated by two acrylic sheets of the same dimensions where the formers are connected by flexible wires and the whole assembly is laminated with the latter one. The outer wires are connected to the measurement circuit of the system. The acrylic or polymer sheets thickness are similar to paper. It contains plug connectors of coaxial wire for the oscilloscope.

The working principle of PD detection is depicted in Figure 5. The data acquired from the oscilloscope in excel format is transferred to ORIGIN-PRO software and analyzed in time and frequency domain to obtain the resolution of PD peaks. The piezo film sensor element selected for this test was the SDT1-028K made by Measurement Specialties, Inc. It was selected because (a) it is very sensitive to low level mechanical movements, (b) it has an electrostatic shield located on both sides of the element (to minimize 50/60 Hz AC line interference), (c) it is responsive to low frequency movements in the 0.7 – 12 Hz range of interest, (d) the foil size was about right (1 inch / 2.54 cm long) and (e) it has an integral connector and cable for simple connections. Operating in a reciprocal fashion, changes in length generate a corresponding charge and hence, voltage to appear on the electrodes of the film

RESULTS AND DISCUSSION

Figure 6 illustrates all the waveforms obtained from the sensors and HV probe. The response appears in the channel 1 from the HV probe, in channel 2 from PZT sensor and in channel 3 from the CS. Partial discharge arriving simultaneously at both sensors in the same phase is observed as ripple waves upon igniting the electrodes via high voltages. The minimum of the high-voltage peaks of the PD signal picked up by the two sensors are found to be different. Furthermore, the sensitivity of PZT is observed to be low for the acoustic signal at the minimum part of the high voltage. This Behavior is noticeable to naked-eye. The response of PZT sensor

(Channel 2) is unable to indicate the presence of low discharge level. However, the response of CS (Channel 3) is accompanied by a prominent peak of electric field at various values of PD.

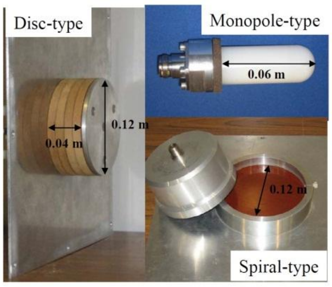

Fig. 1: Three types of UHF sensors (Pinpart & Judd, 2009).

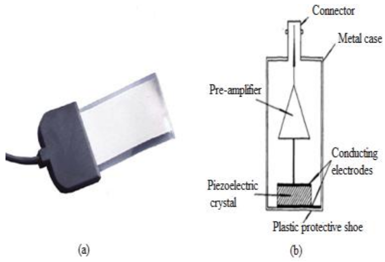

Fig. 2: PZT film sensor (a) with connectors and (b) typical design (Meunier & Vaillancourt, 1996).

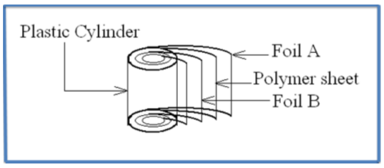

Fig. 3: Typical view of a capacitive sensor.

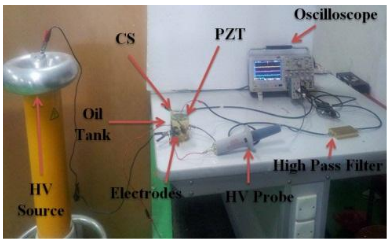

Fig. 4: Experimental set up for PD signal detection in palm oil using PZT and capacitive sensors.

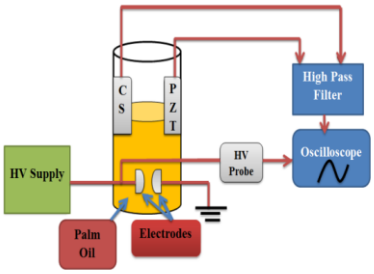

Fig. 5: Experimental design with components and detection processes using two sensors.

A. Time Domain Analyses:

Figure 7 to 9 displays the signal in the time domain as captured by the CS and PZT sensor together with the high voltage probe signal at 5, 10 and 13 kV peak power, respectively. The minima of the high voltage peaks for the acoustic and electrical

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sensors are observed to be entirely different. The characteristics of PD signal and its detailed information contents obtained from both the sensors are analyzed and compared in the time domain. The shapes and peaks of signals from both sensors reveal oscillatory pattern. The HV probe usage is an indicator of the occurrence of PD signal in the oil insulation. The acoustic signal generated by PD as shown in Figure 6 is comprised of sinusoidal pulses with gradually decreasing trend in their intensity. The PZT sensor exhibits noisy signal, while the CS displays rise of electrical pulses at certain time. The response of PZT sensor in Figure 7 reveal less noisy signal with prominent PD peaks due to the application of high voltage stressed on the oil tank. Conversely, the CS detects large number of PD pulses due to the electric field driven activity which is correlated to the high (10 kV) applied voltages on the electrodes. From Figure 8 it is apparent that at higher voltage (13 kV) the PZT sensor displays less noisy PD signal. This observation is ascribed to the occurrence of high levels of partial discharge activity where the palm oil suffers from poor insulation performance. Furthermore, both the sensors demonstrate equal number of PD peaks simultaneously. This same arrival time of the PD signal for the both sensors is due their close proximity in the oil tank.

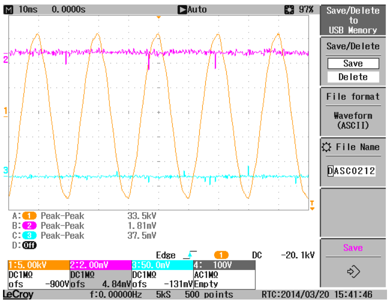

Fig. 6: Patterns for three (HV, CS and PZT sensor) signals from oscilloscope at break down voltage.

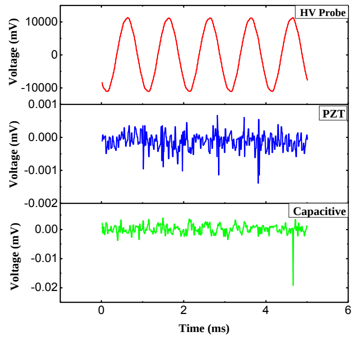

Fig. 7: Signal in time domain captured by CS (green) and PZT (blue) sensor alongside the high voltage probe (red) signal at 5 kV.

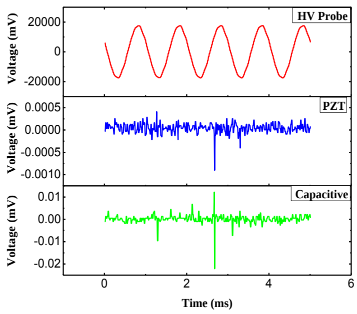

Fig. 8: Signal in time domain captured by CS (green) and PZT (blue) sensor alongside the high voltage probe (red) signal at 10 kV.

B. Frequency Domain Analyses

Figure 10(a) and (b) displays the comparison between the sensitivities of the signal in the frequency domain as captured by the CS and PZT sensor at 13 kV peak power. The frequency for the both sensors is varied in the range of 100-500 kHz. The frequency response of PZT is consisted of a series of peaks with maximum amplitude ~0.1

mV/Hz at frequency of 180 kHz. The most essential information achieved from the FFT analysis is the resolution of PD peaks and the effective influence of the noise level on the detected peaks. The Fast Fourier Transform analysis of the time domain signal is performed. The acoustic and electromagnetic signal detected by the PZT and CS in the frequency domain reveals several peaks. The characteristic responses of AE recorded by the multi-channel oscilloscope reveals the evidence of PD. At high voltage (13 kV p-p) in charging the electrodes, the arc discharges as wave ripples are observed which are detected concurrently by two sensors.

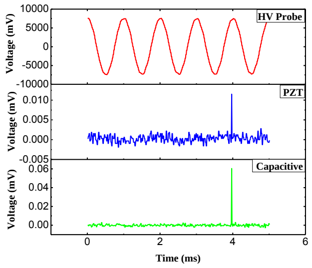

Fig. 9: Signal in time domain captured by CS (green) and PZT (blue) sensor alongside the high voltage probe (red) signal at 13 kV.

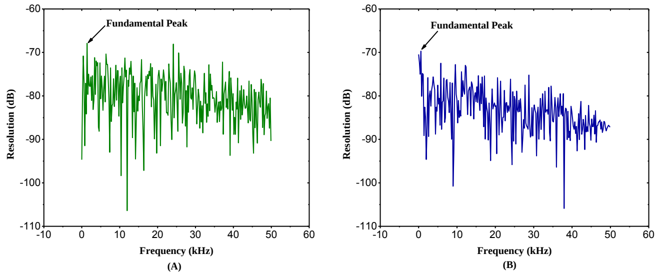

Fig. 10: The signal captured by (a) CS (green) and (b) PZT (blue) sensor at 13 kV in frequency domain after FFT.

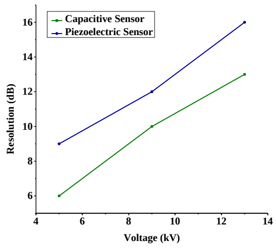

Fig. 11: PD peaks resolution features of CS and PZT sensor.

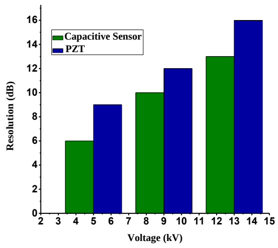

Fig. 12: Comparison displaying the levels of resolution of CS and PZT sensor.

The dips and peaks of the acoustic and electromagnetic signal captured by the two sensors are found to be very different. The CS and PZT are positioned at a distance of 3 cm from the PD location. The velocity of sound in palm oil is measured to be 1.53 mm/µs. The value of captured signal at the fundamental peak for the CS is found to be -68 dB due and the noise level is -81 dB signifying a resolution of 13 dB above the noise floor. However, for PZT sensor the signal level at the fundamental peak is -69 dB and the intrusive noise flat was –85 dB implying that the signal clearance is 16 dB above the noise ground which is much better than CS. Furthermore, the resolution displayed by PZT is determined to be higher than that of CS at 13 kV p-p.

Table 1: Voltage dependent resolution of the CS and PZT sensor.

Voltage kV(RMS)	PZT Sensor			CS		
	Value at Main Peak (dB)	Noise Floor (dB)	Resolution at Peak (dB)	Value at Main Peak (dB)	Noise Floor (dB)	Resolution at Peak(dB)
5 ± 0.05	-81 ± 2	-90 ± 2	9 ± 2	-74 ± 2	-80 ± 2	6 ± 2
10 ± 0.05	-72 ± 2	-84 ± 2	12 ± 2	-70 ± 2	-80 ± 2	10 ± 2
13 ± 0.05	-69 ± 2	-85 ± 2	16 ± 2	-68 ± 2	-81 ± 2	13 ± 2

FFT analysis for the frequency response of the both sensors exhibiting their different clear signal level inside the palm oil tank is demonstrated in Figure11 and 12. It is clear that PZT sensor acquires superior properties in terms of clear image and good resolution above the noise floor in comparison to the CS. Conversely, the CS suffers from fewer clearance images and poor resolution above the noise flat. The resolution achieved by two sensors at different electrode voltages are listed Table.1

The time-domain analysis shows that the acoustic signal of PZT sensor is accompanied by a pronounced peak ~ 0.015 V, while the peak for CS appears at 0.002 V. PZT sensor reveals salient features such as high noise ranges in low level of high voltages (below 10 kV) and ability of detecting more PD peaks in certain time with less noise value. In contrast, the CS has more stable performance in multistage of high voltage. It has respectable properties including detecting the activity of PD with the large number of peaks. It is a suitable sensor for partial discharge phenomena and signal monitor in low level of high voltages. Furthermore, it is observed that the information about the signal is not affected by the change of the distance between the electrodes, even though the breakdown point influences by the increase of the distance. Increasing oil insulation can withstand extra level of high voltages.

3. Conclusion:

A comparative study of the CS and PZT sensor are successfully performed. Sensitivity of CS and PZT sensor for acoustic signal sensing are ascertained and measured. A cylindrical tank filled with palm oil mimicking a transformer is used, where the sensors are immersed. The PD signals are generated in the insulating oil via electrical sparks generated from two steel electrodes by applying high-voltages. The noise below the 100 kHz frequency is eliminated using High-pass filters and multi-channel oscilloscope is used to record the PD signal. FFT is used to transform the signal from time to frequency domain to determine the resolution of PD peaks. PZT sensor with enhanced signal band-width achieved higher resolution compared to that of CS for voltages greater than 10 kV. The data of all sensors are analyzed in the time and frequency domain via PD peak resolution analysis. Time domain spectra exhibits many peaks for CS in comparison to the PZT sensor signal. The higher sensitivity of CS than PZT sensor in the time domain is demonstrated. Conversely, the FFT spectrum of the PZT approved the higher resolution at different voltages. While the capacitive sensor detects a high number of PD peaks but displays the same performance for the low and high level of high voltages applied on the electrodes. The admirable features of the result demonstrate that CS and PZT sensor are prospective for the detection and monitoring of PD activity in palm oil insulating medium for HV transformer.

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