Characterization of an Ultrasonic Low Frequency Fibre Optic Interferometric Sensor for Partial Discharges Detection in Transformers

C. Macià-Sanahuja, J.A. García-Souto and H. Lamela-Rivera

Optoelectronics and Laser Technology Group, Department of Electronics, Universidad Carlos III de Madrid
Av. Universidad 30, 28911 Leganés, Madrid, Spain
E-mail: carlos.macia.sanahuja@uc3m.es

ABSTRACT
Partial Discharges are one of the major sources and symptoms of the deterioration of the dielectric material in power transformers. Such discharges are shown to emit weak acoustic signals in a wide ultrasonic range. A fibre optic sensor based on a Mach-Zender interferometer has been developed to detect these weak signals. It will be demonstrated that fibre optic sensors (FOS), placed within the harsh environment of typical power transformers are the best choice for partial discharge detection. This paper presents a calibrated fibre optic sensor with a high precision at 20kHz, this being a typical partial discharge signal within power transformers. The sensor has been first characterised in a laboratory environment which mimics the real life application proposed for future work.

Keywords: Interferometry, Optical fibre sensors, Acoustic detection, Partial discharges, Power transformers.

1. INTRODUCTION
The present article focuses on acoustic detection of Partial Discharges (PD) within power transformers as they are a clear cause and symptom of their dielectric degradation. A partial discharge can be described as an instantaneous liberation of energy, in the order of nanoseconds of duration. Partial discharges occur within the dielectric insulation and generate high frequency electrical pulses which are transmitted by the electrical network. In power transformers it has been shown that Partial Discharges generate ultrasonic pressure waves in a wide ultrasonic frequency range of between 20-300 kHz. These waves propagate through the dielectric material, typically composed of mineral oil, and are incident on the walls of the transformer. Partial discharge detection is traditionally measured by using suitable sensors located exterior to the transformer and in contact with the outer wall. In order to avoid noise sources produced from the core, recirculating oil, and inner walls of the transformer which are dominated by signals up to 50 kHz sensors with much higher frequency response characteristics are used. PZT sensors with resonance frequencies of 150kHz are typically used for this application.

Using sensors which can be placed within the interior of the transformer increase greatly the sensitivity of the detector and also decrease the effects of possible noise sources. Previously gained experience in optoelectronic sensors has led to the design and construction of a highly precise fibre optic sensor for PD measurement. Fibre optic based sensors are attractive for measuring partial discharges due to their inherent advantages such as large bandwidth and immunity to electromagnetic fields, even when the fibre is in contact with high voltage zones.
Interferometric use of optical fibres within the transformer achieves high levels of sensitivity and allows measurements of small variations in pressure created by the partial discharges\(^5\).

Accurate calibration of the fiber optic sensor increases the precision of PD measurements. This can be achieved by using an ultrasonic wave generator, and allows a resolution of as high as 30pC for electric discharges\(^6\).

This article presents previous calibrations using an ultrasonic acoustic generator which are necessary for the characterisation of the weak acoustic signals produced by PD in the laboratory environment. This allows evaluation of the small pressure waves created by the partial discharges. The pressure waves cause a change in phase of the optical signal within the fiber\(^7\), to increase the sensitivity even further an interferometric configuration is used where a resolution in the order of nanometers is achieved.

This paper is organized as follows. Section 2 presents the characteristics of the interferometric system implemented. Section 3 presents a brief description of partial discharge generation in a laboratory environment. This is followed by Section 4 where the calibration applied to the fibre optic sensor is shown. Section 5 is related to the interferometric results obtained. Also phase shift values are included here after applying an arc-cosine function. This paper finishes with conclusions in Section 6.

### 2. CHARACTERISTICS OF THE INTERFEROMETRIC SYSTEM

The interferometric fibre optic system implemented is based on a Mach-Zehnder interferometer. The optical fibers used in both propagation paths are single-mode\(^6\). The experimental set-up employed is presented in Figure 1.

![Figure 1. Experimental set-up. Mach-Zehnder interferometer configuration, where BS: beamsplitter, L: coupling and collimating lens, OF: optical fibre, He-Ne: Laser.](image)

Both arms are composed of the same length of optical fiber, constructed using two identical fiber coils, this prevents errors due to optical path differences. The coil of the sensing arm of the interferometer/sensor is submerged in the transformer oil. This oil is then exposed to
perturbations caused by partial discharge acoustic waves. The other arm of the interferometer is isolated from the impact of the acoustic wave and it is used as a reference for the optical path of the light that propagates through the fibre (reference arm). The coherent light source used is a He-Ne laser which operates at wavelengths located in the visible range (633nm), this source also facilitates interferometric alignment. The fibre optic sensor is made from single-mode optical fibres, with a core of 4µm in diameter, the sensor is composed of 8 meters of coiled fibre with a diameter of 30cm. In figure 2 a detail of the interferometric implemented system and the fibre optic coil is shown.

![Image of interferometric system](image)

**Figure 2. Detail of the interferometric system implemented**

3. ELECTRICAL GENERATION OF PARTIAL DISCHARGES

As mentioned previously, a partial discharge is a localized electrical discharge, which appears in the form of electrical pulses and partially short-circuits the dielectric material between the high voltage electrodes. In order to implement a physical system to produce electric discharges, the behaviour of these discharges should be known when are generated in a dielectric material under the influence of high alternate voltage. Thus, the dielectric equivalent circuit is presented in figure 3a.

In Figure 3a the ideal case is represented, where only one gaseous cavity is present in the dielectric material, such a cavity can be represented by an air capacitor (Cc). It is assumed that the remainder of the common section in the dielectric column can be represented by an ideal capacitor (Cb), which is in series with the air capacitor. The rest of the dielectric material can be represented by an ideal capacitor (Ca) which is between both electrodes and under voltage. When the circuit is placed under AC voltage excitation, a discharge will occur in the cavity. Cc will charge until the breakdown voltage is achieved in the cavity; at this time the discharge will be produced.
This situation has been reproduced in figure 3b with a real electrode system to simulate a real partial discharge generator in the Mach-Zehnder fibre optic interferometer set-up shown in Figure 1. Its construction involves two metal plates, which form the electrodes, and a Paper based dielectric material, of 0.15 mm thickness. This system maintains internal gaseous cavities that are required for simulation of the real behaviour of a partial discharge which in transformers are formed within a cavity which is composed of transformer oil and is under constant degradation. Thus electrical discharges are produced in the gaseous cavities that have been chosen to simulate partial discharges as the voltage required to produce dielectric breakdown is much less than that required for such breakdown in transformer oil.

4. CALIBRATION OF THE INTERFEROMETRIC SENSOR WITH PRESSURE WAVES

To test the performance of the implemented fibre optic system, an acoustic ultrasonic generator, AR30, is used to create controlled acoustic waves. This has permitted perturbing the fibre optic sensor with a calibrated acoustic signal generator allowing calibration of the sensor. For a precise calibration, a non-linear dynamic behavior has been forced to the fibre coil. Thus the output intensity displays a cosine evolution in which the excitation signal allows more than one full period of the interferometric signal (fringe) to pass the reference point ($\Delta \phi > 2 \pi$ rad). This is commonly referred to as a multi-period response. This interferometric multifringe response has been looked for to achieve a more precise calibration measurement with high sensitivity. The procedure carried out is the following: First an Arc-Cosine process is carried out in order to obtain phase information and next the amount of times the signal passes through zero is counted. This gives the result for the multiples of $\pi$ rad of the displacement of the signal, to which the resolution is $\lambda/2$ (half a fringe). The remaining signal displacement ($< \pi/2$) can be measured using fractions of $\pi$ radians. The experimental set-up is presented in Figure 4a, where the fibre optic sensor is located outside the container.

The AR30 ultrasonic generator has been placed in front of the fibre optic sensor at a distance of 20cm. A sinusoidal wave of 28 kHz has been applied to excite the acoustic emitter. This frequency has been chosen to compare the interferometric signal obtained with our partial discharge generation electrode system, to those results obtained with a controlled emitter. The first results of this calibration are shown in Figure 4b, where the excitation signal of the emitter and the interferometric response are represented.
It can be appreciated a multi-fringe interferometric response to the emitted acoustic waves can be appreciated, (both signals are synchronized) as we have looked for. Increasing the applied voltage to the emitter increases the pressure of the acoustic waves, Figure 4c shows the optical phase shift with respect to variations in the pressure generated, and here a linear response is obtained.

5. INTERFEROMETRIC MEASUREMENTS WITH PARTIAL DISCHARGES GENERATION

In this case we have generated electrical discharges, through the electrode system previously presented, and have detected the acoustic pressure waves associated with the fibre optic sensor coil placed inside mineral oil as in figure 1.

In the current system the intensity response is quasi-linear to the partial discharge waves and is in the range of less than \( \pi \) rad in quadrature operation (\( \phi = \pi/2 \)). This situation is represented in figure 5. For a quasi-linear response, the changes of the optical phase are less than half of a fringe (\( \pi \) rad); selecting the initial phase at the quadrature point (\( \pi/2 \)) the maximum sensitivity will be obtained.

**Figure 4.** a) Calibration detail. b) Interferometric response. c) Phase shift-pressure relationship

**Figure 5.** Quasi-linear response
Thus, the optical phase has been obtained in a small signal range ($\Delta \phi < \pi$ rad) which modulates the intensity around the quasi-static initial optical phase. Perturbations due to the temperature are shown as a low frequency random drift of the optical phase. This is related to the optical path stability of the interferometer set-up and to the response of the fibres to thermal changes. Its impact is far slower than the dynamic behaviour of the pressure changes caused by partial discharges. After the acquisition of the interferometric signal by the detector and its associate signal conditioning, a normalization process is carried out on the information of the previous maximum, minimum and mean intensity values obtained from the interferometric calibration. Arc-cosine processing is applied to give the values of the phase.

Thus, knowledge of the phase change must be known this is extrapolated from the intensity signal at the output of the interferometric system, which is the main objective of the demodulation process. Knowledge of the phase fluctuations gives information as regards changes in length of the optical fibre, thus allowing quantification of the acoustic pressure waves detected$^{9,10}$.

So, the principle interferometric measurements obtained using the fiber optic sensor are shown in Figure 6a. Here a clear interferometric signal is seen with typical acoustic patterns that are attenuated with time. The phase shift obtained is also presented in figure 6b. The optical phase shift is in the order of 2 rad, this corresponds to an equivalent global displacement of the optical fibre of 120nm and represents a pressure of 3530 Pa with a resolution of 30 pC$^6$. The spectrum of the interferometric output signal, which is generated with FFT algorithm, shows frequency components at around 20 kHz.

![Figure 6. a) Interferometric response through FOS. b) Phase shift after arc-cosine processing](image)

**6. CONCLUSIONS**

This paper has presented the results that have been obtained using a fiber optic Mach-Zehnder interferometric system for detection of partial discharges. The measurements which are presented are given as a function of the change in optical phase of light in an optical fibre sensing arm. From experimental results it is shown that this work can be applied to the detection of partial discharges in oil transformers. A clear signal at around 20 kHz has been obtained, this corresponds to the acoustic waves propagating in the oil which are generated by the partial discharges and have been detected by a calibrated FOS. These spectral measurements are in accordance with results obtained from other authors who use fibre optic sensors$^{7,11}$. However there is a difference between these frequency values and those presented in the Fabry-Perot system$^{12}$, which is 120 kHz compared to 20 kHz. This difference is due to the large frequency range, between 20-300 kHz, associated with PD detection$^1$. The
interferometric sensor has been calibrated using an ultrasonic emitter, here a multifringe interferometric output signal was obtained. These calibrations have allowed verification of the acoustic signals produced by partial discharges. Partial discharge levels of 30pC can be measured as the system is limited by $10^{-3}$ rad resolution.

7. REFERENCES