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Asymmetric Capacitive Sensor for On-line and Real-time Partial Discharge Detection in Power Cables

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Abstract

Partial discharges (PD) have long been recognized as a major contributing factor to catastrophic failures in high-power equipment. As the demand for high voltage direct current (HVDC) facilities continues to rise, the significance of on-line and real-time monitoring of PD becomes increasingly prominent. In this study, we have designed, fabricated, and characterized a highly sensitive and cost-effective PD sensor comprising a pair of copper electrodes with different arc lengths. The key advantage of our sensor is its non-invasive nature, as it can be installed at any location along the entire power cable without requiring structural modifications. In contrast, conventional PD sensors are typically limited to installation at cable terminals or insulation joint boxes, often necessitating invasive alterations. Our PD sensor demonstrates exceptional accuracy in estimating PD location, with a success rate exceeding 95% in the straight sections of the power cable and surpassing 89% in curved sections. These remarkable characteristics indicate its high potential for real-time and on-line detection of PD.

Keywords: Partial discharge, Capacitive sensor, HVDC, Power cable

1. INTRODUCTION

Partial discharge (PD) is a localized electrical discharge that occurs between conductors through the insulation of power equipment [1]. It happens when imperfections and discontinuities in the insulation are exposed to an electric field that exceeds a critical value. The accumulated PD activities deteriorate the dielectric material and can eventually lead to catastrophic failures in power equipment. Therefore, online detection and real-time monitoring of PDs have been considered critical techniques for estimating the lifetime of the power system, including power cables and transformers. Identifying the location of PD in a power cable is of particular importance since PD is one of the most probable causes of failure in a high-power transmission system. Additionally, as the demand for high voltage direct current (HVDC) cables steadily increases due to their lower transmission losses compared to high voltage alternating current (HVAC) transmission when transmitting power over long distances, monitoring PD has become even more essential [2]. These HVDC cables can also facilitate the interconnection of power systems with different frequencies or connect power systems to renewable energy plants, including wind generators. To detect PDs and identify the location of the PD source over the entire cable length, it is necessary to install a number of highly sensitive and inexpensive sensors at regular intervals.

PDs in power cables give rise to various physical phenomena, including high-frequency electromagnetic emissions with frequencies up to several hundred MHz, acoustic emissions, and localized temperature increases [3-6]. When PD occurs in the insulation layer of the cable, it generates high-frequency electromagnetic pulses that travel along the metallic shield and the inner conductor in opposite directions. These high-frequency electromagnetic pulses can be detected by capacitive sensors, inductive sensors, or directional couplers [7]. However, most of the PD sensors for power cables are restrictively installed only in the cable terminals or insulation joint boxes. Moreover, some sensors require invasive structural modifications of power cables. One of the most commonly used inductive sensors is the high-frequency current transformer (HFCT), which mutually couples the magnetic fields induced by high-frequency PD pulses [8].

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When PD occurs near the PD source, the electrical current pulses are carried by small portions of the shield circumference, inducing a magnetic field outside the power cable. On the other hand, at a location far from the PD source, high-frequency electromagnetic pulses travel uniformly distributed along the circumference of the metallic shield, resulting in only a small leakage of the magnetic field outside the power cable.

Therefore, to ensure high sensitivity, it is recommended that HFCT be installed not around the power cable itself, but around the bundle of metallic shields that go to the earth ground, typically found in the cable terminals or joint boxes.

Here, we demonstrate a highly sensitive and low-cost asymmetric capacitive sensor (ACS) that can be non-invasively installed at any location along the entire power cable. Using a pair of sensors, we identified the location of the PD source with an accuracy greater than 95%.

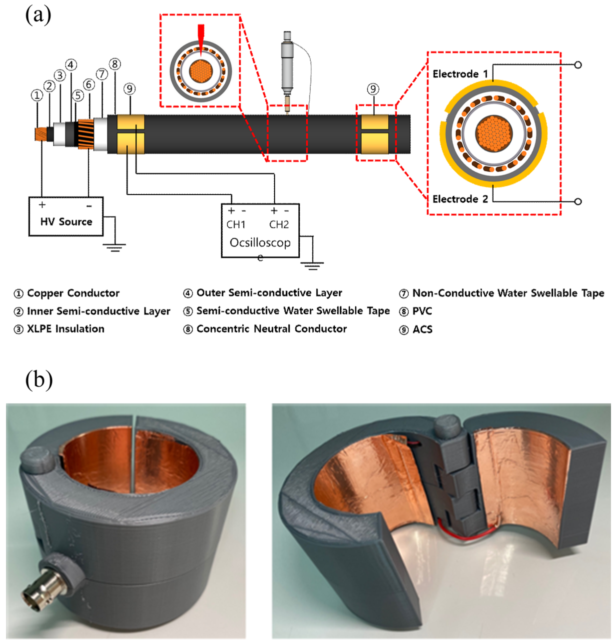

Fig. 1. (a) Experimental setup and structure of the XLPE cable and the asymmetric capacitive sensor. (b) Image of asymmetric capacitive sensor.

2. EXPERIMENTAL

Fig. 1(a) depicts the experimental setup used for PD measurement in the power cable. The measurement utilized a 22.9 kV XLPE insulated cable, which consisted of a stranded copper conductor, inner and outer semiconducting layers, XLPE insulation layer between semiconducting layers, a semi-conductive water swellable tape, helical copper strands as a metallic shield layer, a non-conductive water swellable tape, and an extruded polyvinyl chloride (PVC) jacket. PDs were generated using an artificial defect composed of a needle attached to a micromanipulator. The needle's tip was inserted into the insulation layer near the inner conductor, and the distance between the needle's tip and the inner conductor was controlled by the micromanipulator. The needle was electrically connected to the metal shield, and a high voltage source was applied between the inner conductor and the metal shield. The distance between the needle's tip and the inner conductor was adjusted to induce PDs when the voltage exceeded 3.5 kV. The asymmetric capacitive sensor (ACS) comprised a pair of copper electrodes with different arc lengths as shown in Fig. 1(b). The electrode areas were 72 cm² and 6 cm², respectively.

3. RESULTS AND DISCUSSIONS

In Fig. 2, the operating principle of the ACS is illustrated in two different scenarios: near and far from the PD source. When PD

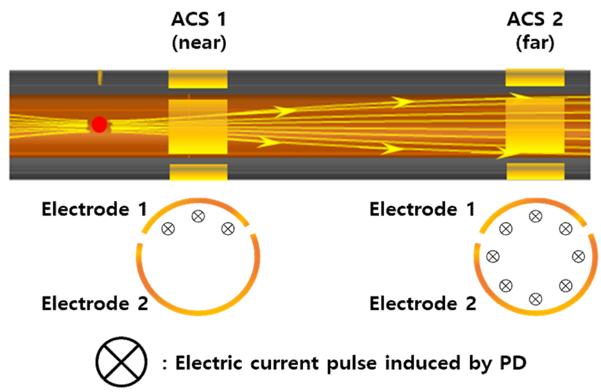

Fig. 2. Illustration of Partial discharge signal distribution along the cable and operation principle of the asymmetric capacitive sensor.

occurs close to the ACS, electrical current pulses are carried by a small portion of the metallic shield, resulting in an uneven number of charges on the two metal electrodes. This induces a voltage difference between the two electrodes. Even if the PD occurs far from the ACS, the different electrode areas cause varying numbers of charges to be capacitively induced on the electrodes, leading to a voltage difference between them.

In Fig. 2, the operating principle of the ACS is illustrated in two different scenarios: near and far from the PD source. When PD occurs close to the ACS, electrical current pulses are carried by a small portion of the metallic shield, resulting in an uneven number of charges on the two metal electrodes. This induces a voltage

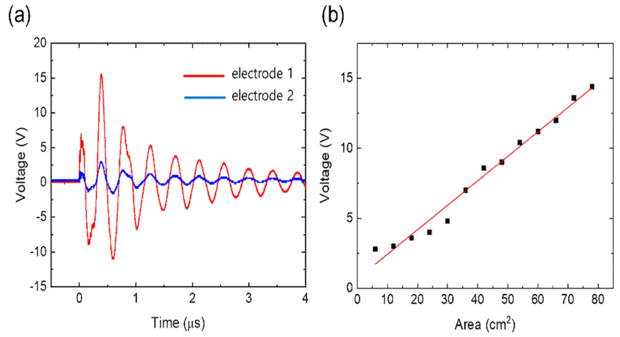

Fig. 3. (a) Partial discharge signal obtain by two electrodes in the asymmetric capacitive sensor. (b) Partial discharge signal as a function of the area of the electrode.

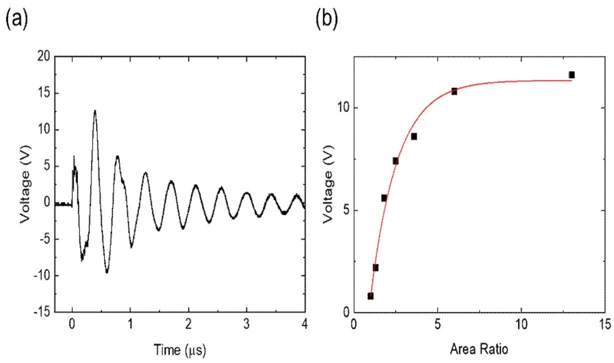

Fig. 4. (a) Partial discharge signal obtained from the asymmetric capacitive sensor operating in differential mode. (b) Partial discharge signal in differential mode as a function of the area ratio between electrode 1 and 2.

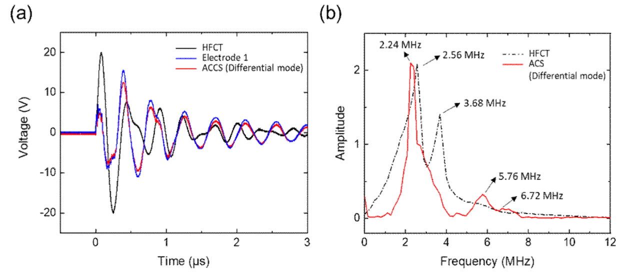

Fig. 5. (a) Comparison of sensitivity among ACS, differential mode ACS, and HFCT. (b) Frequency spectra for ACS in differential mode and HFCT.

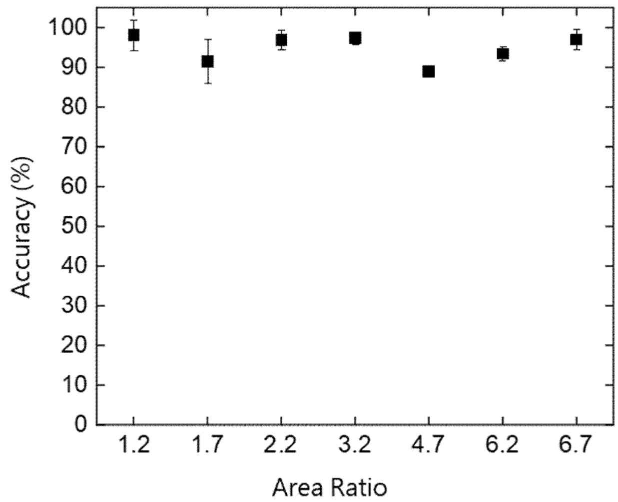

Fig. 6. Accuracy of PD location estimation with a pair of asymmetric capacitive sensor for different sensor distance.

difference between the two electrodes. Even if the PD occurs far from the ACS, the different electrode areas cause varying numbers of charges to be capacitively induced on the electrodes, leading to a voltage difference between them.

In Fig. 4a, the PD signal for the differential mode of the ACS is presented, obtained as the difference in PD signal between electrode 1 and electrode 2. The differential mode of ACS can be implemented by measuring the difference between the two input voltages. Although the PD signal's amplitude for the differential mode is smaller than that obtained from electrode 1 in Fig. 3a, it has the potential to eliminate common mode noises that may be present in the sensor driving circuit, including the analog-to-digital converter and the microprocessor. Fig. 4b demonstrates the PD signal for the differential mode of the ACS as a function of the area ratio of the electrodes. It is observed that the sensitivity increases as the area ratio increases, reaching saturation at a ratio of 6:1.

To evaluate the sensitivity of the ACS, a commercial HFCT was attached around a bundle of metal shields that connect to the earth ground, and the amplitudes of PD signals obtained from the ACS and HFCT were compared. Fig. 5a shows the PD signal obtained using the differential mode of the ACS (red) and HFCT (blue). The sensitivity of the HFCT used in the comparison is less than 1 pC±1%. The low and high frequency 6dB point are 3 MHz and 150 MHz, respectively. The dimension of the HFCT is 105 mm × 60 mm (hole) × 45 mm. The weight is 800 g. When comparing peak voltages, the sensitivity of the ACS was found to be two times lower than that of HFCT. Despite this, the ACS can be easily installed at any location, and the cost for sensors covering the entire length of the cable is incomparably low, requiring only two metal electrodes. Furthermore, the sensitivity of the ACS can be increased by expanding the areas of the electrodes. Fig. 5b shows the frequency spectrum of the PD signal measured using the ACS in differential mode and HFCT, respectively. The dominant frequencies of the spectrum for ACS are 2.24, 5.76, and 6.72 MHz, whereas the dominant frequencies for the HFCT are 2.56 and 3.68 MHz.

Fig. 6 demonstrates the accuracy of PD location estimation measured by a pair of ACS. The PD location can be estimated using two ACSs placed on both sides of the PD source. By knowing the average propagation velocity of the PD current pulse, the location of the PD source can be estimated by measuring the difference in the time of arrival of the PD signal between the two ACSs. The average propagation velocity of the PD signal in the power cable was measured at 31.66 cm/ns. The distance between two ACSs varied from 1.2 m to 6.7 m. The accuracy was measured to be higher than 95% in most cases, except when the distance between two ACSs is 4.7 m. The lower accuracy obtained in this case is attributed to the curvature of the power cable. In this particular case, two ACSs are placed on the curved section of the power cable, while all the other cases are measured along the straight section.

4. CONCLUSIONS

In summary, we have designed, fabricated, and characterized a partial discharge sensor with high sensitivity and low cost. The ACS can be installed at any location along the entire power cable without requiring any invasive modifications to the cable. The accuracy of PD location estimation exceeds 95% in the straight section of the power cable, while it is greater than 89% in the curved section. With its high sensitivity, low cost, and high accuracy, the ACS shows great potential for the real-time and on-line detection of PD.

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