High Sensitivity Interferometric Detection of Partial Discharges for High Power Transformer Applications

Carlos Macià-Sanahuja and Horacio Lamela-Rivera
Optoelectronics and Laser Technology group, Universidad Carlos III de Madrid
Av. Universidad 30, 28911 Leganés, Madrid, Spain
e-mail: carlos.macia.sanahuja@uc3m.es

Abstract – Partial Discharges are a clear cause and symptom of transformer degradation. This paper focuses on interferometric fibre optic system developed for the detection of partial discharges in transformers allowing knowledge of the status of degradation. The results obtained presents an interferometric signal associated to acoustic patterns with a 20 kHz frequency spectrum, which is a typical value in transformers. These results are compared with signals obtained using commercial piezoelectric sensors, with the results showing that fibre optic sensing is more accurate.

1 INTRODUCTION

This paper is based on the fact that power transformers, in service, suffer an incessant degradation process that limits its lifetime. As a consequence the dielectric isolation is reduced and partial discharges are shown to be a clear symptom of the degradation status of such transformers. In fact, partial discharges are electric phenomena that cause a large amount of the shortcomings of the isolation. Partial discharges generate ultrasonic pressure waves, which is a consequence of the occurred energy “explosion”. These waves are used to detect the intensity and location of the PD’s. Previous studies had confirmed that a wide ultrasonic frequency spectrum, between 20 kHz and 300 kHz, is obtained in detection of partial discharges in mineral oil, which is the most common dielectric isolation in high power transformers [1]. Thus, two acoustic methods are useful in detection of partial discharges. These are based on electronic and optical acoustic detection respectively.

- Electronic detection: The most commonly used electronic detection system of acoustic waves is based on the use of PZT sensors [2]. However these sensors have three important disadvantages which are shown to be solved using optical methods. These disadvantages are: Non-immunity of the sensor to the EMI produced by the transformer (note acoustic waves are immune to this effect), attenuation problems due to the structure of the transformer, (inner and outer walls), and finally the problem that arises due to simultaneous arrival of multiple acoustic signals from reflections within the transformer. This way a low precision is reached [3].
The attenuation problem is solved by placing the sensor within the transformer an option which is not possible with PZT sensors, due to the harsh conditions of EM fields, high voltage and high temperature.

- **Optical detection**: Sensors based on the use of optical fibres are shown to be an attractive improvement to the use of electronic sensors. They have many inherent advantages which facilitate their use in many sensing applications. For this current application, the most important characteristics which stand out amongst electrical sensors are: Complete immunity to EMI, even when in direct contact with high voltage areas, very high sensitivity to the low acoustic signals produced by partial discharges, since optical fibres are resistant to the harsh conditions within a transformer the sensitivity is further increased by placing the sensors within the transformer. Sensitivity of the system can also be increased by using longer lengths of optical fibre within the sensor [4][5]. Optical fibre methods involve optical phase modulation by the pressure and quantified using interferometry based on optical fibre intrinsic interferometers such as Michelson and Mach-Zehnder [4].

The fundamental disadvantages to optical fibre sensors are fluctuations in the interference patterns due to misalignments in the optical setup and more importantly effects incurred from birefringence discrepancies due to the polarization effects within the fibre caused by the surrounding temperature changes. Another problem associated with optical fibre sensors are their high sensitivity within a high frequency range making them susceptible to signals which are not a consequence of Partial discharge activity, this problem is easily solved using electronic filtering at the output of the detector.

The objective of this paper is to detect partial discharges in power transformers, through a Mach-Zehnder fibre optic interferometric system, in order to know its degradation status allowing an improved maintenance process. An interferometric optical fibre system has been developed and consists of a fibre optic sensor which can be placed inside power transformers. Currently the development is focused on a laboratory environment allowing characterization of the acoustic patterns before implementing this system in a real transformer. Results are obtained and compared with those using both previously mentioned acoustic methods.

The paper is organized as follows. Section 2 presents the characteristics of the interferometric system. In section 3 the interferometric and electronic results are presented, and also the calibration of the system is described. Finally in section 4 the conclusions are presented.
2 SYSTEM IMPLEMENTED

The experimental set-up is presented in figure 1. The interferometric fibre optic system is based on a Mach-Zehnder configuration, using single-mode optical fibres, with a 4 μm core, in both propagation paths (arms). Both arms have the same length and are constructed with identical coils preventing measurement errors due to optical path differences. The sensor arm has the sensing coil submerged in transformer oil and is exposed to the perturbations caused by the pressure waves generated from the discharges. Acoustic waves are measured by optical phase displacements in the sensing arm, and are compared to the reference arm which is isolated from the perturbations. Output intensity variations at the optical detector are thus produced. The interferometer is illuminated with a coherent light source from a He-Ne laser (633 nm). This visible wavelength also facilitates the alignment and measurement operations.

The fibre optic sensor and reference arm consist of an 8 m fibre coil with a 25mm diameter. A PZT ultrasonic receiver is placed outside the oil container receiving acoustic waves externally and is compared to the fibre optic sensor, placed within the oil [5].

The signal obtained at the output of the interferometer, after the recombination of two beams or light-waves, is a cosine-wave given by equation (1).

\[ I = I_0 / 2 \cdot (1 + \cos \phi) \]  

(1)

The optical phase \( \phi \) is the term of interest which is to be measured and does not have a linear relation with the output light intensity. In order to enhance the output of the detector a transimpedance amplifier is employed to convert the photocurrent to a useable voltage signal which is feed into an oscilloscope for further analysis. This signal also follows the form of a cosine wave.

The phase information of the signal is extracted from the output signal through arc-cosine processing [6]. The interferometric results and the phase information are presented in the next section.
It is important to note that since the voltage required to breakdown the transformer oil is high, the following alternative has been used. The partial discharges are produced through an electrode system as can be shown in figure 1. These are constructed using two metal plates, which form the electrodes, and a paper based dielectric material, of 0.15 mm thickness. Partial discharges appear in the gaseous cavities retained in the dielectric material when exposed to a high voltage condition. This voltage is 4~5 times less than that required for breaking down the oil.

3 EXPERIMENTAL RESULTS

The experimental results are shown in this section. As it has already been mentioned, the signal obtained is a cosine, but it is necessary to consider that the acoustic pressure variations have not been enough to cause increases of interferential signal of more than a fringe (2π rad.). For this reason it has been centered at the Quadrature point (π/2), which is of shown by maximum sensitivity interferometric transfer function, referred in (1). Thus small phase variations caused by partial discharges acoustic waves, less than π rad with an initial phase of π/2 rad, allows maximum output intensity variations. The principal results are shown in figure 2a.

![Figure 2a: Interferometric output intensity signal.](image-a)

![Figure 2b: Phase shift.](image-b)

Figure 2. a) Interferometric output intensity signal. b) Phase shift

A clear interferometric signal has been obtained with the fibre optic sensor. This interferential signal presents a succession of ultrasonic patterns that are attenuated in time. Also the phase information is presented in figure 2b, where it has been extracted from the intensity signal with a \( \cos^{-1} \) processing [6]. The optical phase shift is up to 2 rad, which corresponds to an equivalent global displacement of the fibre of 120nm. Moreover, a pressure measurement of 3.5 kPa is obtained [5].

In order to compare these interferometric measurements with PZT classic acoustic detection, a typical PZT widely used in partial discharges detection, R15I, has been acquired. It presents good isolation to perturbations out of the working frequency range, and it operates in the range from 70-200 kHz. It has a high sensitivity to acoustic waves close to 150 kHz, its resonant frequency. The
most significant results are presented in figure 3, in two different temporal visualization scales.

![Figure 3. Piezoelectric sensor measurements outside the vessel](image)

Compared to interferometric measurements, these signals present a very low amplitude level, 5 times less. This being primarily due to the attenuation of the acoustic wave between the interfaces of the oil-vessel and vessel-sensor. For a frequency spectrum comparison, we have generated in both cases, interferometric and PZT sensing, its FFT response. These are presented in figure 4, it can be shown that the interferometric detection presents frequency components around 20kHz while PZT has a spectrum response at around 150kHz.

![Figure 4. a) Frequency spectrum PZT. b) Frequency spectrum of interferometric phase shift](image)

These spectral measurements are in accordance with results obtained from other authors who use fibre optic sensors [4][7]. However there is a difference between these frequency components and those presented in the Fabry-Perot system [8] and those obtained with PZT sensors, 120-150 kHz compared to 20 kHz. This is in accordance with the large workable frequency range, between 20-300 kHz, in PD detection [1].
CONCLUSIONS

The results indicate that this work can be applied to the detection of partial discharges in mineral oil. The sensitivity of the system is enough for the generated discharges. The electronic detection with an ultrasonic PZT is shown to be inferior for this application, since an amplification process is necessary. Also, we have shown the wide frequency response associated with partial discharges, from 20 kHz with fibre optic sensors to 150 kHz with PZT sensors. Finally, future work includes fibre cover which can be used to make the fibre sensor receptive to the same frequency as the PZT. This way fibre based sensors are more suitable to PD detection than commonly used PZT electronic detectors, avoiding problems associated with EMI immunity and attenuation of the already weak signals due to the transformer structure.

REFERENCES