# Partial Discharge Detection and Characterization with Optical Acoustic Emission Sensors

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**Abstract**

Partial discharge measurement is one of the main tools for monitoring and diagnostic of the insulation of HV assets. This paper presents a novel acoustic PD monitoring system developed by Optics11. Thanks to its unique fiber optic technology, this system offers several advantages over classic PD sensing solutions that will be discussed in this paper. Optics11's solution was tested in a one to one comparison with a HFCT sensor in detecting internal PD's in a medium voltage joint. The Optics11 system was able to successfully detect PD events down to 70 pC with an SNR of 25 dB, with potential to detect PD events down to a few pC's in instances with lower inception PD levels.

*Keywords:* Acoustic Emission, Fiber Optics, High voltage, Medium voltage, Medium voltage joint, Optical AE, Optics11, Partial discharge, PD.

## 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 switchgears. PD's are originally caused by defects of insulation materials such as voids or protrusions. When undetected or overlooked, PD's can erode insulation layers, resulting in irreparable damages to the HV component. To date, PD is considered the predominant cause of premature degradation of electrical assets and it is responsible for 85% of failures in substations [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 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, sensing technologies developed for periodic inspections have been adapted and integrated into continuous monitoring systems. However challenges such as interfering electromagnetic noise, lack of in-field power supplies and the remote location of the assets complicate the permanent deployment of classic sensing technologies and limit their effectiveness as monitoring solutions.

To overcome such challenges alternative sensing technologies have been investigated. Fiber optic sensing in particular offers a unique set of advantages which overcome most of the challenges related to continuous PD monitoring. Fiber optic sensors are completely passive, do not require power at the sensing location, can be installed in remote locations and are immune to electromagnetic interference. This paper investigates the potential of fiber optic sensing in the field of PD detection, using a novel sensing system: OptimAE.

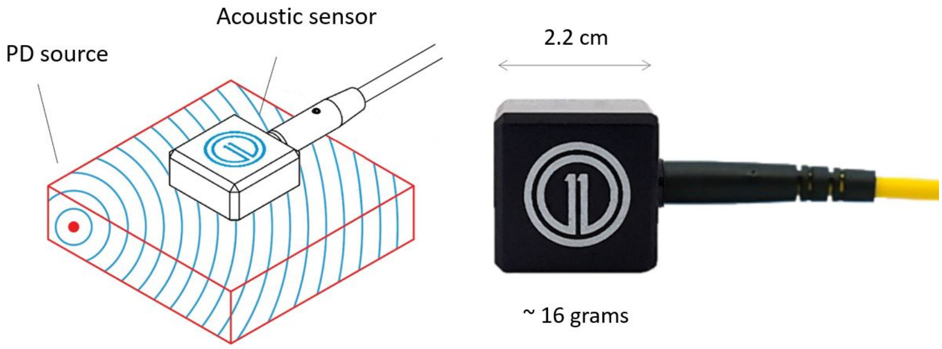
Developed and commercialized by Optics11, OptimAE is the world's first fiber optic acoustic emission sensing system. It enables to measure the ultra-sonic ($> 20$ kHz) acoustic footprints of partial discharge and to track their evolution over time. OptimAE sensors are passive and can be easily coupled and retrofitted to different HV assets, enabling the detection of close-by internal and surface partial discharges.

In this work OptimAE capabilities are demonstrated by inspecting a medium voltage cable joint presenting internal PD. Classic state-of-the-art PD detection instrumentation is used in parallel to verify and qualify the results obtained with OptimAE fiber optic acoustic sensors.

## Fiber Optic Sensing Technology

The operating principle of the OptimAE 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 on 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, or a rubber clamp, or using an adhesive material.
Upon the passing of the acoustic wave through the optical 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 OptimAE readout box for signal acquisition, demodulation of the acoustic emission (AE) signal, and communication to a computer with OptimAE software for acoustic event detection and further processing. Previous comparisons of the Optics11 AE sensors with the state of the art piezoelectric-based AE sensors shows a similar sensitivity and functionality [2].




(a) (b)

Figure 1: (a): Transfer of the PD generated acoustic signal to the OptimAE sensor. (b): The OptimAE PD sensor.

In the case of partial discharge application, the PD event generates an acoustic wave inside the insulation layer that propagates through the different insulation and semiconductor layers to reach the surface, where it will be picked up by the optical AE sensors. The frequency response of this perceived signal has a frequency band much lower than that of the electrical PD signal, and it is usually in the range of 20 kHz to 150 kHz [3]. Furthermore, depending on the material composition of the electrical asset and its geometry, there might be a slight delay between the electrical PD signal and the acoustic PD signal. This delay is due to the slower speed of the acoustic waves compared to electrical waves, and it is no more than a few microseconds. It is therefore not expected that such delays will affect the phase resolved PD patterns. This will be discussed in more details in the results sections.
Throughout the remaining sections of this paper, we will refer to the optical AE sensors as optical PD sensors.

## Advantages of PD Detection Using Fiber Optic Sensing

Fiber optic sensing has several advantages over electrical sensing systems, which is not just limited to partial discharge detection. Optical sensors are

inherently passive and intrinsically safe, immune to electromagnetic interferences, 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 preamplifiers or electronic circuitry. Further, they are suitable for harsh environments, such as ATEX zones, extreme temperatures, radiation zones, and in liquid or humid environments.
The optical PD sensors can be made out of non-metal components. They can be directly placed on the high voltage asset, where they will only be sensitive to PD's at that particular location, and 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 interrogate up to 32 optical PD sensors that can be concentrated in a single substation, or distributed across several locations kilometers apart from each other. The OptimAE system can provide uninterrupted continuous-time and unsupervised monitoring of the electrical assets, for both indoor and outdoor applications.

## Setup description

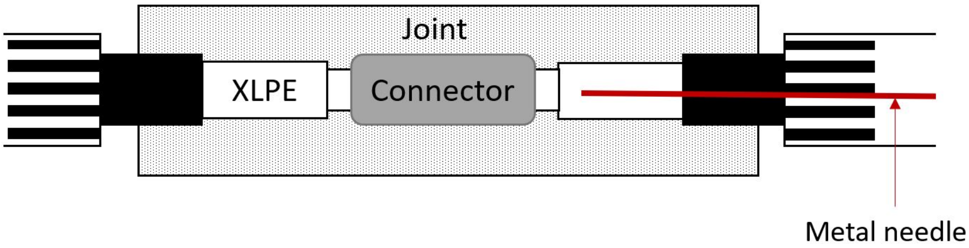
High voltage and medium voltage joints and terminations are among electrical equipment that are most susceptible to partial discharge defects [4], [5]. Consequently, a medium voltage joint was chosen as the test object for our partial discharge detection experiment. The cable used for the experiments was a 4 m long, 6/10 kV cross-linked polyethylene (XLPE) MV cable provided with outdoor cold-shrink termination and an inline splice acting as a joint. The high voltage source was regulated by an auto-transformer, making it possible to adjust the voltage from a few Volts to 10 kV RMS. The frequency of the AC source was 50 Hz.

### Test Setup

In order to evaluate our partial discharge detection system, we needed a PD source to generate such PD's in the cable joint. For this purpose, an artificial PD source was introduced into the joint by placing a grounded metal needle in between the XLPE insulation and the cold-shrink semiconductive tube. One end of the needle remains close to the the metallic connector of the joint and the other stretches all the way out of the joint reaching the ground connection at the termination [6]. For laboratory experiments of the current study, this setup proved to generate stable and repeatable internal partial discharges from a few tens of picocoulomb to hundreds of picocoulombs. Figure 2 shows a schematic of the constructed joint, along with a picture of the joint assembly.

### Reference PD Measurement System

To evaluate the performance of OptimAE as partial discharge monitoring system, two reference PD detection systems were used. The first one was the Haefely DDX9101 which is a conventional PD detector system complying




(a)

(b)

Figure 2: (a): Schematic of the medium voltage joint construction with the addition of the needle for creating internal PD. (b): The constructed joint with the artificial PD.

with the IEC60270 standard. Once calibrated, this system provided us with the accurate measurement of the apparent charge and the phase resolved partial discharge (PRPD) patterns. However, with this commercial system it was not possible to acquire the individual PD waveforms in continuous form and synchronize them with the OptimAE AE outputs. Subsequently, the measuring impedance of the Haefely detector in series with the 1 nF coupling capacitor was replaced with a high frequency current transformer (HFCT) sensor with a gain of 9.1 and a bandwidth of 60 kHz-136 MHz. The HFCT sensor was connected to a Tektronix MSO series 5 oscilloscope, which also probed the PD phase angle with help of an external synchronization circuit [7]. For this particular test the sampling frequency of the oscilloscope was 625 MSa/s with a bandwidth of 250 MHz and the PD signals were acquired in FastFrame mode.

The other advantage of using the oscilloscope measuring system was its trigger function. The oscilloscope was used in a way that the first true PD signal acquired by the scope also triggered the OptimAE interrogator unit with a TTL input. This way, both systems are synchronized during the full period of the acquisition.

## Optical PD Sensor Placement

Unlike electrical sensors, acoustic PD sensors are only locally sensitive. This property of acoustic sensors offers the advantage of inspecting the asset for

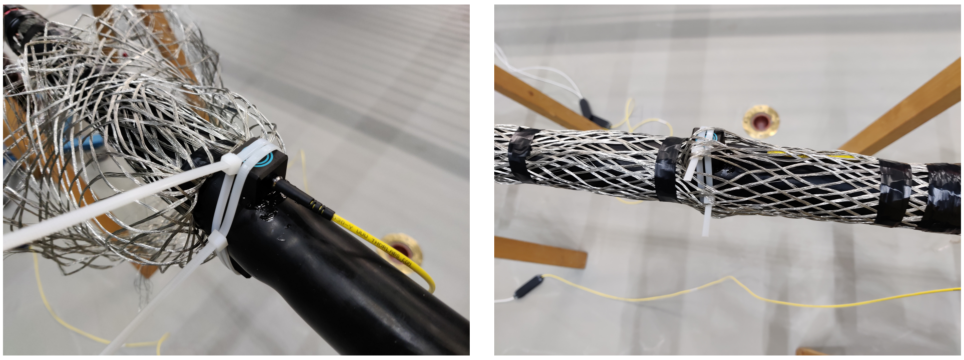
PD only at the location of the sensor and being insensitive to noise from other loads on the network, but it also entails discretion in sensor placement and its contact with the surface of the asset. Further, for a better transfer of the acoustic signal to the sensor core, it is recommended to use a couplant gel or paste between the surface of the asset and the core of the sensor.

For the above-mentioned reasons, the optical PD sensor was placed in the proximity of the PD defect in the joint area. We also used an ultrasonic gel as a couplant (from the company Magnaflux), which was applied on site and right before attaching the sensor to the joint, and used zip ties to fix the sensor in place and prevent it from sliding off. Following these steps, we could ensure that the PD signal was acquired with a good signal to noise ratio (defined in Equation 1).

$$\text{SNR} = 20 \times \log_{10}\left(\frac{\text{Peak amplitude}}{\text{Noise floor RMS}}\right) \tag{1}$$

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

Figure 3 shows the attachment of the PD sensor to the joint. Basically, the ground mesh was peeled back, the sensor was placed in position and was fixed with zip ties, and the ground mesh was placed above the sensor.



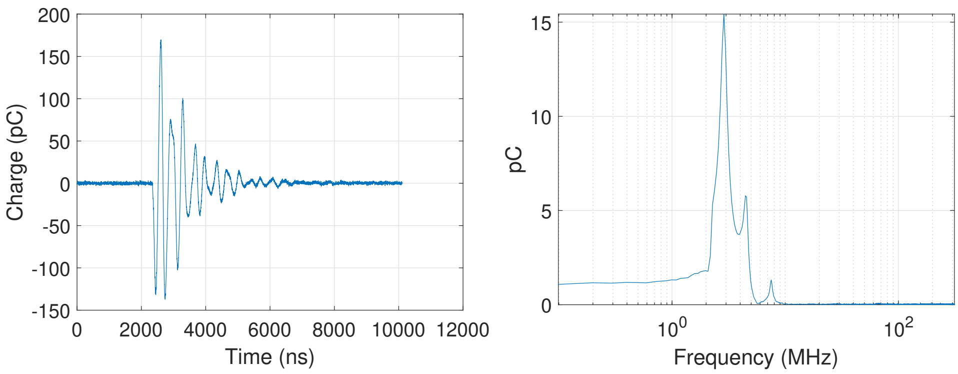
(a) (b)

Figure 3: (a): Placement of the optical PD sensor on the joint and fixing it with zip ties. (b): The ground mesh covers the sensor and the complete joint is constructed.

## Results

### HFCT PD response

As mentioned before, the sampling frequency of the Tektronix system was 625 MS/s. Therefore, the amount of acquired data over a few seconds of measurement would be significant and hard to process. The way that this problem was handled was by recording only the PD event (over a few microseconds), and the timestamp of the event. The data was then processed and organized using the PDflex [6] software (FastFrame mode) developed by the high voltage laboratory of TU Delft, and then post-processed using MATLAB 2020b software. A sample PD event sensed by the HFCT sensor is depicted in Figure 4. As evident from this figure, the duration of the electrical PD signals is 10us and their frequency content is up to about 10 MHz, including resonance peaks resulting from the LC network of the measuring loop. As a result, the PD pulses are acquired as oscillating signals which makes it difficult to estimate the charge of the PD pulses in time domain. Since PD levels are conventionally measured in pC, the signals were processed in frequency domain according to [7] in order to approximate the pC levels of the signals. Nevertheless, any other PD parameter such its peak amplitude in mV could have also served the comparison purpose of this paper.




(a) (b)

Figure 4: (a): The time domain PD response from the HFCT sensor. (b): The frequency response of the same pulse.

## OptimAE PD Response

The sampling frequency of the OptimAE 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. 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. The optical PD sensor commercialized by Optics11 is therefore designed so that it has a boosted sensitivity within this frequency range, making it particularly suitable for PD applications. The frequency response of the optical PD sensor is depicted in Figure 5. The partial discharge generated in the medium voltage joint under investigation resulted in the acoustic responses such as given in Figure 6. This particular event was in response to a partial discharge with an apparent charge of 175 pC.

As apparent from the Figure 6b, most of the frequency content of the acoustic PD signals are between the range of 20 kHz to around 90 kHz. With that, the acquired data was bandpass filtered within this range to suppress the backscattering noise from the optical fiber, and improve the SNR of the acquired signals. The SNR of the signal for the particular example shown in Figure 6a, was 25.56 dBm (using Equation 1) before bandpass filtering, and 32.91 dBm after bandpass filtering between 20 kHz to 90 kHz. The time domain PD signals before and after bandpass filtering is shown in Figure 7.

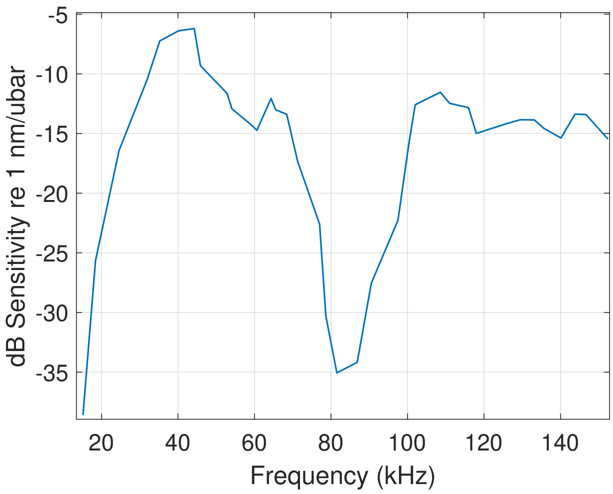



Figure 5: The sensitivity response of the optical PD sensor.

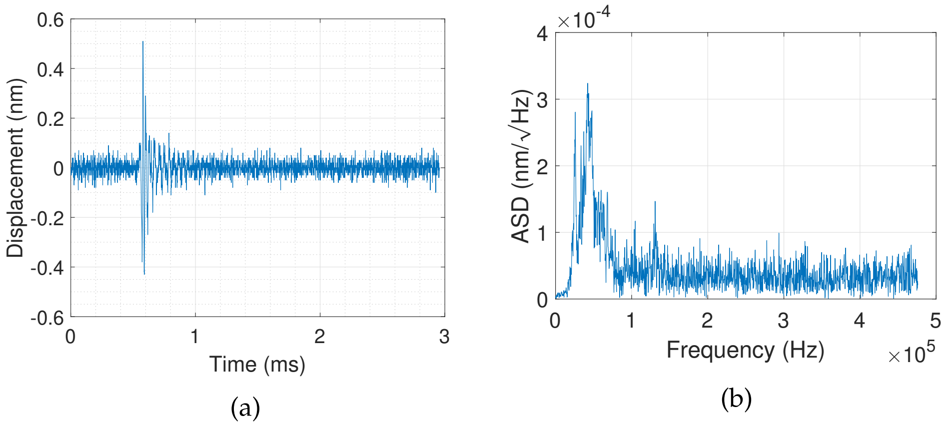



Figure 6: (a): Unfiltered PD response from the OptimAE system in time domain. (b): The frequency content of the same signal. The concentration of the PD information below 100 kHz range is evident from this figure.

Similar behaviour was observed throughout the other measurements of this study, and all the acquired OptimAE data was subsequently bandpass filtered in a similar way. Throughout the measurements of the current study, internal PD events that were above around 70 pC were detected with an SNR of at least 25 dB and up to 37.6 dB.

## OptimAE vs HFCT PD sensor

Figure 8 shows the response of the two PD detection systems, e.g. the HFCT sensor system and the OptimAE PD system in continuous time domain.

The level of the PD signals detected using the HFCT sensor were between 80 pC to around 300 pC, and the corresponding acoustic responses of the same PD events were between 0.3 nm to 0.6 nm and are presented in the same figure in the bottom. It is evident that the OptimAE system can provide information about the PD event's occurrence and relative phase in line with the one obtained with the HFCT sensor. In this figure, the 50 Hz input signal

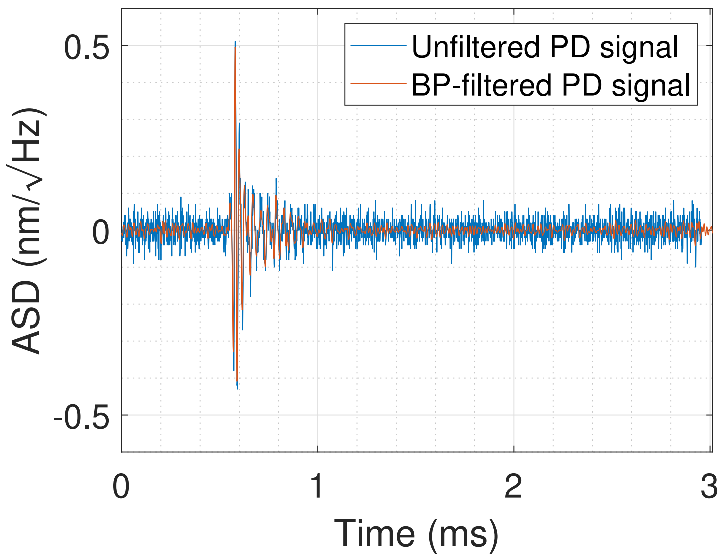



Figure 7: Time domain PD signal acquired from the OptimAE system, before (in blue) and after (in red) bandpass filtering.

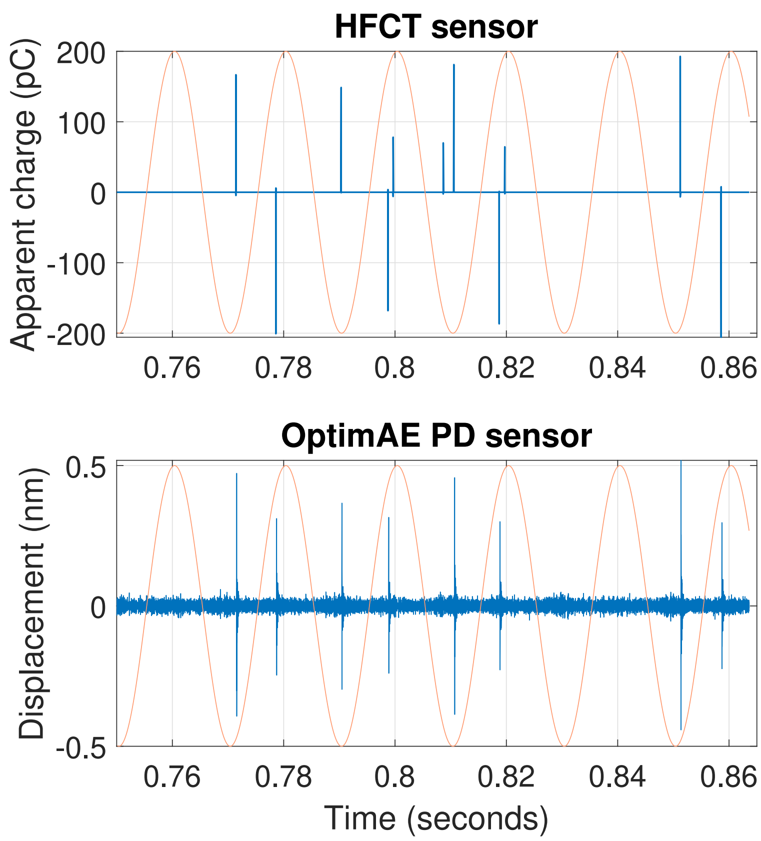



Figure 8: Continuous time domain PD response from the HFCT sensor (in blue), and the corresponding acoustic PD response from the OptimAE PD sensor (in red). The 50 Hz input voltage is also shown in black.

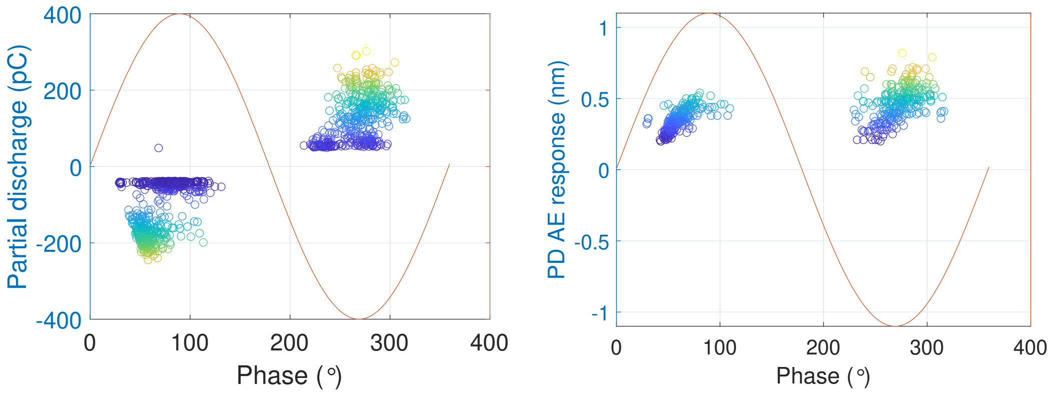



Figure 9: (a): PRPD pattern from the HFCT sensor. (b): PRPD pattern from the optical sensor.

is also synchronized with the PD signals. The concentration of the PD events near the positive and the negative peaks of the 50 Hz input is an indication of internal PD in the asset, which both systems successfully demonstrate. The phase resolved partial discharge (PRPD) patterns from the electrical sensor is shown in Figure 9a, and for the optical sensor is shown in Figure 9b.

Based on the Figures 9 it is evident that the OptimAE system has a comparable PRPD pattern to the HFCT sensor, and has the capability of identifying low amplitude partial discharges, along with having the potential of classifying the type of defect (internal discharge in the current study). It is noteworthy that both positive and negative discharges in the joint result in an acoustic signal with a positive displacement amplitude, which is evident from Figure 9b.

## Amplitude response correlation

From the previous experiments, it was expected that there should be a correlation between the electrical PD sensor output, and that of the OptimAE. The idea is to explore the possibility of estimating the apparent charge during a PD event by only looking at a calibrated OptimAE PD output. Although the correlation is not fully linear, the dependence of the amplitude of the optical PD sensor's output to the partial discharge level measured from the HFCT sensor is evident from the Figure 10. In this figure, the relationship between the apparent charge measurement from the HFCT sensor, and the strength of the acoustic wave (1-norm of the acoustic signal, defined in Equation 2) captured by the OptimAE system is depicted. The linear correlation between the two outputs is 65%, and the root mean square error of the linear fit is 30.784 pC. In Equation 2, $\mathbf{X}$ is the acoustic PD signal in time domain, containing the datapoints $x_i$ where $i = 1, 2, ..., N$.

$$\text{Strength} = ||\mathbf{X}||_1 = \sum_{i=1}^{N} |x_i| \tag{2}$$

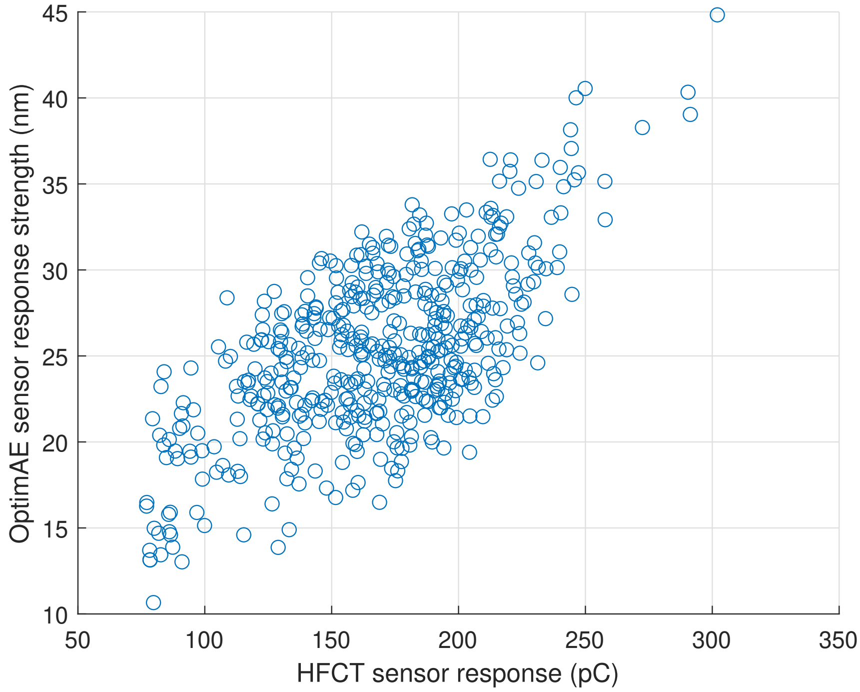



Figure 10: Correlation between the strength of the acoustic signals and the apparent charge from the HFCT sensor.

## Conclusions

This paper presents the first commercial acoustic fiber optic based partial discharge sensing system developed by Optics11: OptimAE. The system was validated in a lab environment by comparing it to classic and state-of-the-art PD sensing technologies. An MV cable joint presenting internal partial discharge was used as a test object to validate the performance of OptimAE and compare it to the performance of HFCT sensors.

The MV joint was inspected using an acoustic sensor optimized for PD detection, characterized by high sensitivity in the 20 kHz-150 kHz bandwidth, where most of the frequency content of the PD related acoustic events is concentrated. Such a sensor can be easily retrofitted to various electrical assets with simple mechanical fixing, provided that proper acoustic coupling between the sensor and the test object is obtained during the installation.

Installed on the MV joint, the Optics11 PD sensor was able to detect PD events down to 70 pC with an SNR of more than 25 dB. The high SNR of the recorded responses shows that lower levels of PD can also be detected (not within the scope of the setup in the current experiments).

Acoustic signals obtained with the Optics11 sensor were also analyzed to produce PRPD patterns. The phase plot showed a good resemblance with the one obtained using the HFCT reference sensor except for the sign of the responses, as expected from an acoustic technology. Such results demonstrate that OptimAE could enable not only PD detection, but also an in-depth signal analysis for defect classification.

The results obtained in this work show how fiber optic acoustic sensing is a valid alternative to classic sensing technologies for PD detection and classification. While providing reliable data, Optics11 technology introduces the benefits of fiber optics in the PD sensing landscape, providing the industry with a reliable solution for in-field monitoring challenges.


## Acknowledgement

The experiments of the current study were performed in the High Voltage Laboratory (HVL) of Delft University of Technology. The preparation of the joint and the inclusion of the artificial partial discharge source was also done by the HV experts at HVL, along with preparing and operating the reference PD measurements using conventional capacitive sensors and a non-conventional HFCT sensor.


## Nomenclatura

| | |
|---|---|
| AC | Alternating Current |
| AE | Acoustic Emission |
| ATEX | Atmosphere Explosible |
| HFCT | High Frequency Current Transformer |
| HV | High Voltage |
| MV | Medium Voltage |
| PD | Partial Discharge |
| PRPD | Phase Resolved Partial Discharge |
| RMS | Root Mean Square |
| SNR | Signal to Noise Ratio |
| TTL | Transistor-Transistor Logic |
| XLPE | Cross-Linked PolyEthylene |

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