Partial Discharge Detection Using Distributed Acoustic Sensing at the Oil-Pressboard Interface

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***Abstract*—This paper investigates novel, initial experimentation in detecting and analysing Partial Discharge at the Oil-Pressboard interface using a continuous fibre-optic-based Distributed Acoustic Sensing (DAS) system. Discharge was successfully detected at a minimum of 223 pC despite the sample rate of DAS being lower than the spectra of acoustic emission. DAS presents multiple advantages over conventional Partial Discharge techniques including inherent localisation, immunity to electrical and magnetic noise, as well as much greater detection distances.**

***Index Terms*—Distributed Acoustic Sensing, Partial Discharge, Pressboard, High Voltage, Oil-Pressboard Interface**

I. Introduction

Ageing of insulation systems within High-Voltage equipment during operational life is natural [1]; however, it is established that ageing is accelerated when the systems are under increased electrical, mechanical or thermal stresses [2]. This then contributes heavily increases chances of breakdown or failure [3]. Partial Discharge (PD) is a localised electrical discharge that adds to these stresses, and is known to degrade insulation [3]. Therefore, as partial discharges are known to be a cause and symptom of degradation across many different types of insulation systems, detection and monitoring are of key importance [4].

Typical detection methods for monitoring partial discharge within a transformer include transient voltage [5], Ultra High Frequency (UHF) [6], Acoustic Emission (AE) [7] and Dissolved Gas Analysis(DGA) [8]. Electrical measurements looking for transients are not easily able to distinguish between different discharge sources. UHF however, can even provide triangulation of discharges, but relies on many high bandwidth sensors; which can be expensive and hard to install [8], [9]. DGA does not provide location information and can only be sampled periodically [10]. Conversely, AE can provide all of these benefits with the main drawback of being sensitive to external vibrations and mechanical noise.

Fibre optic sensors have been used to detect AE [11]–[13], however these are single discrete sensors mounted at the end of fibre optic cable, as opposed to using the fibre itself as a sensor. Distributed Acoustic Sensing (DAS) provides a continuous, distributed set of vibration sensors along a fibre optic cable [14] that are able to detect and locate possible PD events whilst being inherently immune to electrically or magnetically induced noise [15]. DAS has previously been utilised on high voltage systems for detection of breakdown events [16]: much greater in amplitude than PD events.

This paper presents the first stage of experimental results and initial analysis for continuous on-line detection of pressboard-based partial discharge using DAS, focussing on the techniques required to detect AE at much lower sample rates than standard techniques [17].

A. Principle of Distributed Acoustic Sensing

Coherent Optical Time Domain Reflectometry (c-OTDR) is a well understood technique used to measure the Rayleigh backscatter along an optical fibre. A highly coherent laser pulse is launched into the sensing fibre which generates Rayleigh backscatter due to random imperfections in the fibre [18]. The returning scatter interferes constructively and destructively, as in an interferometer, causing a change in the phase that is measured. However, as this Rayleigh backscatter changes based on the strain of the optical fibre; by interrogation of the Rayleigh backscatter generated by periodic pulsing of a coherent laser down the fibre, the acoustic signal disturbing the fibre can be reproduced. From comparison between the time of launch to detected reflections and the known speed of light down the fibre, the distance at which those scattered reflections originate from can be determined.

The fibre distance channels at which positions of reflections can be determined are separated by “spatial sampling” distances. The measurement at each spatial sample distance represents the average measurement of all spatial samples within a fixed spatial resolution. The spatial sampling and spatial resolution are both fixed values, so that as the position increases in number of spatial samples, the fibre distance channel always represents the average measurement of the surrounding samples within the spatial resolution. By increasing the repetition of interrogation, time resolution can be increased. However, without additional methods [19], the maximum speed that can be achieved is the light round-trip time along the fibre. To achieve the 20 kHz sampling rate used in this paper, the longest length of fibre that can be achieved at this time is 5.1 km with 1.27 m spatial sampling and a gauge length of 5 m.

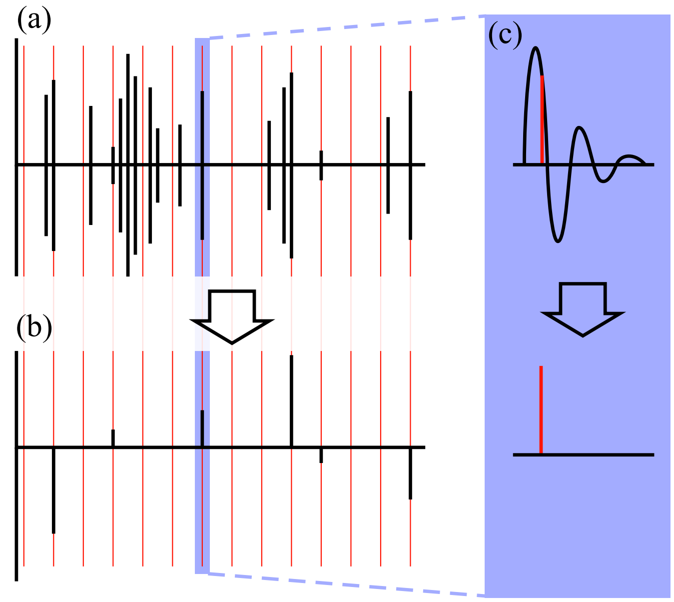

Fig. 1. Exaggerated example of how high-frequency events are sampled, missed and distorted from being sampled at a lower rate. (a) example high-frequency events in the time domain to be observed occurring randomly with random amplitude. The regular red lines indicate the intervals at which these events are sampled with a very short interrogation. (b) shows the resultant data producing events only when the interrogation happens to line up with an event. Zoomed inset (c) details the effect of the interrogation sample being much shorter than width of the event causing distortion of the resultant amplitude.

B. Undersampling

At sample rates that DAS is currently capable of [20], at longer distances (i.e. >5 km) there is a mismatch between this sampling rate and the time scale of individual PD acoustic events. It may be construed that under normal sampling, these events would be aliased removing all but the largest amplitudes of acoustic impulses due to inherent time-averaging between sampling points. However, DAS sampling relies on a very short (<10 nS) interrogation pulses that can allow the detection of higher-frequency signals than the sampling rate, albeit with distortion-causing aliasing.

As demonstrated in Figure 1, when a high-frequency signal or impulse interacts with the fibre at the same time as that fibre-section being interrogated, a very short impulse-like event will be observed in the results. In Figure 1c, it can be seen that the interaction between the high frequency acoustic signal and fibre interrogation has to occur within the sampling window. Therefore, there is a chance the event may be missed, as well as the recorded data not being representative of the original signal other than detection of existence. As originating PD acoustic emission comprises of mostly impulse-like discharge, it is most likely that the DAS will sample the reverberant ringing and not the highest peak value. By decreasing the length of fibre, the sample rate can be increased as the round-trip time of the fibre is less, thereby increasing the chance of detecting events; but the detection range is shortened.

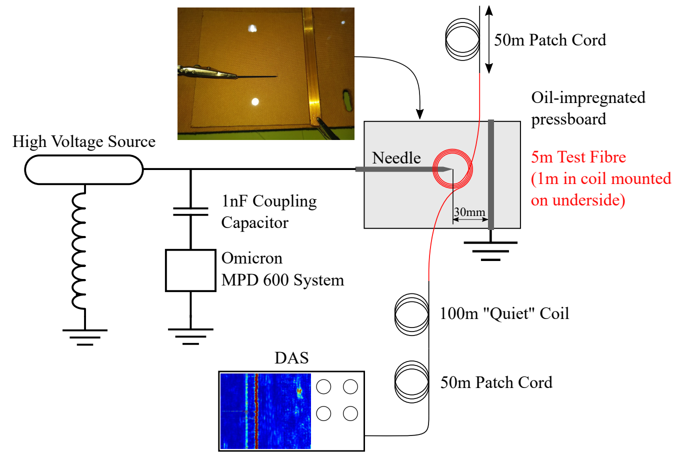

Fig. 2. Mixed electrical and optical schematic of the pressboard setup compromising of the DAS firing through the patch and quiet coils into the 5 m of test section of which 1 m is mounted to the pressboard; as well as electrical omicron measurement connected in parallel with the HV source. Needle is set at 30mm from the grounded bar at an angle of 10°.

II. Experiment

A. Setup

A needle-bar setup (Figure 2) is used as a discharge source across an oil-pressboard interface, allowing for easy attachment of fibre-optic components. The construction is the same as in [21] with the bar grounded, and the needle elevated to between 20 and 25 kVrms, reliably initiating partial discharge. The needle is positioned at a shallow angle (10°) to the 5 mm thick pressboard to induce tracking along the interface. The pressboard was conditioned to 6% moisture by weight, achieved by 48 hours of drying in an oven at 90 °C and then allowing re-absorption from the ambient air. 1m of bare SMF28e unbuffered fibre in a loose coil is clamped to the underside of the pressboard.

The pressboard and close fibre assembly was immersed in Nitro Gemini X mineral oil, with the setup sat on high-density foam to reduce direct-coupled environmental noise. As shown in Figure 2, an APSensing DAS system is connected to the fibre in the test area through a 50 m patch cable and then through a 100 m acoustically-decoupled reference coil. The repetition rate of the DAS system was set to the maximum 20 kHz with a gauge length of 1.27 m, spatial resolution 5 m.

The system was monitored electrically with an Omicron MPD600 system, though a 1 nF coupling capacitor connected in parallel to the experiment. The system was tested to be PD free (<5 pC) up to 35 kV with no needle.

As most PD events are missed due to the sampling mechanism, as well as lack of synchronisation methods with the Omicron system, single discharge events can not be individually compared and therefore the envelope of the events are compared other a greater time period.

B. Processing

As events in the DAS data takes the form of spikes, most standard denoising techniques [22], such as wavelet or spectral

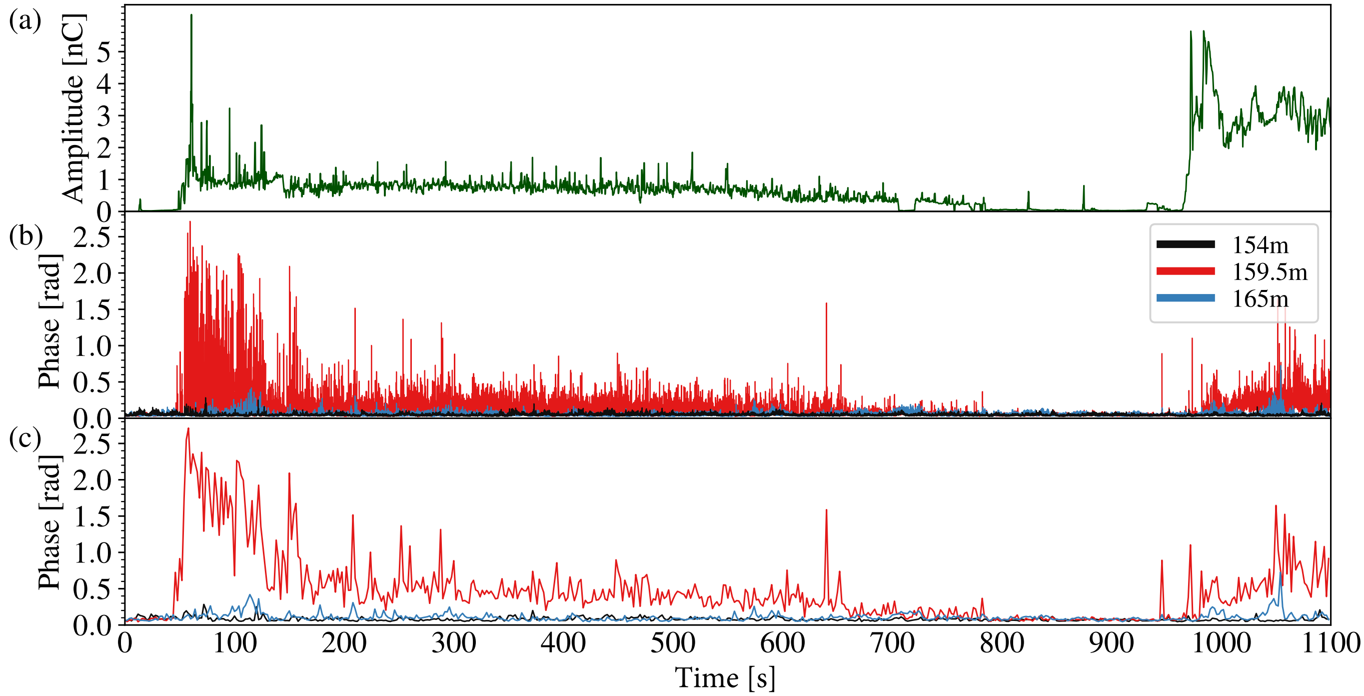

Fig. 3. (a) Amplitude trend of PDs electrically measured with Omicron MPD system. (b) Phase output of the DAS system at 3 different locations: 154m before pressboard in black, 159m within pressboard in red, 165m after pressboard in blue. (c) Data from (b) has been downconverted using the peak-detect method as described above with a ratio of 100:1; peak values are maintained whilst reducing data.

subtraction, do not show any SNR improvement at this time. Furthermore, the amount of data recorded per minute can be in excess of gigabytes, therefore the data must be reduced before analysis. The data from each location bin is segregated into chunks: the highest value in the absolute values of each chunk is taken as a new point in an output array at that location and starting time. This allows for downsampling the data whilst maintaining any peak values that may exist. Unfortunately, processing data in this form may also pronounce and mask signals along with the events. Results in this report are above the noise level and therefore not an issue in presented data.

III. Results and Discussion

Figure 3a shows the amplitude trend of the Omicron PD measuring system, starting with large discharge averaging $1\,\mathrm{nC}$ to $2\,\mathrm{nC}$, peaking at $6\,\mathrm{nC}$; and then decreasing to a steady $0.9\,\mathrm{nC}$ to $1.5\,\mathrm{nC}$ at $150\,\mathrm{s}$ until $600\,\mathrm{s}$. The discharge then peters out to below $50\,\mathrm{pC}$ until at $970\,\mathrm{s}$ in discharge rapidly climbs to above $2\,\mathrm{nC}$. The output of DAS system in Figure 3b, at the pressboard location $159.5\,\mathrm{m}$ shown in red, closely follows this trend seen by the electrical measurements with peak values of $2.72\,\mathrm{rad}$ at $1.8\,\mathrm{nC}$ of discharge. During the steady $0.9\,\mathrm{nC}$ to $1.2\,\mathrm{nC}$ range, average spikes are seen in the DAS of $0.73\,\mathrm{rad}$. Noise floor was measured without voltage applied at $0.056\,\mathrm{rad}$(rms) across a period of 30 seconds.

As expected, the occurrence of these spikes is, like the originating discharge, stochastic; but loosely correlated with the amplitude and number of discharges. Locations surrounding the pressboard, shown at $154\,\mathrm{m}$ and $165\,\mathrm{m}$, only background

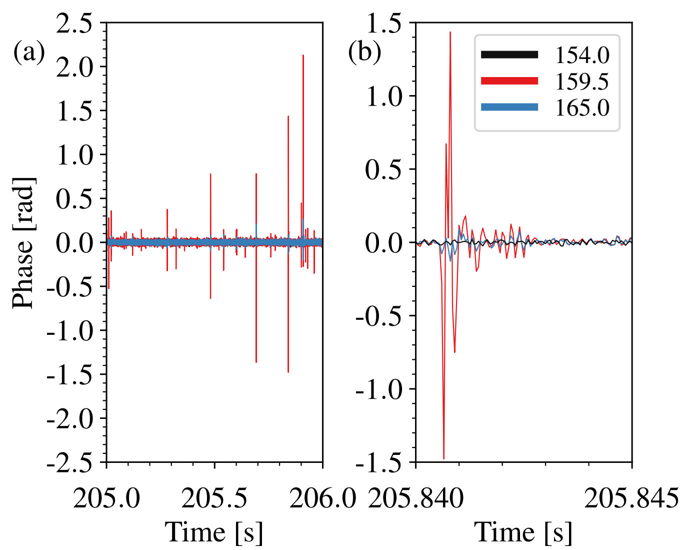

Fig. 4. Greater detail of single events between 205 and 206 s; same data as in Figure 3 without any downconversion. (a) 1 second of DAS data, distances: 154m before pressboard in black, 159m within pressboard in red, 165m after pressboard in blue. (b) Greater detail across time frame of 5 ms showing an impulse-like single PD event in DAS data at pressboard location.

noise is observed, and does not correlate with PD events. The increased resolution of a single event in Figure 4 shows acoustic events are picked up as a major peak and then ringing causedby the elasticity of the materials and acoustic reverberations of the system.

Due to undersampling, the majority of the DAS data shows amplitudes less than peak value of the originating acoustic emission; as due to chance, this highest impulse peak is missed and instead the remaining reverberation is sampled. Peaks at 150 s and 640 s, however, show events during which this is not the case, and produce an uncharacteristically high peak in the data.

Figure 3c shows the peak-detect downsampled data, producing a more similar plot to the trend given by the Omicron allowing for easier visual comparisons between the datasets. As PD amplitude decreases over time, the overall envelope of the resultant DAS data at that location decreases until at 800-950 s, the spikes are within the noise floor giving a minimum sensitivity of 0.147 rad at 223 pC.

IV. Conclusion

The purpose of this study was to analyse whether a DAS system was capable of detecting partial discharges, specifically in the case of oil-pressboard interfaces. Based upon the tests carried out, DAS is able to detect discharges of larger levels given that the acoustic coupling between the fibre and discharge source is good enough.

These results are early in the development of DAS for PD detection and show promising results. The data described in this report due to the effect of undersampling of events, and the stochastic nature of the PD itself, means that recorded minimum sensitivities may not be the best achievable. Additionally, the noise floor of the DAS system in this report is within a working laboratory environment, and therefore is not typically representative of a permanent fixture. Thus, it would be expected that in such a system, high sensitivities of PD detection would be achieved.

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