УДК 681.7.068

ВОЛОКОННО-ОПТИЧЕСКИЙ ИНТЕРФЕРОМЕТРИЧЕСКИЙ ДАТЧИК ДЛЯ АКУСТИЧЕСКОГО ОБНАРУЖЕНИЯ МИКРОПРОБОЯ

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Предложен датчик для обнаружения частичного разряда (ЧР) в силовых трансформаторах акустических сигналов. Обнаружение сигналов основано на изменениях оптической фазы во встроенном волоконно-оптическом интерферометрическом датчике высокой чувствительности с использованием схемы Маха–Цендера. Датчик может быть расположен внутри трансформаторов и является удобным для обнаружения слабых акустических сигналов, связанных с ЧР. Проведена калибровка интерферометрического волоконно-оптического акустического датчика на типичных частотах, которые проявляются при ЧР. Интерферометрические выходы используются для высокоточных измерений в процессе калибровки. Демодуляция сигналов использована для индикации оптической фазы. Частичные разряды генерируются в лабораторных условиях и обнаруживаются волоконно-оптическим датчиком, погруженным в иммерсионную среду.

Коды OCIS: 060.2370.

Поступила в редакцию 08.07.2005.

FIBRE-OPTIC INTERFEROMETRIC SENSOR FOR ACOUSTIC DETECTION OF PARTIAL DISCHARGES

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The detection of acoustic partial discharge (PD) signals produced in power transformers are reported. Detection is based on optic phase changes in an intrinsic Mach-Zehnder fibre optic interferometric sensor of high sensitivity. The sensor can be placed within transformers and is suitable for the detection of weak acoustic signals associated with the PD. The calibration of the interferometric fibre optic acoustic sensor at typical frequencies displayed by PD is presents. Interferometric multi-fringe outputs are used for high precision measurements during calibration. The demodulation of such signals is presented for obtaining the optical phase read-out. Partial discharges are generated in laboratory conditions and they are detected using the fibre optic sensor immersed in mineral oil.

1. Introduction

Maintenance of high power equipment, such as gas insulated substations (GIS), engines, cables and transformers, is necessary for prolongation of their in-service lifetime. A detailed knowledge of the state of the dielectric isolation material is directly related to the degradation process of such high voltage apparatus. It has been proven that partial discharges (PD) are a clear symptom and cause of the degradation process. This enforces the need for accurate detection of this phenomenon.

It is well known that PD generates ultrasonic pressure waves, which can be used to detect the intensity and location of the partial discharges. These waves propagate through the dielectric material, typically composed of mineral oil, and are incident on the walls of the transformer. Also it has been shown that the acoustic frequency range associated with PD's is between 20 to 300 kHz [1]. This acoustic phenomenon has been studied through the detection of the signals by piezoelectric sensors (PZT) located externally to the transformer and in contact with the outer walls. However, the signals detected in the outer walls are weak and the signals reflected in the transformer will also mask the external measurement of the straight path.

The measurements within the transformer based on fibre optic technology are of great interest [2]. Currently, several interferometric fibre optic sensors have been proposed as an alternative to PZT sensors. They have become the best option for greatly increasing the sensitivity to acoustic signals, this is mainly due to the fact that the sensor can be placed within the transformer.

Interferometric configurations are used because they have high levels of sensitivity. Many proposals of fibre optic PD detection and location are based on Mach-Zehnder interferometers with a coiled optical fibre that is used as an intrinsic sensor of the acoustic waves [2–5]. The main advantage associated with this approach is that the sensitivity of the sensing head can be enhanced increasing the length of the coiled optical fibre. An extrinsic Fabry-Perot is also proposed for PD detection [6] because of the reduced dimensions of the sensing head. However, in this case the sensitivity is limited compared with the interferometric intrinsic sensing using optical fibre.

Previously gained experience in intrinsic interferometric sensing for transformers applications has led to the design and construction of a fibre optic sensor for PD measurements [7, 8]. Our results are within the framework of Future project, in collaboration with the Spanish electric power company Uniyn Fenosa S.A. The objective of the project is the study and monitoring of the lifetime and degradation of power transformers, where the detection of partial discharges is highlighted. It also includes the installation of several fibre optic sensing heads within two power transformers and onsite measurements of mechanical vibrations. The installed fibre optic coils inside the real transformers are expected to be also used for the detection of PD, since both phenomena are clearly of different frequencies, thus their discrimination is possible.

In this paper, we present a fibre optic interferometric sensor for acoustic detection of partial discharges. Using an ultrasonic generation system and multi-fringe interferometric outputs, we have been able of calibrate the sensor at different pressure values. The paper is organized as follows. Section 2 is devoted to the experimental set-up for PD detection in a laboratory environment and the fibre optic interferometric system used for this purpose. This is followed by Section 3 where the generation of controlled PDs in mineral oil is presented for experimental tests similar to the real conditions of operation within transformers. In Section 4 results obtained from interferometric measurements are presented. The demodulation of the multi-fringe output is described for calibrated measurements of the pressure applied with an ultrasound generator. Calibration of the system is performed with this source. The results of partial discharges detected with the sensor in transformer oil are presented and discussed in Section 5. This paper finishes with conclusions in Section 6, where indications of future work are also included.

2. Characteristics of the interferometric fibre optic sensor

The fibre optic interferometric system implemented is based on a Mach-Zehnder interferometer. The optical fibres used in both propagation paths are single-mode to the optical wavelength used (633 nm). The transduction of the acoustic stimulus on the fibre optic sensing arm is made through changes in the optical phase which are proportional to the pressure changes on the fibre. The experimental set-up employed for characterization is presented in Fig. 1.

Both arms are composed of the same length of optical fibre, constructed using two identical fibre coils, this prevents errors due to optical path differences. The coil of the sensing arm of the interferometer is submerged in transformer oil (Fig. 1). 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 is used as the reference optical path (Fig. 1). The coherent light source used is a He-Ne laser which operates at wavelengths located in the visible range (633 nm), this source also facilitates the alignment of the optical arrangement. A photo-detector with transimpedance amplifier is used for detecting the interferometric signals.

In this interferometric system, where the optic fibre is the sensing part, a specific design of the fibre coil is required. The principal requisites concern the sensitiv-

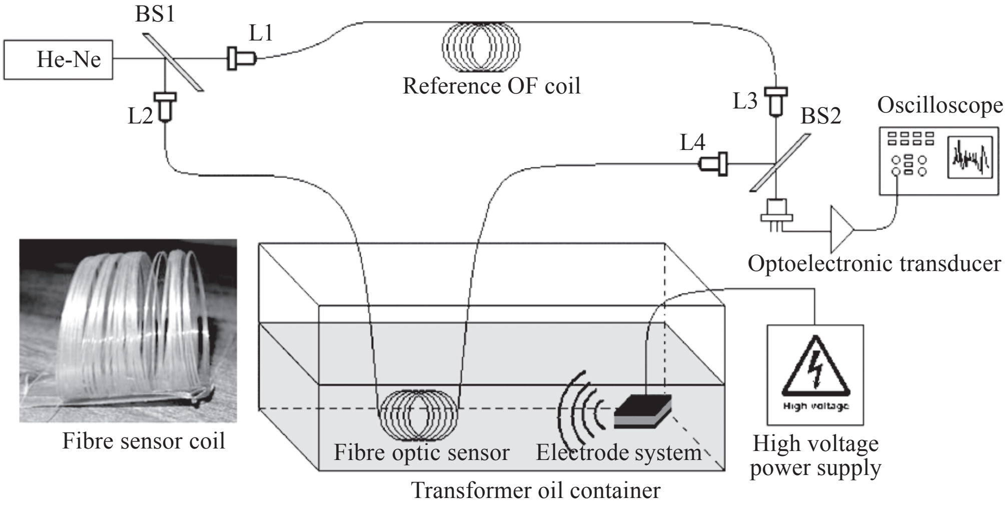

Fig. 1. Experimental set-up for the detection of partial discharges generated in laboratory conditions: Mach-Zehnder interferometer configuration and detail of the fibre optic sensor coil within transformer oil.

ity and the acoustic frequency spectrum to be detected. Real power transformers demonstrate major acoustic noise between 40 and 60 kHz (core noise) [1], thus in order to avoid these effects, sensors with frequency response out of this range are required. Acoustic sensors within the range of 100 to 300 kHz, or detecting in a bandwidth bellow 40 kHz are suitable for PD detection [9].

An inverse relation of the pressure with the distance ($1/D$) is assumed as a good approximation of the acoustic propagation. Therefore, a resolution up to 0,2 Pa at 1m distances is necessary for detecting the discharges in a real transformer, which reach at least tens to hundreds of pC [10]. Pressures in the range from 0,2–10 000 Pa are expected [10]. In order to define the sensitivity of the fibre optic sensing coil we have taken single-mode optical fibre with a core diameter of 4μm and approximately 8 m in length forming a single-layer fibre sensor with a diameter of 25 mm. With a theoretical sensitivity of about 40 μrad m^{-1} Pa^{-1} [11] this sensor leads to an optical phase shift above 2π rad from discharges of 10 000 pC at a distance of 1 cm.

The interferometric optical intensity is converted into an electrical signal with a photo-diode focused on the central ring of the interference pattern (Fig. 1). Thus, the perturbations due to partial discharges vary the electrical signal on the detector with the cosine transfer function between the interferometric output and the optical phase. In order to recover the optical phase from the interferometric output signal, a demodulation process is needed.

3. Electrical generation of partial discharges

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. The dielectric equivalent circuit is presented in Fig. 2a.

As a good approach, in the ideal case only one gaseous cavity is present in the dielectric material (Fig. 2a), such a cavity can be represented by an air capacitor (C_c). It is assumed that the remainder of the common section in the dielectric column can be represented by an ideal capacitor (C_b), which is in series with the air capacitor. The rest of the dielectric material can be represented by an ideal capacitor (C_a) which is between both electrodes and under voltage. When the circuit is placed under AC voltage excitation, a discharge will occur in the cavity. C_c will charge until the breakdown voltage is achieved in the cavity; at this time the discharge will be produced.

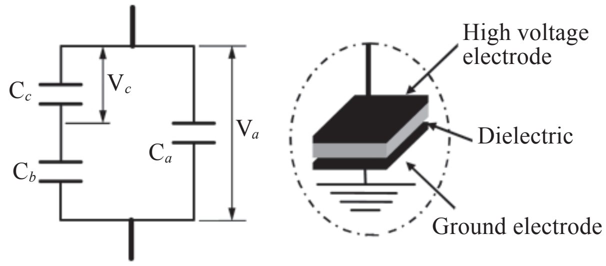

Fig. 2. Generation of a partial discharge. (a) Equivalent circuit of the dielectric, where the partial discharges are generated. (b) Electrode system composed of two metals plates and a dielectric of cellulose.

This situation has been reproduced in Fig. 2b with a real electrode system to simulate a real partial discharge generator in the Mach-Zehnder fibre optic interferometer set-up shown in Fig. 1 within the oil. 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.

4. Calibration of the fibre optic sensor with ultrasonic pressure waves

In order to perform calibrated measurements, it is useful to obtain an optical phase change above 2π rad. Thus, the intensity output involves a cosine evolution in which more than one period of the interferometric signal is observed (multi-fringe interferometric output). For this case, the dynamic change of the phase is obtained independently of the conditions of initial phase, low-frequency drift or visibility changes. The references of the intensity for the optical phase read-out are available every time.

The performance of the implemented fibre optic system was tested with ultrasonic harmonic signals. An air-acoustic ultrasonic transducer was used to create controlled acoustic waves at a frequency of 28 kHz. Ultrasonic detectors matched at those frequencies have been used as a reference of the pressure at a distance from the source. The selected frequencies are in the range used for PD detection in transformers and the ultrasonic transducers used in this experiment are suitable for the study of PD in a laboratory environment.

The ultrasonic transmitter is placed in front of the fibre optic coil at a distance of 20 cm. A sinusoidal wave of 28 kHz is applied to excite the acoustic transducer. For a precise calibration, a multi-fringe dynamic response is forced to the amplitude of the applied acoustic pressure. The results of this calibration are shown in

Fig. 3a, where the excitation signal applied to the emitter and the interferometric response are represented. The measurements with the fibre optic interferometer show the cosine response of several periods (optical phase change above 2π rad) for each excitation signal semi-period (Fig. 3a).

With this multi-fringe output for the amplitude of the stimulus, a successfully arccosine processing [7] can be used as follows: The amount of times the signal passes through zero is counted. This gives the result for the multiples of π rad of the displacement of the signal, to which the resolution is λ/2 (half a fringe). The remaining of the signal into the range of half a fringe (optical phase up to π rad) can be measured using fractions within π radians and the arccosine function. Notice that the direction of the fringe displacement has to be detected in order to complete the demodulation, but in this system, it is easily achieved through the synchronism with the excitation signal used as a reference for the calibration. Figure 3b and 3c show the multi-fringe interferometric output for two different amplitudes of the applied pressure (22 and 49 Pa). The correspondent optical phase obtained for each case with this demodulation approach is also presented in units of a fringe (2π rad).

A static curve of calibration with different values of applied pressure has also been done. A linear response is observed between the optical phase shift and the increase of the acoustic pressure, as it is expected. This characteristic is presented in Fig. 3d. With 8 m of length coil of bare fibre and at a distance of 20 cm from the ultrasonic source, a sensitivity of about 0,5 rad/Pa has been found.

An example of the frequency response is presented in fig. 4b, which shows the spectral signals after demodulation (*C*) and onto the photo-detector (*D*). As can be seen, the bandwidth used by the multi-fringe interferometric output is about 400 kHz and the optical phase read-out has a main frequency about 20 kHz. Since the modulation index is above 4 fringes each semi-period of the excitation (see optical phase of Fig. 4a that is linear with the excitation), an interferometric response centred around 160 kHz is obtained with main frequencies up to 300 kHz (Fig. 4b).

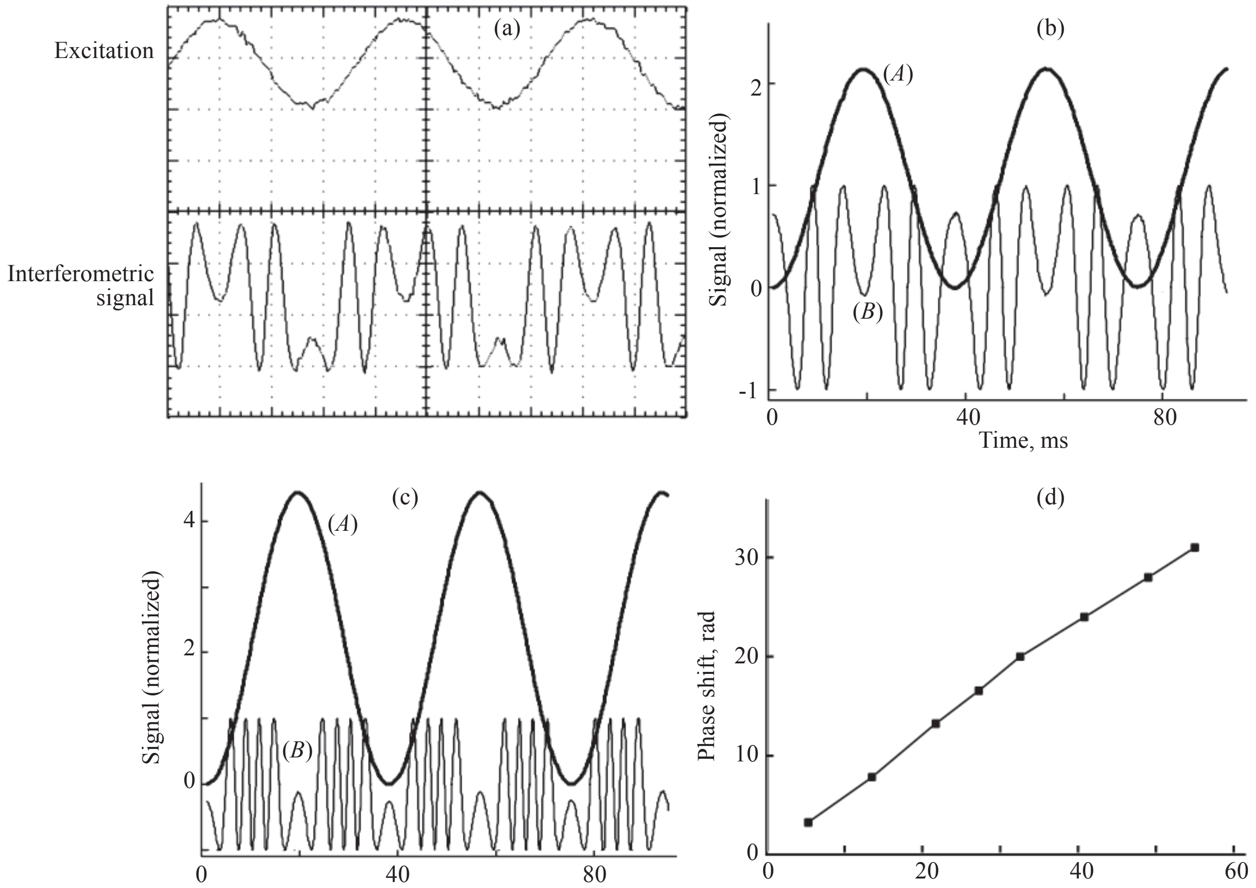

Fig. 3. Experimental results of the calibration tests with ultrasonic waves of 28 kHz. (a) Excitation and sensor response as a calibrated multi-fringe interferometric output. (b) Calibrated optical phase read-out with a pressure of 22 Pa. (c) Calibrated optical phase read-out with a pressure of 49 Pa. (d) Static calibration of the fibre optic interferometric sensor as the optical phase shift for different acoustic pressure applied with the ultrasonic source. (*A*) Optical phase, (*B*) Interferometric output.

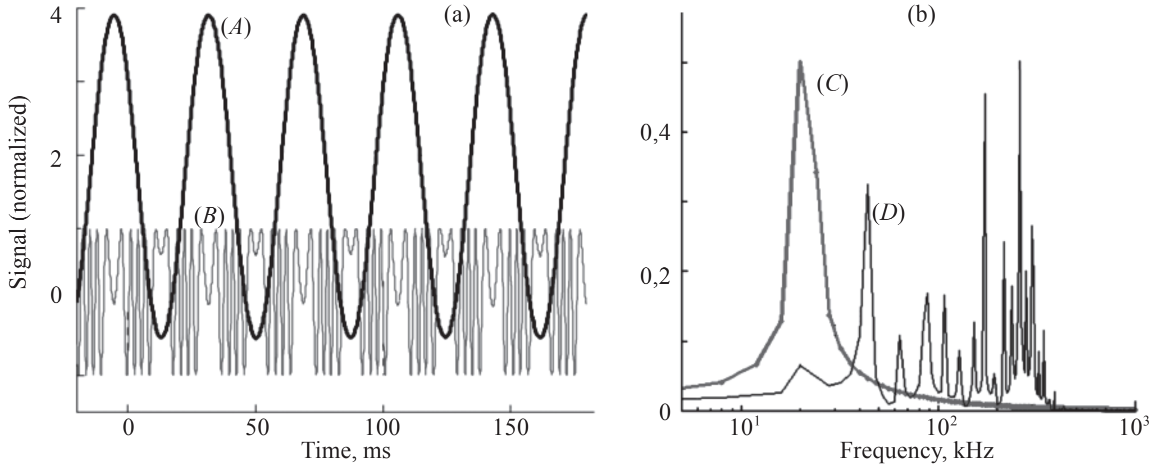

Fig. 4. Calibrated optical phase read-out using the demodulation based on the multi-fringe output. (a) Normalized intensity and the correspondent optical phase waveform: (*A*) Optical phase, (*B*) Interferometric output. (b) Spectrum of both signals: (*C*) Optical Phase, (*D*) Interferometric output.

5. Partial discharges measurements

We have generated electrical discharges, through the electrode system previously presented, and the acoustic pressure waves associated with these discharges have been detected by the fibre optic sensor coil placed inside mineral oil, following the scheme of Fig. 1.

In this case, a small signal of optical phase has been obtained in a range up to π rad. If the intensity is modulated around a quasi-static optical phase of π/2 rad (quadrature operation), there is a quasi-linear response of the intensity to the optical phase. Therefore, the intensity onto the photo-detector can be used as the sensor read-out. However, an arc cosine [7] processing of the optical phase is possible if the references of the transfer function are known. After the acquisition and conditioning of the interferometric signal, a normalization process is carried out on the information of the maximum, minimum and mean intensity values obtained from a previous calibration. Arc cosine processing will be applied to obtain the values of the optical phase [7], directly related to the strain onto the optical fibre, and the acoustic pressure detected [3, 11].

The detected interferometric signal clearly presents a typical acoustic pattern that is attenuated with time. The phase shift obtained is presented in Fig. 5a, after the arc cosine demodulation process. The optical phase shift is in the range of 2 rad peak to peak, this represents a theoretical pressure of 3530 Pa [8, 12]. Neither pressure gradient onto the fibre length, nor influence of the coating due to damping is considered.

Experimental measurements with the calibration setup have shown a sensitivity of the fibre sensor about 0,5 rad/Pa at a distance of 20 cm (Fig. 3d). Assuming that the attenuation of the acoustic signal is inversely proportional to the distance from the sensor (1/*D*), the detected optical phase (Fig. 5a) represents about 160 Pa at 0,5 cm from the PD source. It is approximately one

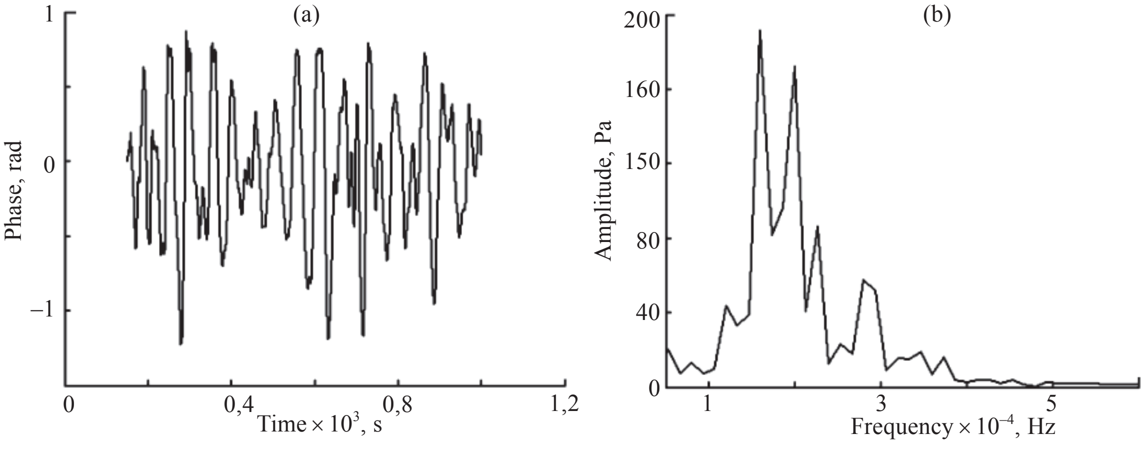

Fig. 5. Experimental interferometric results when detecting acoustic waves generated from high voltage electrodes. (a) Optical phase shift after arc cosine processing. (b) Frequency spectrum as a function of the applied pressure.

order of magnitude less than the theoretical calculation [8] as is stated when the fibre coating is considered [12]. The spectrum of the interferometric output signal, generated using the FFT algorithm, shows frequency components close to 20 kHz (Fig. 5b), that are in good agreement with the selected frequencies of the calibration tests. However there is a difference between these frequency values and those presented with a Fabry-Perot fibre sensor [6], which is 120 kHz. This difference is due to the large frequency range, between 20–300 kHz, associated with PD detection [1].

In order to cover all the frequency range of PD with the fibre sensing coil, it should ideally have a diameter less than 5 mm. Considering the speed of sound in oil as 1400 m/s and the spectrum range up to 100 or 300 kHz, the acoustic wavelengths will be up to 14 and 5 mm. This implementation can be obtained employing bend-insensitive fibres.

6. Conclusions and future work

This paper has presented the results that have been obtained using a fibre optic interferometric sensor for the detection of partial discharges. The measurements were performed using the optical fibre as an optical phase based intrinsic sensor of the acoustic pressure. From the experimental results it is shown that this work can be applied to the detection of partial discharges in oil transformers. A clear signal of about 20 kHz has been obtained, which is in accordance with results from other authors using fibre optic sensors [2–5]. The interferometric sensor was calibrated using an ultrasonic transmitter; here a multi-fringe interferometric output signal was obtained. These calibrations have allowed verification with the acoustic signals of low ultrasonic frequency produced by partial discharges.

Future work is with obtaining the maximum bandwidth that can be reached with mandrel fibre coils of lower-dimensions. First, the use of the sensor in a range of frequencies about 150 kHz will be performed in order to compare the signals obtained at different frequencies associated to the partial discharges and compared with the typical bandwidth of PZT sensors outside the transformer. Frequencies up to 1 MHz will also be explored, even with ultrasonic signals not associated to PD.

Acknowledgements

This work is co-supported by the FEDER-Comunidad de Madrid (Spain) GR/MAT/0508/2004. The authors would like to thank Spanish electric power Company Uniyn Fenosa S.A. The authors are collaborating with them in the framework of the FUTURE Project and the Partial Discharges Diagnosis and part of this work is also supported by them.

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