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PARTIAL DISCHARGE DETECTION IN HIGH-VOLTAGE GAS INSULATED SWITCHGEAR USING FIBER OPTIC BASED ACOUSTIC SENSORS

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Introduction

Partial discharges (PD) are small current pulses that can occur within the insulation of medium and high voltage (HV) electrical assets such as cable accessories, transformers and switchgear. In GIS units, PD's can occur near the high-voltage conductor or at other locations commonly due to metallic particles from the erosion of the switchgear contacts or left behind after maintenance. For that reason, GIS units are usually equipped with multiple embedded UHF sensors in selected compartments that can detect PD in their vicinity.

PD's are originally caused by defects of insulation materials, defects within the spacers such as voids, or protrusions in the HV conductor that can affect the electric field within the GIS. When undetected or overlooked, PD's can result in the breakdown or failures in GIS units. [1].

To prevent unplanned outages and costly repairs caused by PD, the industry developed various strategies through the years. In this regard, periodic inspection of HV assets using various sensing technologies has been the most common practice to detect and assess PD. However, in recent years there has been an increased demand for continuous online monitoring of the assets instead of periodic inspections. Such a trend is fostered by the need for higher grid reliability and the dynamic nature of modern smart grids, which subjects components to higher stresses and therefore earlier degradation.

In this context of the generation of PD in GIS, defects in the insulation can initiate near the high voltage conductor or at other locations, either by degradation of the insulation, or the inclusion or detachment of conductive particles inside the enclosure [6]. In this paper, the effect of having a free-moving metal particle and the associated PD events inside the compartments of the GIS will be investigated. GIS units can be equipped with ultra-high frequency (UHF) sensors embedded in the enclosure during their manufacturing. UHF sensors can normally detect PD activities in their own compartment and the adjacent ones with a good signal-to-noise ratio. However, retrofitting an existing GIS with PD monitoring devices can be challenging, as the electromagnetic interference around the GIS units can affect the measurements of electrical sensing systems.

In this paper, a novel fiber optic based acoustic sensing solution will be presented that can be retrofitted on existing GIS units. The fiber optic PD sensors are passive, galvanically isolated, and fully immune to electromagnetic interference (EMI). This solution is developed and commercially available by Optics11 is under the trademark OptiFender, and it is a highly sensitive acoustic PD sensing system based on fiber optics technology. It measures ultra-sonic

(> 20 kHz) acoustic signals of partial discharge and tracks their evolution over time. OptiFender PD sensors are passive, immune to EMI, and can be easily retrofitted to different HV assets, enabling the detection of close-by internal and surface partial discharges.

In this study, OptiFender capabilities are demonstrated by inspecting an HV SF_6 filled GIS with a free-moving particle inside. The free-moving particle was mobilized at voltages above 150 kV. The same technology was previously implemented in the detection of PD in MV cable joints [3], detection of PD in MV and HV terminations, detection and localization of PD in HV transformers

and reactors, detection of PD in inverted fed machines [4], and developing a smart HV cable joint by embedding OptiFender PD sensors inside the joint and detecting PD all across it.

Fiber Optic Sensing Technology

The operating principle of the OptiFender system is based on interferometry, where two fibers of the same length are configured in a Michelson interferometry setup. Both the sensing fiber and the reference fiber in such setup are packaged inside the acoustic emission sensor. The reference fiber is coiled around a damper and is isolated from vibration and mechanical disturbances, and the sensing fiber is coiled around a mandrel with a flat bottom. The sensor is attached to the structure with the sensitive mandrel in direct contact with its surface for optimum transmission of the surface acoustic wave to the sensing fiber. The sensor is fixed in position using either a magnetic clamp, rubber clamp, or adhesive material.

Upon the passing of the acoustic wave through the fiber optic sensor, the vibration is transferred to the sensing mandrel and then to the coiled fiber around it (see Figure 1). The resulting interferometric signal is transferred to the OptiFender readout box for signal acquisition, demodulation of the acoustic emission (AE) signal, and communication to a computer with OptiFender software for acoustic event detection, phase-resolved partial discharge (PRPD) map formation, and further processing. Previous comparisons of the OptiFender sensors with the state-of-the-art piezoelectric-based AE sensors show a similar sensitivity and functionality, with the additional benefits of being passive, galvanically isolated, and immune to EMI [2].

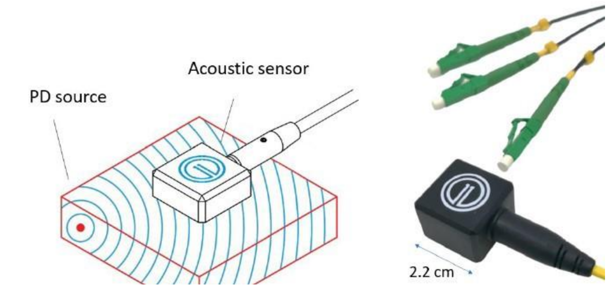

Figure 1 (a): Transfer of the acoustic signal from the generation of the PD to the OptiFender PD sensor, (b): The OptiFender non-metallic PD sensor.

In the case of partial discharge from a moving particle in GIS, the PD event is generated after the mobilization of the free-moving particle between the particle and the compartments of the GIS. Such discharge generates acoustic events in the frequency ranges above 20 kHz [5] that travel through the body of the GIS compartment. Installing OptiFender PD sensors on the outer body of the GIS can detect such PD events, even at inception voltages, as will be seen from the results of this study.

Advantages of PD Detection Using Fiber Optic Sensing

Fiber optic sensing has several advantages over electrical sensing systems, which are not just limited to partial discharge detection. Fiber optics sensors are inherently passive, immune to electromagnetic interference, and can be used in remote sensing setups where the sensors are as far as tens of kilometers from the readout system without any need for pre-amplifiers or electronic circuitry. Further, they are intrinsically safe and suitable for harsh environments, such as ATEX zones, extreme temperatures, radiation zones, and in liquid or humid environments.
The OptiFender fiber optic PD sensors are fully non-metallic and are galvanically isolated. They can be installed directly on the HV asset while being insensitive to electrical noise from other loads and PD's in other parts of the network. Further, they are immune to electromagnetic interference which is a particular advantage over electrical acoustic sensors which tend to raise false alarms in response to such effects. A single readout unit can simultaneously monitor up to 32 fiber optic PD sensors that can be concentrated in a single substation, or distributed across several locations kilometers apart from each other. The OptiFender system can provide continuous, uninterrupted, and unsupervised PD monitoring of many different types of electrical assets, including GIS, cable accessories, and power transformers.

Setup description

The tests of this study were performed at the high voltage laboratory (HVL) of Delft University of Technology. The test object was a SF6 filled high voltage GIS, energized with voltages of up to 180 kV, as seen in Figure 2a. The free-moving particle was introduced inside the last compartment of the GIS artificially and confined inside a dielectric container that held the small particle in a small volume of a few centimeters across. There was a window opening on the last compartment of the GIS, and a camera was pointing at the window to view the status of the particle during the whole test, as seen in Figure 2b. The video from the camera was the reference for determining the inception voltage at which the particle was mobilized.

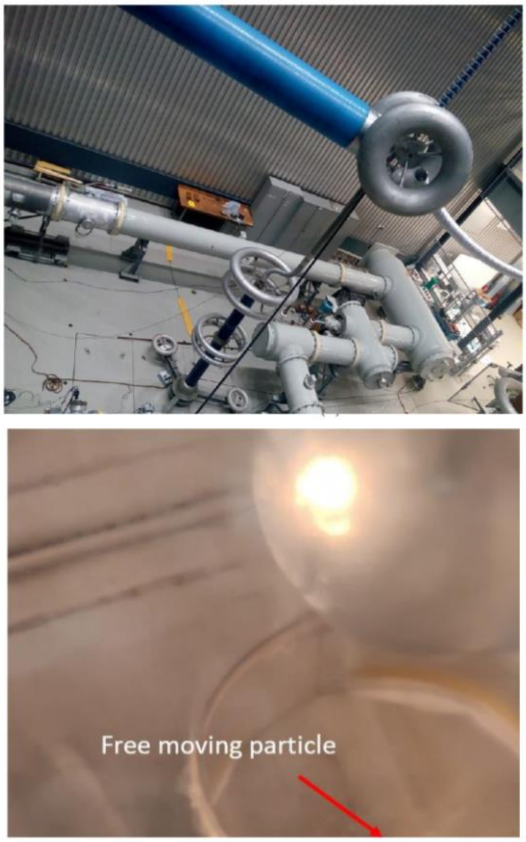

Figure 2 (a): High voltage GIS setup at the high voltage laboratory of TU Delft, (b): The artificially added particle to induce PD in the last compartment of the GIS.

Reference PD Measurement System

Embedded UHF sensors' outputs were used as a reference sensing solution in this test. The UHF sensor's outputs were recorded in mV units. However, both the UHF sensors and the OptiFender system exhibited similar PD activity at inception voltages and at higher voltage activities.

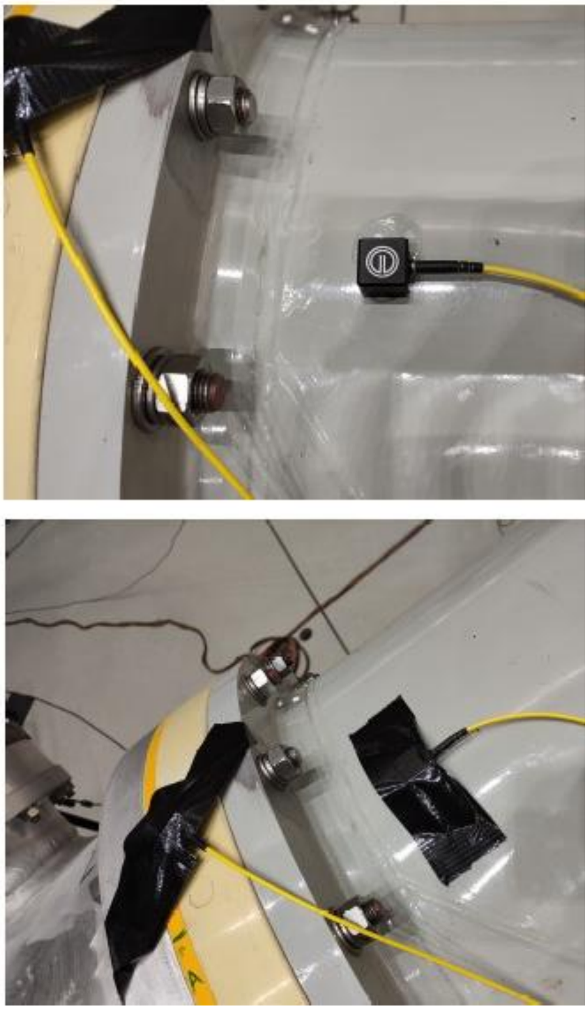

Figure 3 (a): Placement of the fiber optic PD sensor on the GIS compartment. (b): Fixing the sensors in place using tape.

Fiber optic PD Sensor Placement

The OptiFender PD sensors were placed on the outer body of the GIS enclosure and were fixed in place by tape. To improve the acoustic coupling of the sensors to the surface, an acoustic couplant was used between the sensing element of the sensor and the surface. In order to investigate the sensitivity of the OptiFender system in response to distance from the PD location, several PD sensors were placed at different locations along the GIS body. The first sensor which was also the reference sensor for peak sensitivity was placed directly below the PD location. The 2nd sensor was placed on the same compartment, but at the radially opposite side of the PD location and on top of the compartment. Then another sensor was placed on top of the spacer between the two compartments and the final sensor was placed on the adjacent compartment after the spacer. Figure 3 shows the attachment of the PD sensor to the GIS body.

Results

OptiFender PD Response

The sampling frequency of the OptiFender system is approximately 1 MS/s, and the signals are high pass filtered with a cut-off frequency of 20 kHz. This means that the effective bandwidth of the system is from 20 kHz to around 500 kHz [2]. However, based on the literature and preliminary tests, it was evident that the frequency content of the acoustic waves generated by the partial discharges is generally between 20 kHz to around 150 kHz. Therefore, the fiber optic PD sensor developed by Optics11 was optimized to have a boosted sensitivity within this frequency range, with a resonance frequency of 45kHz, making it particularly suitable for PD applications. The frequency response of the fiber optic PD sensor is depicted in Figure 4.

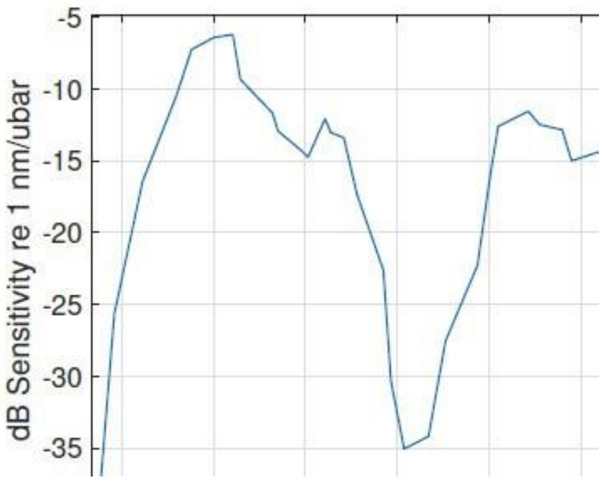

Figure 4 The sensitivity response of the fiber optic PD sensor.

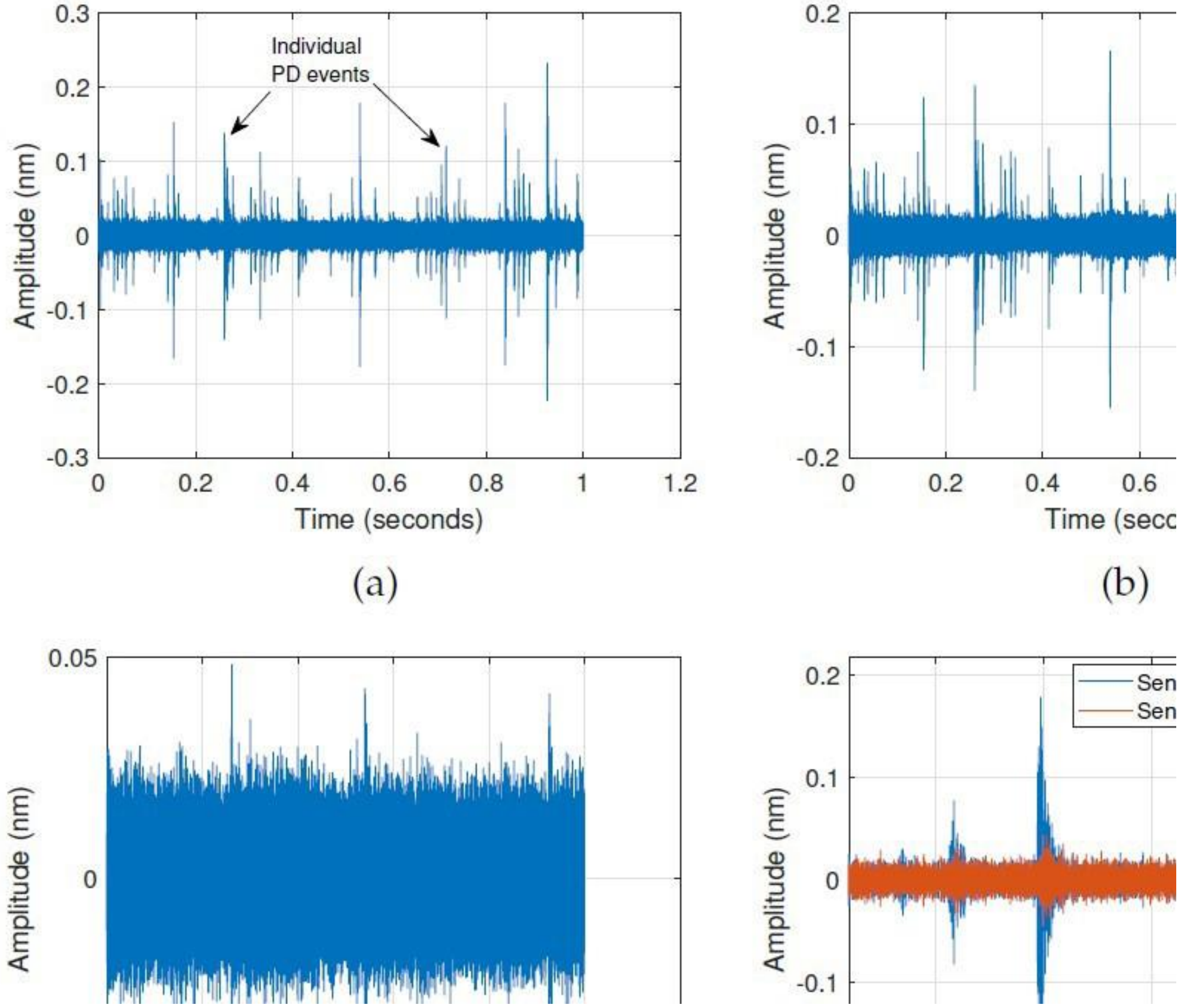

Figure 5 (a): OptiFender PD sensor directly below the PD location. (b): OptiFender PD sensor at the radially opposite side of the PD location at the same compartment. (c): OptiFender PD sensor on the adjacent compartment. (d): Comparison between the sensor response on the PD location (in blue) and on the adjacent compartment (in red).

At the moment that the particle was mobilized by a high voltage, the recorded PD activity on the different fiber optic PD sensors for 1 second of measurement is shown in Figure 5. Further, a comparison was made between the UHF sensor's response to that of the OptiFender system. Figure 6a shows a sample UHF sensor signal at 160 kV. Calculating the signal-to-noise ratios (SNR) of the two systems' response to the same PD events resulted in the graph of Figure 6. The SNR values of the sensors were measured using Equation 1.

$$SNR = 20 \times \log_{10}\left(\frac{\text{Peak amplitude}}{\text{Noise floor RMS}}\right)$$

In this equation, the noise floor RMS is the root mean square of the noise floor, for the last 500 milliseconds before the PD event starts.

Discussions

As seen from the graphs of Figure 5, as the OptiFender PD sensor is placed further and further away from the PD source, the resulting signal amplitude drops significantly. This is mainly due to the acoustic pathways of the outer body of the GIS metallic enclosure. The acoustic waves generated by the partial discharges attenuate as they propagate along the GIS metallic body. As a result, the energy of the acoustic wave decreases polynomially the further the sensor is placed from the PD location.

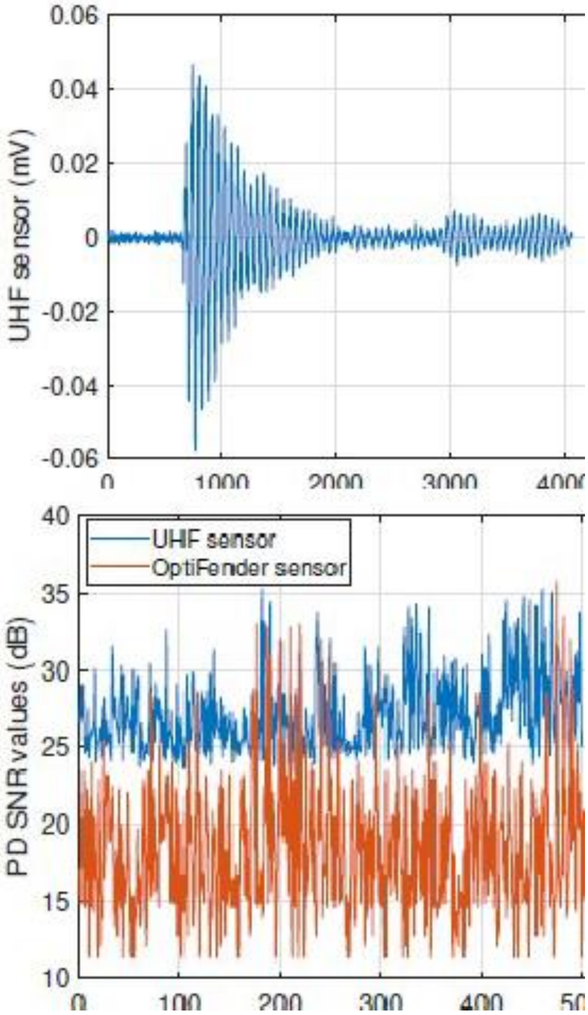

Figure 6 (a): Sample of the UHF sensor output (b): Comparison of the UHF sensor SNR (in blue) and OptiFender sensor SNR values (in red) over 500 PD events at 160 kV.

Moreover, at the intersection of 2 different materials, a percentage of the acoustic wave will be reflected, which is related to the acoustic impedance matching of the two environments. The best acoustic transfer happens between materials of the same kind or of generally the same stiffness. In the case of GIS structures, the epoxy spacer between the compartments has an acoustic impedance that is significantly different from that of the GIS metallic body, and its acoustic absorption is also much higher than metal. Therefore, the PD signals that were recorded at the adjacent compartment show lower SNR, even though the sensor is at the same distance from the PD location as the 2nd PD sensor on top of the last compartment.
Nevertheless, it can be seen from Figure 5 that in an ideal case, every OptiFender PD sensor can be assigned to an individual compartment of the GIS. Such a limitation with respect to spatial resolution can be overcome by a new OptiFender PD sensor architecture, where multiple sensing cores are inspected by a single readout channel.

Conclusions

This paper presents the successful implementation of the OptiFender fiber optic PD sensing system for the detection of PD signals in high-voltage GIS units. The PD event was generated from a free-moving particle that was artificially placed inside a GIS compartment and mobilized at voltages of above 150 kV. The OptiFender sensing solution could detect PD activity even at the inception voltage (as seen by the camera pointing at the particle), and it was completely unaffected by the electromagnetic interference around the GIS unit. Based on the results of this study, it can be deduced that the sensitivity range of the OptiFender PD sensors is currently one sensing point per compartment. However, a new OptiFender PD sensor architecture has since been devised to integrate multiple PD sensing cores per channel, extending the monitoring range to 2 or more GIS compartments per channel.

Acknowledgments

The experiments of the current study were performed in the High Voltage Laboratory (HVL) of Delft University of Technology. The preparation of the GIS and the inclusion of the artificial partial discharge source were also done by the HV experts at HVL, along with operating the reference PD measurements using conventional UHF sensors.

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