Performances of a PCB-based Loop Antenna Inductive Sensor for Partial Discharges Detection

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***Abstract*—This paper presents the test results of an electrically small loop antenna sensor towards detecting the radiated magnetic field due to partial discharge (PD) activities. The loop antenna prototype was printed on an FR-4 substrate with a thickness of 1.6 mm, featuring a compact size of 20 mm × 20 mm × 1.7 mm. The proposed sensor, initially simulated with Ansys HFSS software, has a resonant frequency of about 100 MHz. Its detection capability for three types of partial discharges (i.e., corona, surface and internal PDs) has been evaluated. Laboratory experiments showed that the evaluated loop spiral antenna is appropriate for the detection of the three types of PDs. Indeed, the results show a peak-to-peak voltage equal to 22.87 mV, 74.8 mV, and 79.72 mV, respectively, for corona, surface, and internal PDs, with a frequency spectrum showing a maximum at 42.19 MHz, 16.41 MHz, and 35.1 MHz, respectively. Lastly, the performance of the proposed small loop sensor was compared to that of the commercial HFT sensor. The results show that the two sensors present comparative sensitivity for the three types of PD.**

Keywords—Inductive spiral loop, PCB-based sensor, partial discharge detection, HFCT sensor

I. Introduction

Insulation materials and systems are critical to the safe supply of electrical power. Hence, any negligence may result in the unexpected breakdown of high voltage (HV) and medium voltage (MV) power equipment, potentially resulting in an explosion and fire, which may injure individuals in the proximity of electrical equipment [1]. The partial discharge (PD) phenomenon is one of the extrinsic accelerated aging factors that impact and reduce insulation health and reliability. The presence of PD in insulation strained by a strong electric field produces local and usually rapid insulation degradation, eventually leading to premature collapse. According to the IEC 60270 standard, a partial discharge is a localized electrical discharge that partially short-circuits or bridges the insulation between two conductors [2]. When a sufficiently high voltage is applied, PD can appear in solid, liquid, or gas insulation systems with defects (such as cavities, detachments, protrusions, etc.) [3] [4]. Depending on their location, PD can be divided into four types: internal, corona, surface, and tree discharges. The detection of the PD at an early stage helps in avoiding system failures and allows for optimizing required maintenance procedures [5]. PD pulses can generate energy in a variety of forms, including pulsed currents, mechanical (acoustic) waves, electromagnetic waves, light, and heat, that can be sensed by several sensor types [6]. In recent years, various sensors that make use of the electromagnetic waves created by PD pulses have been experimentally and commercially developed. These sensors have been shown to be effective in a variety of settings, such as in laboratories or industries [7]. Inductive loop sensors (ILSs), Rogowski coils (RCs) [8], on-chip loop antennas [4], and high-frequency current transformers (HFCTs) [9] are a few examples. These sensors are typically made up of one or more copper turns wrapped around a magnetic or non-magnetic core that is situated close to (e.g., FTCs and RCs) or surrounding the line through which the PD pulses propagate (e.g., ILSs). Furthermore, they do not require galvanic contact with the measuring circuit, thus enabling real-time PD monitoring.

In recent years, UHF antenna sensors have attracted research and development attention. Various UHF sensors have been developed to detect PD in different applications, such as power transformers and gas-insulated switchgear (GIS). Such antennas can be located internally or externally on HV or MV equipment to detect the electromagnetic waves (EM) induced by the PD source. Some examples of sensors utilized in GIS include planar equiangular spiral antennas, UHF Moore fractal antennas, and dipole and log-periodic antennas [10]. Other UHF sensors for PD detection in power transformers have been developed, including fourth-order Hilbert fractal antennas [11], circular microstrip antennas [12], and microstrip-fed planar elliptical monopole antennas [13]. In this paper, a PCB-based double-layer spiral inductor will be evaluated as an inductive sensor for PD monitoring on HV and MV power equipment. The basic parameters of the loop antenna, such as the resonance frequency and the bandwidth, are investigated using Ansys HFSS (High-Frequency Structure Simulator) software based on the Finite Element Method (FEM). Through laboratory experiments, the evaluation of the sensor performance as regards to sensitivity and noise rejection is carried out. At the end, a comparison between the newly introduced inductive sensor and the HFCT common industrial sensor is presented.

II. Sensor Design and Evaluation

The investigated PD measurement system consists of a double-layer planar spiral inductive sensor, as shown in Fig. 1. The manufacturing process technology of the double-layer inductor needs two levels of metallization (the spiral and the underpass), as well as two vias. The sensor is made with 17 µm-thick copper lines, on an FR-4 substrate with a thickness of 0.8 mm and a relative dielectric constant of 4.4. Table I shows the geometric dimensions of the designed loop antenna, where *D* and *d* represent the outer and inner diameters, *n* the turns number, and *w* and *s* the track width and spacing, respectively. The outward dimension of the loop antenna is 20 × 20 mm^2, which yields an external perimeter of ~80 mm. This kind of sensor features several benefits over traditional ones, including its compact size, inexpensive cost, and the fact that there is no need for an external power supply. Furthermore, it can be placed quite close to the PD source to increase sensitivity. Next, numerical extraction of the spiral inductor parameters will be carried out using the Ansys HFSS® FEM simulator.

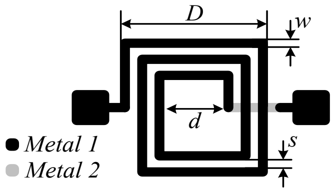


Fig. 1. Layout of the investigated inductive spiral sensor.

TABLE I. PLANAR INDUCTIVE SENSOR DIMENSIONS VALUES.

Parameter	*n*	*D*	*d*	*w*	*s*
Value (mm)	6.5	20	10.4	0.4	0.4

HFSS software is utilized for simulating electromagnetic structures and determining their high-frequency response. Fig. 2 shows the HFSS graphical user interface (GUI) showing the spiral inductive sensor placed on an FR-4 substrate and surrounded by an air box. Fig. 3 illustrates the simulated impedance module and phase angle of the inductive sensor. As seen, the sensor shows a first self-resonance frequency (SRF) at about 100 MHz. The spiral inductor will behave inductively up to its resonant frequency, beyond which it will behave capacitively. At frequencies below 100 MHz, the phase angle is 90 degrees, and the inductive sensor could act as an electrically small loop antenna. Unlike large loop antennas, whose circumferences are less than 0.1 λ at the highest frequencies, where λ denotes the wavelength; small loops are suitable for receiving signals up to about 30 MHz. Based on these notes, the PD-designed sensor could be classified as an electrically small loop antenna for PD detection, working within the high frequency (HF) and very high frequency (VHF) ranges and operating in the near-field region. In these circumstances, the electrically small loop antenna will be used to measure the magnetic component of the emitted electromagnetic field from the PD presence.

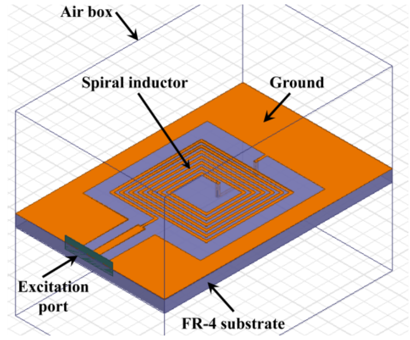


Fig. 2. The spiral inductive sensor layout simulated in HFSS.

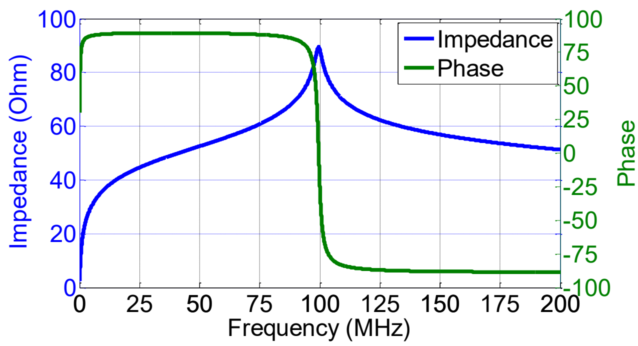


Fig. 3. Impedance module and phase angle simulations of the inductive planar spiral sensor.

III. Measurement Setup

The next phase of this work was to exploit laboratory experiments to evaluate the PCB-based sensor for PD detection. The goal of these studies was to confirm the capability of the manufactured PCB-based sensor for detecting the three basic types of PD pulses (i.e., corona, surface, and internal discharges) on high voltage equipment. Fig. 4 shows the different specimens used to generate an artificial partial discharge [14]. *(i)* As shown in Fig. 4a, the corona discharge is generated using the needle-plane specimen with a 1.6 cm air gap. *(ii)* To simulate the internal discharge (Fig. 4b), a specimen composed of XPLE layers, also called cross-linked polyethylene, which is a type of insulation material (0.3 mm thickness) interposed between two layers of XPLE (thickness of 0.5 mm), combined with an air void defect (obtained by making a hole in the middle foil), has been realized. *(iii)* For generating surface discharges, the specimen has been made using a single XLPE layer interposed between two electrodes with different diameters (10 mm and 60 mm), as shown in Fig. 4c. Common PD evaluation circuit components for the three types are presented in Fig. 5. In this figure, a simple needle-plate electrode is shown in the experiment to generate corona, which will be identified by discharge activity in the air. The space between the needle electrode and the plate electrode was set at 16 mm. The HV power supply used in the experiment is a 100 kV issued from a step-up transformer, which feeds the needle-plate electrode (PD source). A dc voltage regulator with a range of 0–400 V was used to set the required ac HV applied voltage. In this experimental setup for a PD measurement, the designed sensor and a commercial high-frequency current transformer (HFCT 140-100 HVPD) sensor are connected to the ground wire. The HFCT has been used to compare and validate the sensor measurements. The spiral inductor and HFCT sensors were connected to the Pry Cam grid acquisition system using a 50 Ω coaxial cable [14].

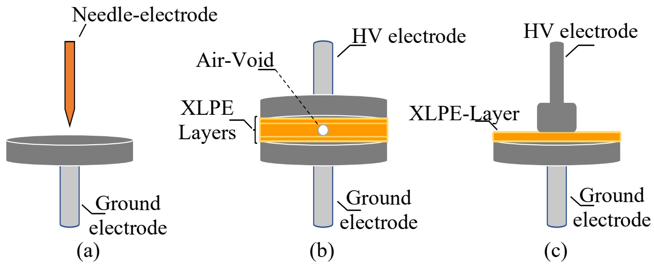


Fig. 4. Specimens for artificial PD: (a) Corona, (b) Internal, and (c) Surface.

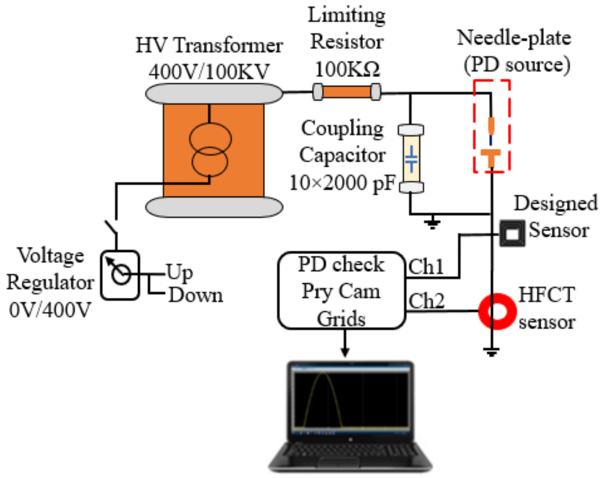


Fig. 5. PD measurement setup for corona PD.

IV. PD MEASUREMENT RESULT

The three different specimens used for generating the artificial PD have been stressed with a voltage in the range of 3–10 kV. The applied voltage was gradually raised until the first PD pulse signals appeared (this is known as the Partial Discharge Inception Voltage, or PDIV). The same setup conditions are applied to produce the three types of PD. All the reported sub-figures in Fig. 6 are related to the Phase-Resolved Partial Discharge patterns (PRPD). The detected PD pulse and the frequency spectrum have been provided by the PryCam Grids acquisition software. The PRPD patterns are used to identify noise and PD sources. The obtained PD patterns are illustrated in Fig. 6, in which it is possible to identify internal (Fig. 6a), corona (Fig. 6b), and surface (Fig. 6c) PD phenomena. In each experiment, over 3000 pulses of PDs (black dots in Fig. 6) were acquired in order to obtain statistically significant results. The red curve in the results is the reference of the ac applied voltage to define the phase of the acquired PDs.

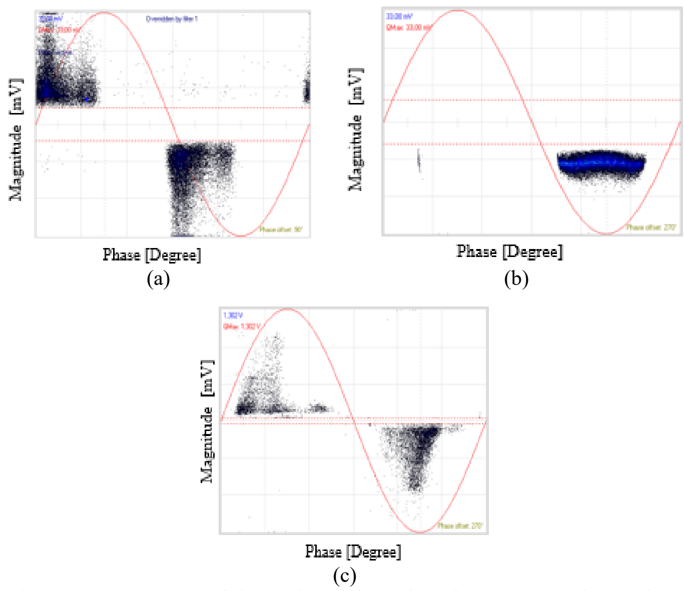


Fig. 6. PRPD patterns of the (a) internal at 8 kV, (b) corona at 4 kV, and (c) surface at 8 kV, discharges detected by the inductive sensor.

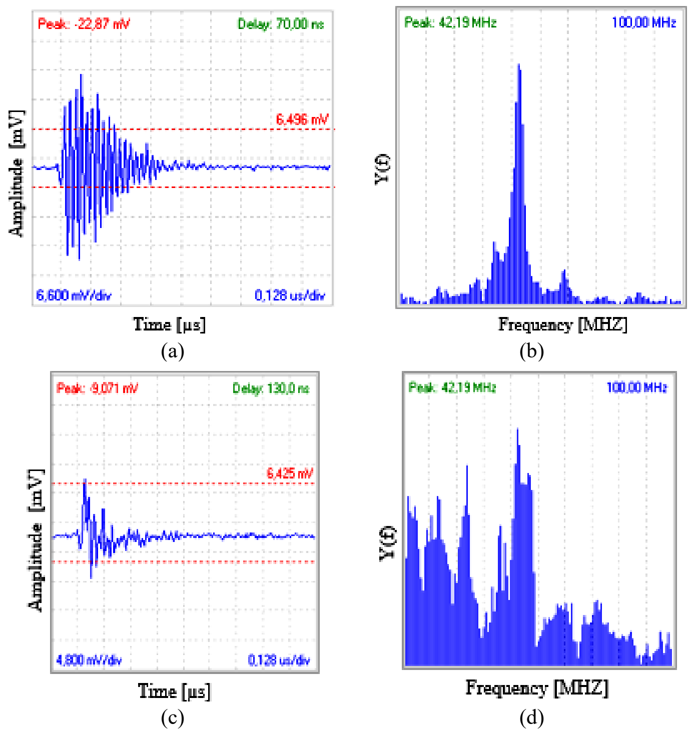
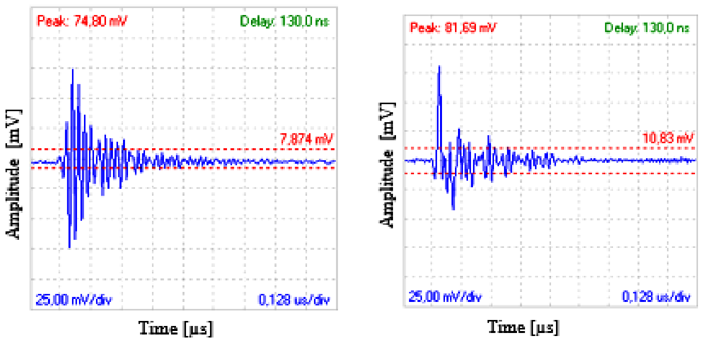


Fig. 7. Corona PD pulse detected by the spiral inductor sensor in (a) and its frequency spectrum in (b), corona PD pulse detected by the HFCT sensor in (c) and its frequency spectrum in (d).

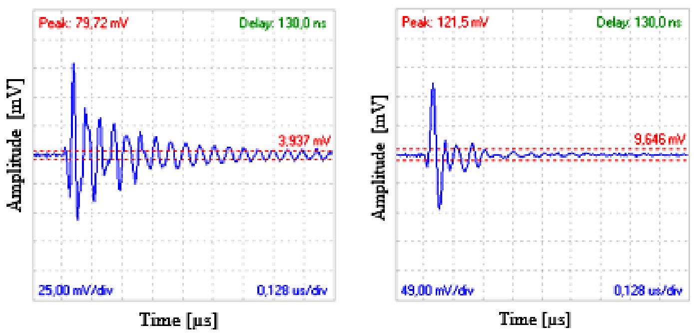
Figs. 7a and 7c depict the time domain corona PD signal waveforms detected by the proposed sensor and the commercial HFCT sensor, respectively, at 4 kV (PDIV). Figs. 7b and 7d present the spectrum frequency of the pulse signal of the small loop antenna sensor and the HFCT sensor, respectively. As can be seen at 4 kV, the peak-to-peak voltages of the PD signal detected by the designed sensor and HFCT sensor are, respectively, 22.87 mV and 9.07 mV. This indicates that the designed sensor is roughly twice as sensitive as the commercial HFCT sensor. However, it is worth noticing that the two sensors present the same maximum amplitude of the fundamental lobe of the PD signal at the frequency of 42.19 MHz. Moreover, the small loop antenna has a greater attenuation in the lower frequency range.

Figs. 8 and 9 illustrate the surface and internal PD signal pulses detected by the loop antenna sensor and the HFCT sensor at 8 kV (PDIV), respectively. As can be observed, the peak-to-peak voltage of the PD signal detected by the designed sensor is 74.8 mV, while 81.6 mV is detected by the HFCT sensor. The frequency spectrum shows a maximum amplitude at 16.41 MHz with the designed sensor and 17.19 MHz with the HFCT sensor. Figs. 9a and 9b show the PD signal pulse of the internal discharge. As can be seen, the peak-to-peak voltage of the PD signal detected by the designed sensor is 79.72 mV, while 121.5 mV is detected by the HFCT sensor. The frequency spectrum shows a maximum amplitude at 36.1 MHz with the designed sensor and 35.94 MHz with the HFCT sensor. In conclusion, it should be pointed out that the HFCT sensor and the loop antenna exhibit comparative sensitivity towards the three types of PD.



(a) (b)

Fig. 8. Surface PD pulse detected at 8 kV (PDIV) by (a) the spiral inductor sensor and (b) the HFCT sensor.



(a) (b)

Fig. 9. Internal PD pulse detected at 8 kV (PDIV) by (a) the spiral inductor sensor, and (b) the HFCT sensor.

V. Conclusion

This paper deals with the performance evaluation of an electrically small loop antenna sensor used for partial discharge monitoring on high and medium-voltage power equipment. From simulations, the proposed inductive sensor showed a first resonant frequency of 100 MHz. Up to this frequency, the sensor acts as an inductor, but beyond that, as a capacitor. To investigate the magnetic field sensor sensitivity, the latter was used to detect PD signals through laboratory experiments. Moreover, its capabilities were compared for three types of partial discharges (i.e., corona, surface, and internal PDs) with those obtained from a commercial HFCT sensor. It has been shown that the proposed inductive sensor has higher sensitivity than the HFCT in detecting EM waves emitted by corona PD activity, but it shows lower sensitivity in detecting EM waves emitted by internal and surface PD activities. The PDIV measurements of the two sensors are relatively close, as are the PRPD peak pulse amplitudes and peak spectral responses. In conclusion, it could be confirmed that the proposed spiral inductive sensor seems to be a suitable and promising candidate for PD monitoring in high voltage power apparatuses, where irradiated magnetic fields should potentially be monitored.

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