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Monitoring Partial Discharge in Transformer Oil Using a Newly Designed Single Mode Fiber Optic Sensor

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Abstract: The quest of finding accurate fault diagnostics and assessing the oil quality of electrical power transformer for life-long safeguard is never-ending. The longevity of transformers function is critically decided by the quality of its insulation. Developing a sensor for accurate and efficient detection of partial discharge (PD) in high voltage transformer oil in assessing its insulation quality and integrity is the key issue. The optical fiber sensor being economical and highly reliable can provide ultimate safety due to total isolation from the high voltage line. The small electrical sparks called PD appears in the insulating oil due to the electrical breakdown of interior air or the occurrence of highly non-uniform electric field needs to be monitored. The acoustic emission (AE) that occurs near the discharge zone is used to detect PD. We compare the sensitivity of single mode fiber optic sensor (FOS) with conventional capacitive sensor (CS). These sensors are immersed in a mineral oil tank (transformer) fitted with two steel electrodes those are connected to different high voltage sources. The data are analyzed in time and frequency domain to obtain the resolution of PD peaks. The achieved higher resolution of FOS (~9 dB) compare to that of CS (~15 dB) for voltages greater than 15 kV demonstrates that single mode optical fiber is capable of serving as acoustic sensor with enhanced signal band-width. The admirable features of the result suggest that our method may constitute a basis for precise detection of AE and PD as per different smart standards with approved specifications.

Keywords: Acoustic emission, capacitive sensor, mineral oil, Optical fiber sensor, partial discharge.

Introduction

Undoubtedly, the endurance and working efficiency of high voltage (HV) electrical transformers are decisively judged by the insulating quality of its mineral oil. The judgment of faults and the assessment of oil quality is one of the most important sources in protecting transformers from potential failures that occur during operation [1]. Generally, this insulation deteriorates over a time span due to the cumulative effects such as mechanical, thermal and electrical stresses, temperature, moisture and oxygen. The HV transformers are exceptionally expensive and the damage in insulation system often causes high economic loss. In the past, several methodologies are adopted for the diagnosis of faults in the transformer oil to assess the oil quality and different smart standards are developed with the approved specifications including IEEE and IEC standard. Despite many efforts the efficient and precise determination of the nature of faults and subsequent rectification mechanism for superior performance is far from being understood [2, 3].

A significant mode for improving the reliability of HV insulation systems are regular monitoring and measurements of PD. The interpretation of such measurements aims at extracting information regarding insulation defects from the measured data and their subsequent use for estimating the risk of insulation failure. Modeling of PD provides essential insight of insulation diagnostics [4, 5]. According to IEC 60270 standard [6, 7], PD is localized electrical release that only partially bridges the insulation between conductors whose chance of occurrence adjacent to a conductor is probabilistic. It occurs when the electric field in the transformer exceeds the local ionization threshold of the dielectric insulation. In fact, short streamers of current built up by the electric field intensify in a finite region. The energy emitted during PD may range from audible to ultrasonic region of the electromagnetic spectrum. Specifically, PD generates acoustic, radio, heat and light waves. Interestingly, the PD detection is widely used for monitoring and assessing the insulation condition of high voltage equipment. However, determination of the mechanism of PD requires thorough characterizations of the insulating oil quality and careful fault diagnosis in HV transformer [8, 9]

Generally, two types of electrical detection techniques are used for analyzing PD. First one is the ultra high frequency (UHF) and the other one is the capacitive coupler technique. Figure 1 displays three different types of ultra-high frequency (UHF) sensors used to detect PD in unconventional method. This technique uses the 300-1500 MHz frequency band and avoids the local interference at 100 MHz. Furthermore, the immunity against external noise makes it suitable for connecting inside the transformer [10-12].

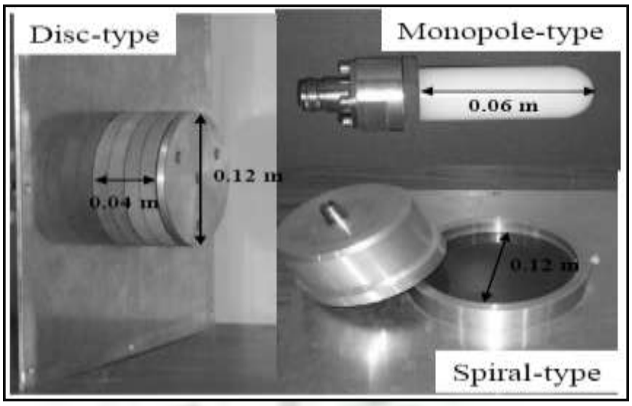


Figure 1: Disc, monopole and spiral -type UHF sensors [10].

The chemical techniques for detecting PD in high voltage transformer oil are based on determining various gases released during the discharge. Currently, two chemical methods such as High Performance Liquid Chromatography (HPLC) and the Dissolved Gas Analysis (DGA) are popularly used. HPLC analyses the PD expelled byproducts including forms of glucose induced by the degradation of insulation oil. While DGA analyses the accumulated volume of gas produced from PD. In fact, chemical methods are unsuitable for real time monitoring. Existing chemical as well as electrical methods are incapable of locating and determining the exact sources of PD [13].

Acoustic methods identify and locate the position of PD by examining the amplitude attenuation or phase delay of the acoustic waves propagated from the PD. These acoustic waves can be detected using sensors called Piezoelectric Transducers (PZT) as shown in Fig. 2. The application of PZT becomes limited while mounted outside (on the wall) the transformer because it captures interferences from noisy environment. However, noise and signal attenuation of the sensor can significantly be reduced by placing it inside the oil tank [14-17]

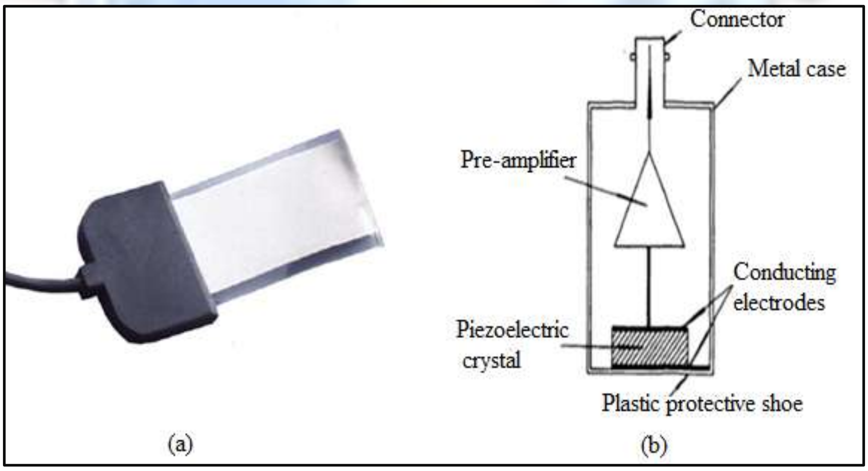


Figure 2: Piezoelectric transducer sensor: (a) film sensor with connectors and (b) typical design [8].

Functionally, optical based methods of PD detection based on fiber optic intrinsic interferometers of Michelson are highly sensitive and accurate. Fiber optic acoustic sensors being small in size and light weight produce enhanced frequency response and possess considerably high immunity against electromagnetic interference. They can easily measure a wide range of chemical and physical parameters. Apart from PD detection and assessment, optical fiber acoustic sensors are successfully exploited in sundry applications such as underwater hydrophones, constructing non-destructive diagnosis, analyzing material properties, traffic monitoring and vehicle detection [18-21]. We report the characteristics of PD in mineral oil by examining the condition of high voltage transformer insulation using single mode FOS. The response is analyzed in time and frequency domain. The resolutions of PD peaks are determined and compared with CS to examine the sensitivity.

Detection of acoustic emission

Acoustic emission in the proximity of high voltage discharge zone renders the variables for PD detection and monitoring. The signal for FOS is achieved from the modulating effects of AE using 850 nm light source (laser) where a photo-detector is used to convert optical signal into electrical signal. The AE modulated 850 nm laser signals in the fiber acts as input to the photo-detector. As mentioned before, AE signal is originated from the creation of high voltage discharge between two electrodes. Figure 3 illustrates how the single mode optical fiber picks up the AE signal. This AE generates dynamic mechanical strain which produces linear variation on the photo-elasticity of the single mode fiber. The optical signal from the light source gets modulated by the refractive index variation at the micro-bends due to induced energy from AE. The change in the refractive index (n) follows,

$$\partial n = 2npe * P/2E$$
(1)

where∂n is the change in refractive index, pe is the effective photo-elastic constant, P is the applied pressure and E is the Young's Modulus. This change in refractive index produces the following phase shift,

$$\partial \emptyset = 2n\, \partial n * I/\lambda$$
(2)

whereI is the interaction length, λ is the light wavelength and $\partial \emptyset$ is the phase difference.

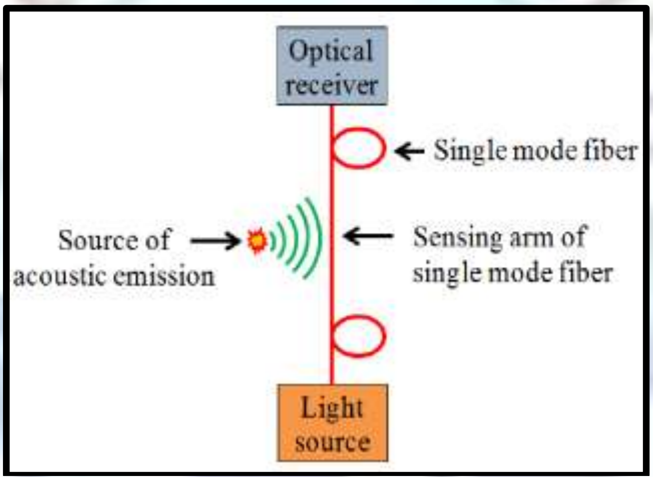


Figure 3: Schematic for AE detection.

Capacitive sensor

Figure 4 depicts a foil capacitor consisting of two layers of metal foil sheets isolated by dielectric and insulating polymer sheets. The shape of the capacitive sensor is very similar to a flexible card which can easily be mounted on the high voltage cable. Usually, in CS two sheets of aluminium foils are separated by two acrylic sheets of the same dimensions. The aluminium sheets are connected by flexible wires and the whole assembly is laminated with the acrylic sheets. The outer wires are connected to the measurement circuit of the system.

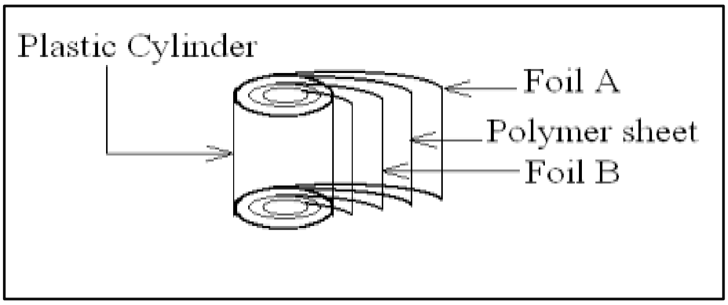


Figure 4: Design of a capacitive sensor.

Experimental

The CS and single mode FOS used for the PD detection are immersed in a cylindrical oil tank of dimension 8 cm x 12 cm as shown in Fig. 5. The PD is simulated using a 5 kV power source (1-50 kV, 50 Hz) within two round shaped steel electrodes separated by a distance of 6 millimeter. Specifically, the generation of high voltage discharge (mimicking PD) produced AE between two steel electrodes. These acoustic waves created interference in the light that propagates through the optical fiber of FOS. High voltage discharge parameters are collected using a multi-channel TDS 3052C Digital Phosphor Oscilloscope (500 MHz) via HV probe (Tektronix). These discharge parameters are measured by connecting the probe having attenuation ratio of 1000:1 (20 kV DC/40kV AC) to the third channel of the digital oscilloscope.

A light source consisting of a LED type OV-LS (850 nm) with output power 0.01 mW is coupled to the single mode optical fiber (type PS 1250/ 1500, ID=30690 /B-00BA) of length 1 meter as shown in Fig. 6. Output from FOS is picked up by the photo-detector (BPX65) which is connected to the optical fiber via a fiber adapter. The cladding diameter of the fiber is 125 µm including the soft coating of acrylate based elastomers. It is worth mentioning that the use of acrylate material possessing narrower band pass sensitivity to ultrasound of AE exhibits superior performance in PD detection. The photo-detector associated with FOS for converting the light into electrical signal is further enhanced using low noise amplifier. The CS is placed inside the oil tank at the same distance from the electrodes.

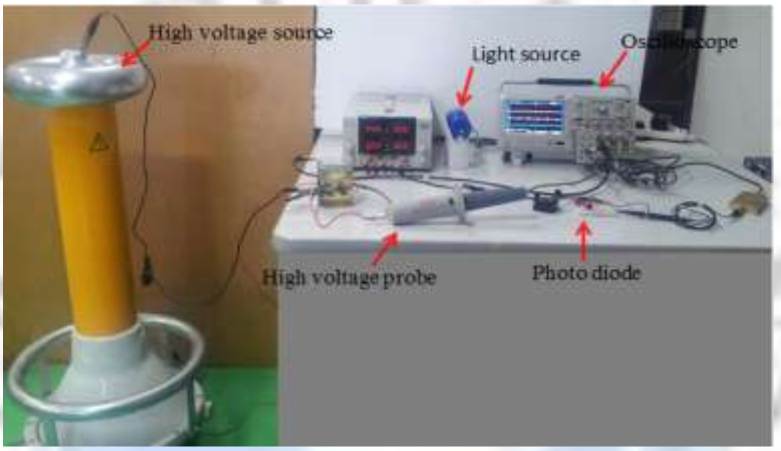


Figure 5: Experimental set up for PD signal detection in the insulation oil using FOS and CS.

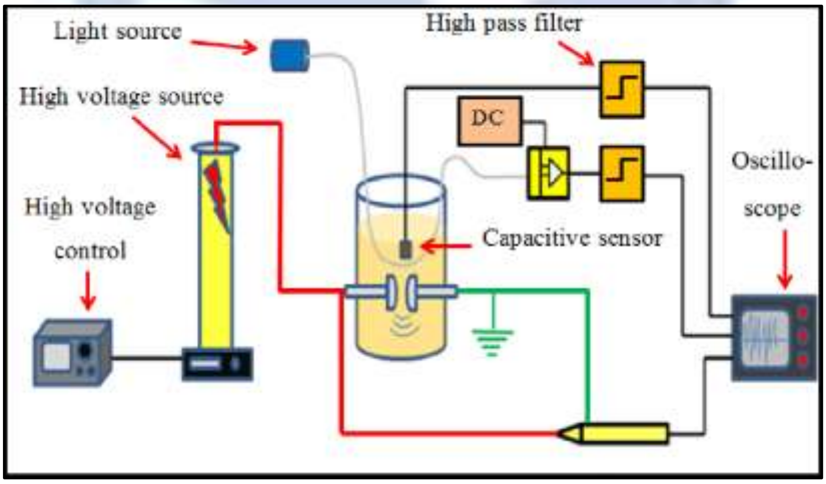


Figure 6: Schematics showing working principle of the detection using two sensors.

Results and Discussion

Figure 7 depicts the response of CS and FOS in the time and frequency domain when 5.5 kV p-p voltage probe signal is used. The number of peaks of the acoustic and electromagnetic signal in terms of response and their positions are found to be entirely different in two cases. Furthermore, the partial discharge signal is not clearly evidenced in both the sensors. The number of strong peaks reveal by the FOS is comparatively more than the capacitive.

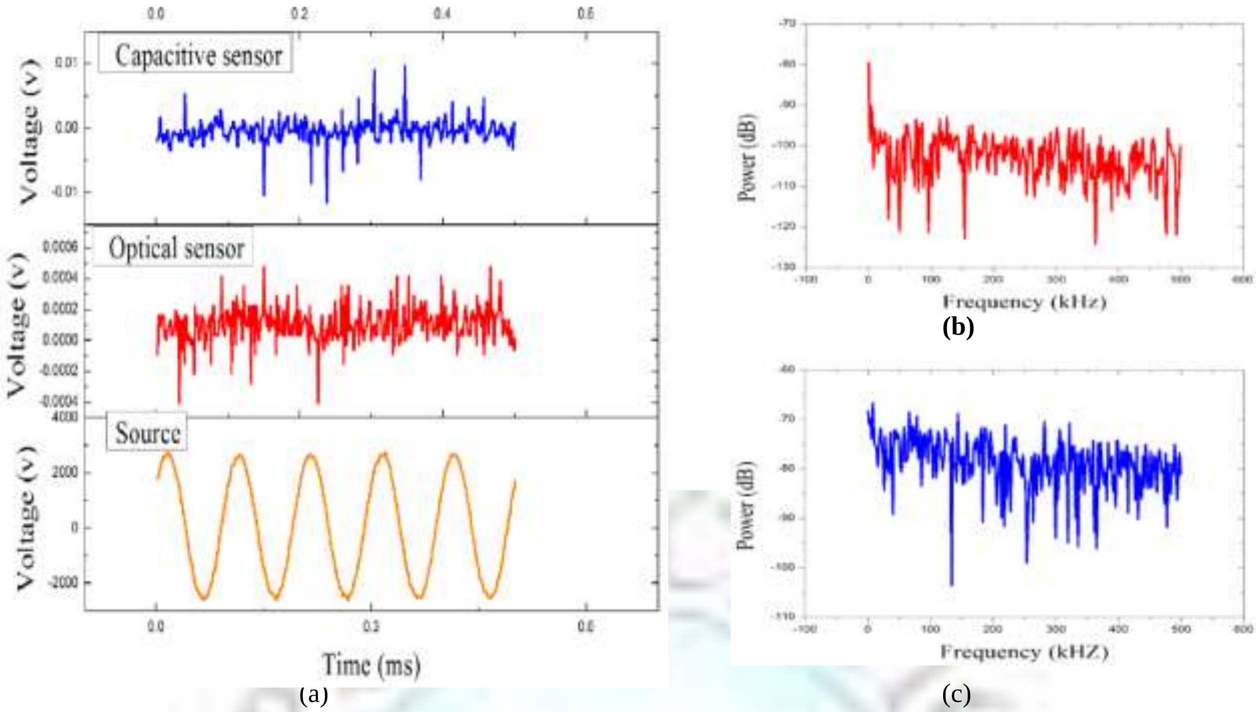


Figure 7: (a) The signal (in time domain) captured by CS and FOS together with the high voltage probe signal at 5.5 kV p-p. The signal after FFT of (b) FOS and (c) CS.

Figure 8 and 9 displays the signal in the time and frequency domain as captured by the CS and FOS together with the high voltage probe signal at 20 and 28 kV p-p, respectively. The dip of the high voltage peaks of the acoustic signal and electromagnetic signal picked up by the two sensors are found to be very different. The sensitivity of CS for the wave signal at the minima of the high voltage is observed to be lower than that captured by FOS. The response of the CS is found to be much weaker than the FOS.

Figure 10(a) and (b) illustrates the break down voltages of the three signals simultaneously. FOS revealing a prominent peak of the acoustic signal for the same value of PD indicates its higher sensitivity compared to that of CS.

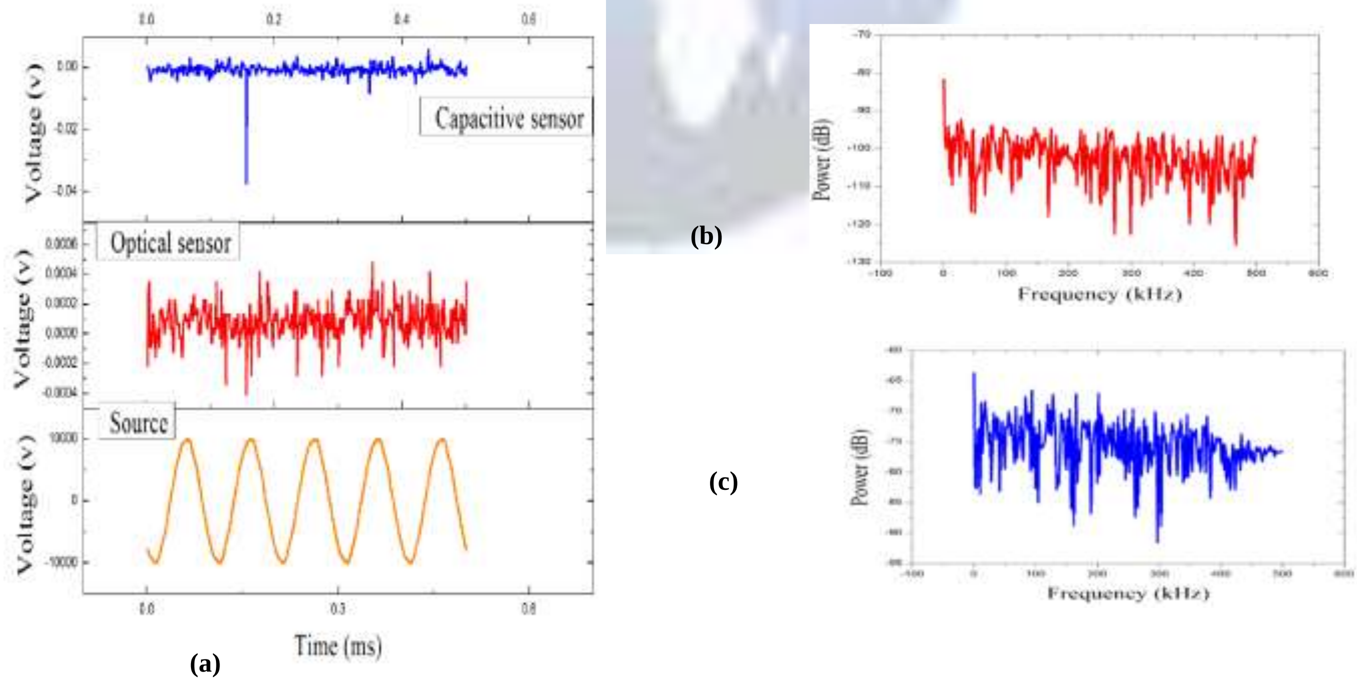


Figure 8: (a) The signal (in time domain) captured by CS and FOS together with the high voltage probe signal at 20 kV p-p. The signal after FFT of (b) FOS and (c) CS.

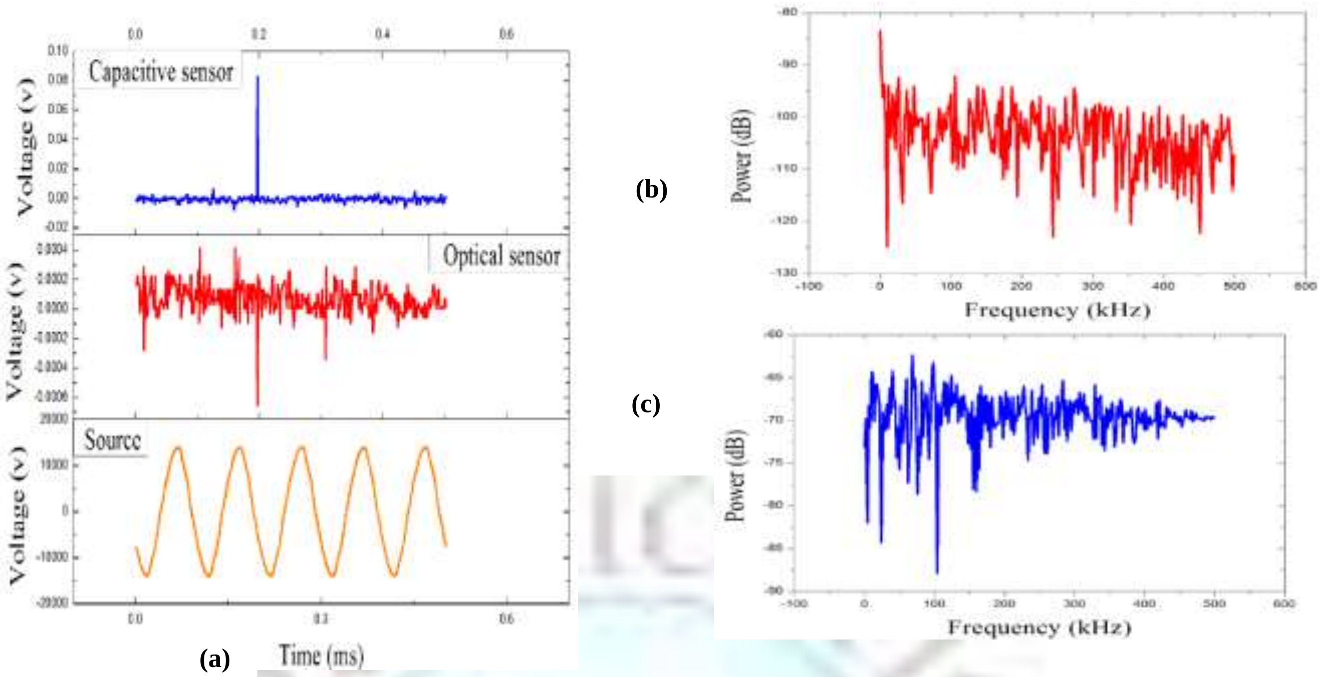
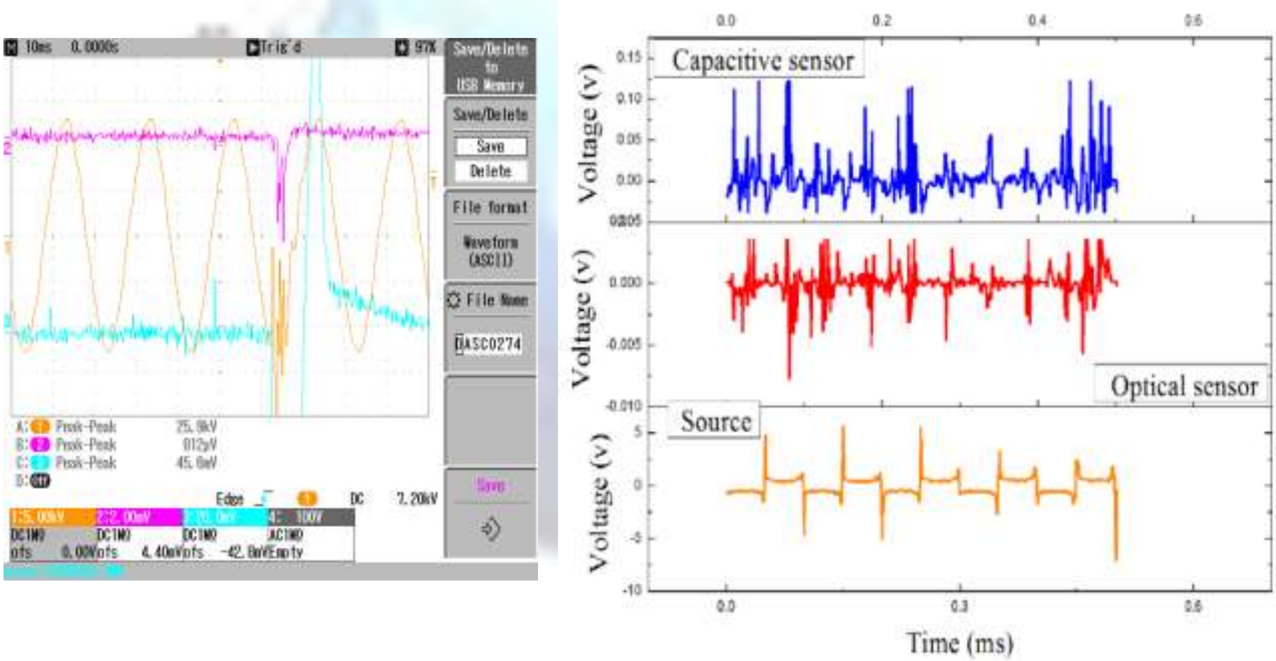


Figure 9: (a) The signal (in time domain) captured by CS and FOS together with the high voltage probe signal at 28 kV p-p. The FFT signal of (b) FOS and (c) CS.



(a) (b)

Figure 10: Patterns for three signals at break down voltage (a) from oscilloscope and (b) in time domain.

Figure 11 shows the comparison between the sensitivities of CS and single mode FOS. Typical acoustic and electromagnetic signal detected by the single mode FOS and CS in the frequency domain are displayed. The characteristics of responses captured by the multi-channel oscilloscope caused by AE generated by PD are evident. Upon charging the electrodes with high voltage of 28 kV p-p the arc discharges is evidenced as wave ripples arriving concurrently at two sensors. The dip of the high voltage peaks of the acoustic signal and electromagnetic signal picked up by the two sensors are observed to be entirely different. The CS and FOS are kept at a distance of 3 cm from the source of PD. The velocity of sound in transformer mineral oil is measured to be 1.5 mm/µs. The value of noise for the single mode FOS at the peaks 1 and 2 are found to be -92 dB and -105 dB, respectively with a signal resolution of 13 dB above the noise floor which is much better than that of CS. Conversely, for CS the corresponding values at the peaks

1 and 2 are found to be -63 dB and -73 dB, respectively with a signal resolution of 10 dB above the noise floor. Furthermore, the resolution displayed by FOS is higher than that of CS for the voltage greater than 15 kv p-p. However, for voltage lower than 15 kv p-p, the resolution of CS (~14 dB) appeared to be higher than the FOS (~9 dB).

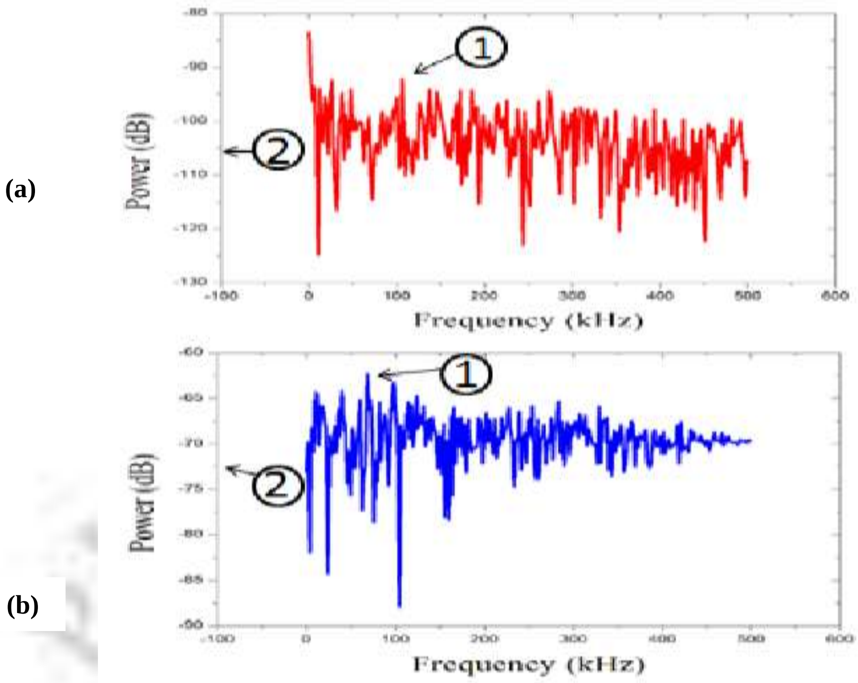


Figure 11: The FFT spectra of the output corresponding to 28 kV p-p probe signal for (a) FOS and (b) CS.

The resolution of the two sensors at different electrode voltages are summarized Table 1. The resolution characteristics as shown in Fig. 12 clearly reveal the point of intersection between the optical and capacitive resolution at 15 kV p-p. The resolution of FOS compared to the CS is enhanced beyond this voltage. The corresponding level of resolution is illustrated in Fig. 13.

Table 1: Resolution of the two sensors at different voltage

Sensor	FOS			CS		
Voltage kV(p-p)	Value of peak (1)	Noise floor	Resolution at peak (1)	Value of peak (1)	Noise floor	Resolution at peak (1)
5.5	-93	-102	9	-68	-82	14
20	-92	-103	11	-66	-75	9
28	-92	-105	13	-63	-73	10

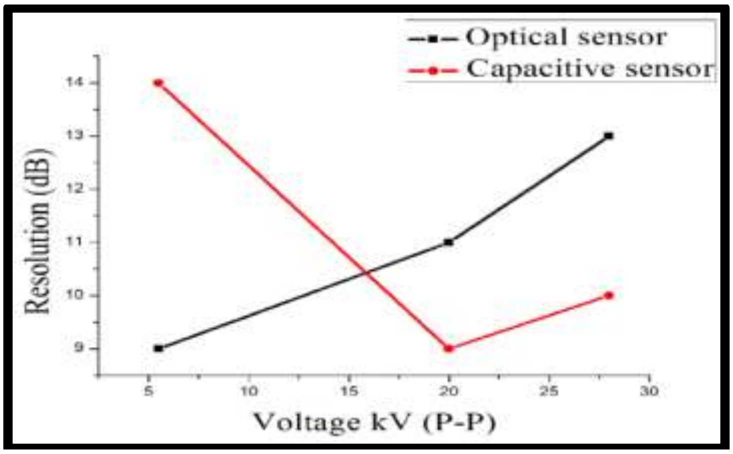


Figure 12: Resolution characteristics of FOS and CS.

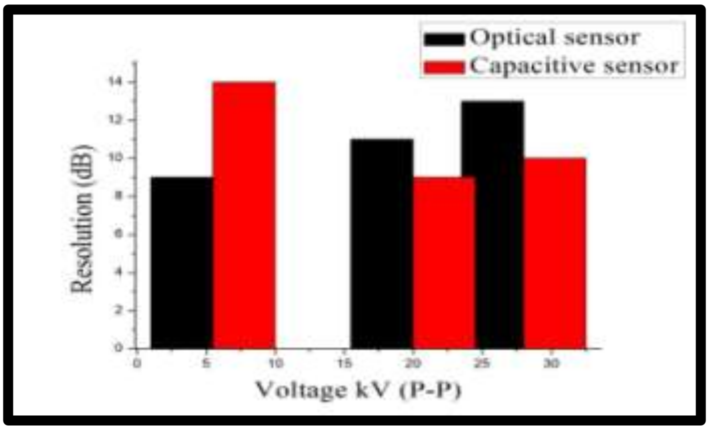


Figure 13: Levels of resolution for FOS and CS.

Conclusion

Determination of the nature of faults due to PD effects and subsequent rectification mechanism for superior performance of transformer is a challenging task. To support the protection program by identifying preventive maintenance schedules for transformers the exact detection of faults location and origin in insulation oil is pre-requisite. In this view, the performance sensitivity of single mode FOS for measuring PD in mineral oil is compared with conventional CS where the AE emerging in the vicinity of discharge zone is used to detect PD. These sensors are submerged in the transformer mineral oil tank and coupled with electrodes for producing voltage discharge. The resolution peaks for the PD are analyzed in time and frequency domain to obtain the noise levels for comparison. It is demonstrated that the sensitivity of single mode FOS is higher compared to CS for voltages of PD greater than 15 kV. Furthermore, FOS possessing superior signal band-width can be applied as acoustic sensor. It is asserted that the acoustic signal having high amplitude can successfully be captured by FOS. The FFT spectrums of single mode FOS exhibiting higher resolution indicate the usefulness of optical technique. The achieved enhanced sensitivity and resolution of FOS advocates that it can be nominated for accurate and efficient detection of AE and PD in the transformer oil.

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