Distributed Acoustic Sensing of Partial Discharge: Initial Findings

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ABSTRACT

This report investigates novel, initial experimentation in detecting and measuring Partial Discharge along an insulated cable using a fibre-optic-based Distributed Acoustic Sensing system. Initial detection of in-air corona and discharge has successfully been observed with a high signal-to-noise ratio, thus more sensitive signals will be able to be measured towards the goal of detecting partial discharge. This method could present numerous advantages over conventional Partial Discharge measurement techniques including accurate positional information, greater detection distance and immunity from electrical noise.

KEYWORDS

Distributed Acoustic Sensing (DAS), Partial Discharge (PD), measurement, detection, void discharge, distributed measurement, fibre-optic, power cable monitoring

INTRODUCTION

Power cable PD detection and location is now a necessary part of operating and maintaining a cable system and is routinely used for condition monitoring. Conventional test methods do not allow for the location of PD along cable circuits to be determined accurately. This work presents an optical fibre-based detection system that uses the minute vibrations caused by Partial Discharge which disturb the fibre, providing location and possible characterisation about the event. A Distributed Acoustic Sensing (DAS) system allows for precise localisation of PD without electrical signal degradation at great distances. Other measurements could be taken using the same system using multiplexing, such as detection of mechanical damage or larger discharges such as break-down events.

Present online detection methods such as high frequency (HF) current and single-point acoustical emission monitoring only provide very limited range and have no ability to provide accurate localisation data other than through time of flight between multiple sensors. By knowing the location and size of discharges, it is possible to make more informed asset management decisions.

Currently as far as the authors are aware, DAS systems have not been used for fully distributed detection or location of discharge activity. Therefore, this research is required to investigate whether DAS is suitable for the detection of discharge activity within a cable. Further research can demonstrate whether discharge characterisation is possible from DAS measurements alone.

OUTLINE OF DAS SYSTEMS

DAS typically uses a method called c-OTDR for detection of vibrations that can be reconstituted into an acoustic signal. 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 scattered light that is then collected on a detector. The returning scatter then constructively and destructively interferes with each other, as in an interferometer, causing a change in the phase relation and/or amplitude that is measured. However, as this Rayleigh backscatter changes based on the strain that the optical fibre experiences, by use of a fast-repetitive scan of the fibre acoustical signals can be reproduced along the continuous length of fibre. 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.

As the returning signal is of very low power, collection of this scattered light has to be taken over a measurable amount of time. These time slots in which the scattered light is measured, gives an inherent "binning" of physical segments along the fibre known as spatial resolution or gauge length. The sensitivity and SNR (Signal to Noise Ratio) of the system is affected by the selection of this spatial resolution. The measurement sections overlap by a length known as "spatial sampling distance" thereby allowing the spatial resolution to be accurately sampled.
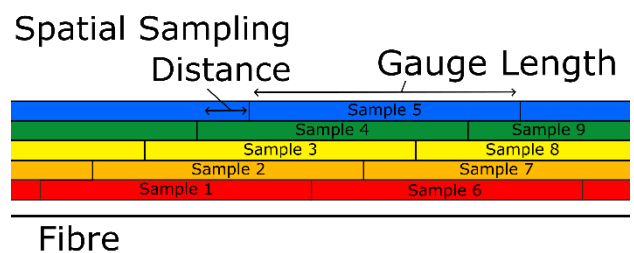

Figure 1: Graphical drawing of sampling terms used in DAS

c-OTDR techniques are able to provide a long measurement range, however longer ranges do provide a limitation in that the spatial resolution and repetition frequency are often impacted. A DAS system has recently been reported with a measurement range of 125km, with a spatial resolution of 8m [1]. As the measurement range increases, the amplitude of the received backscatter decreases due to fibre attenuation and therefore increased light should be launched into the fibre to maintain a good SNR. This can be achieved by increasing the optical pulse width which therefore decreases the spatial resolution. The

repetition frequency decreases simply due to the time that the light pulse takes to reach the end of the fibre before a new pulse can be launched. Therefore, experiments in lab conditions can achieve much greater sampling frequency than real-world cable lengths. For example, a 50km length fibre optic can only achieve a theoretical maximum of $f = \frac{c}{2.n.d} = \frac{2.998e8\left(\frac{m}{s}\right)}{149820\ (m)} = 2001Hz$ where n is the refractive index, which for single mode fibre is 1.4982. Frequency division multiplexing (FDM) techniques could be used to increase the sampling rate in a linear fashion.

ACOUSTIC EMISSION (AE) OF PD

Partial discharge creates acoustic signals by exerting force on the surrounding materials of the void discharge due to the rapidly expanding gases. These materials are elastic and therefore oscillate at ultrasonic frequencies producing the acoustic emissions [2]. As the exciting vibration is dependent on the size and shape of the void, it can be seen that different void types create different emission spectra and also that due to the force applied to the surrounding material, the magnitude of the AE is proportional to the magnitude of the PD. Between the AE and where a fibre may be installed, surrounding insulation layers within a cable will distort and reflect the AE due to the differing acoustical properties of the material making the signal less defined. A sensor such as a fibre optic installed inside the cable however, would detect a much better signal than a sensor mounted externally to the cable. The intensity of PD signals is very small and is proportional to the energy released in the discharge. The peak amplitude is reported to be lower than -68dB ref. VµBar which approximately equals 5.979dBSPL, so low that some researchers declare as impossible to sense in a plain optical fibre with a DAS method [3]. However, *Posada-Roman et al.* [4] discusses the detection of AE of 1.3Pa with an optical fibre sensor which is equivalent to 96.26dBSPL, which seems far too large in amplitude for a PD event.

Acoustic detection is normally only carried out on transformers, using discrete sensors and relying on the ultrasonic transmission through the oil within the transformer tank. With a distributed fibre-optic based system, this solution of acoustic sensing can be applied on any power cable that contains, or is mechanically joined to, a fibre optic cable.

From the spectra that can be obtained from acoustic sensors it is possible given enough measurement bandwidth to classify the observed discharge into the different PD types. Other work [5-7] shows that with a high bandwidth of 400kHz, it is possible to characterize AE into different shaped cavity/void discharges and treeing. *Boczar et al.* [8] also demonstrates that the supply voltage at which the PD occurs, does not influence the frequency or time waveforms of the AE. However, this bandwidth is only available to very short OTDR systems or ones that use FDM techniques to improve sampling frequency.

ACOUSTIC ABSORBTION INTO SURROUNDING MATERIAL

As the fibre used for DAS is not directly embedded within the insulation of the cable where discharge may occur, the vibrations must travel through various layers. Also, if the fibre is mounted externally to the cable such as at a cable joint, likewise, vibrations detected by the fibre must pass through the surrounding air.

By using equivalent equations to power transfer in an electrical system, using the acoustic impedance of a material it is possible to approximate the reflected and transmitted power of these vibrations. The larger the mismatch in impedance, the larger the reflected energy and therefore the less energy transmitted, and the smaller the signal detected.

From acoustic theory [9,10]:

$$Reflection_\% = \frac{|Z_1 - Z_2|}{Z_1 + Z_2} \qquad (1)$$

The acoustic impedance of a material (Z) is defined as the product of its density and acoustic velocity of a pressure wave through the material. The acoustic impedance of the various materials used in the construction of a power cable, as they are all solids, are on the order of $MPaSm^{-3}$, and are relatively constant. This results in the losses due to reflection being low within the cable. In contrast, air has a very low impedance at $420PaSm^{-3}$, therefore at an interface between the cable and air such as at a joint site where the two are separated, only around 0.05% of the overall acoustic power is transmitted. Therefore, for good results of a DAS system applied to a cable, the fibre must be in solid vibrational contact.

Due to this high mismatch in acoustic impedance, detection is unlikely other than in perfect conditions with extremely high sensitivity. In these extreme cases, such as violent breakdown, the vibrations could be detected and act as a method to quickly locate a fault site. The reflection between layers inside the cable construction between the dielectric and where the fibre may be mounted is significant at up to 90% reflection.

For cables where the detection fibre may be buried next to the cable, the acoustical transmission varies greatly due to inconsistencies in soil packing and the different constituents. An estimated typical transmission is on the order of 10-20% [11] with additional attenuation of around 0.2-0.8dB/cm-kHz [12] through the soil.

EXPERIMENTAL SETUP

An initial experiment was carried out as to determine the viability of detection of discharge using a DAS system. It is assumed that if a DAS system is unable to detect large discharge that is much higher in amplitude of sound levels than PD, it is extremely unlikely that the system will be able to detect PD when embedded within a cable despite the increased coupling between the insulation and fibre optic.
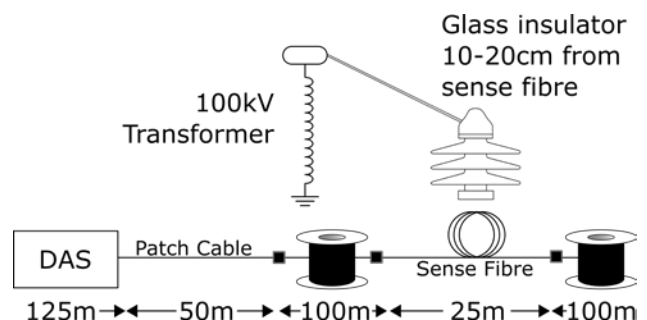
A 25m loop of bare single-mode fibre was initially placed at a distance of 30cm in air, from a glass insulator. A 50m patch cable was connected between the DAS instrument and the beginning of a 100m vibration-isolated spool. Another vibrationally isolated 100m spool was connected after the fibre under test to provide a low-noise section of fibre either side to increase signal to noise ratio. Figure 2 shows the background noise with no voltage applied to the insulator.
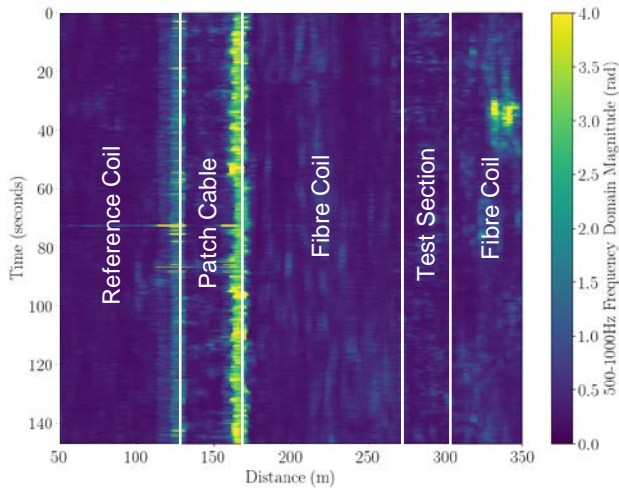
**Figure 2: DAS background noise between 500-1000Hz.**

Down the entire length of fibre, the two large responses in the 100-500Hz region correspond to the distance where the 50m patch cable is coupled on. These large signals (as compared to other coupling sites between the isolating boxes) is attributed to the E2000 fibre connectors acting as an in-line reflector, providing a much higher reflection signal than the normal backscatter. The patch cable had a thicker jacket and therefore was more rigid than the rest of the isolated reels and sense fibre, and therefore might be conducting more vibrations into the connectors than the thinner, more flexible single-mode fibre that was used as other interconnects. Compared with the HV equipment not energised, the amplitude of detected vibrations is significantly increased at a distance of 160m. This is physically the closest point where a sensitive part of the fibre (the connectors) is to the HV transformer and variac and thereby can be concluded that this was the measurement of 50Hz harmonics.

From basic OTDR simulations and the acoustic reflection between air and other materials, it was expected that large discharges could be seen with the fibre in air but anything smaller than catastrophic breakdown would likely not be seen. By moving the fibre so it would be physically attached to the point of acoustic emission, or to something vibrationally coupled, the high acoustic impedance mismatch could be reduced thereby allowing the overall sensitivity to increase by orders of magnitude. This was tested by attaching the fibre to the base of the insulator.

DISCHARGE EXPERIMENT

Measurements were taken with an initial sampling rate of 2kHz, Gauge length of 5m and spatial sampling of 1.25m. Figure 3 shows increasing and decreasing voltage applied
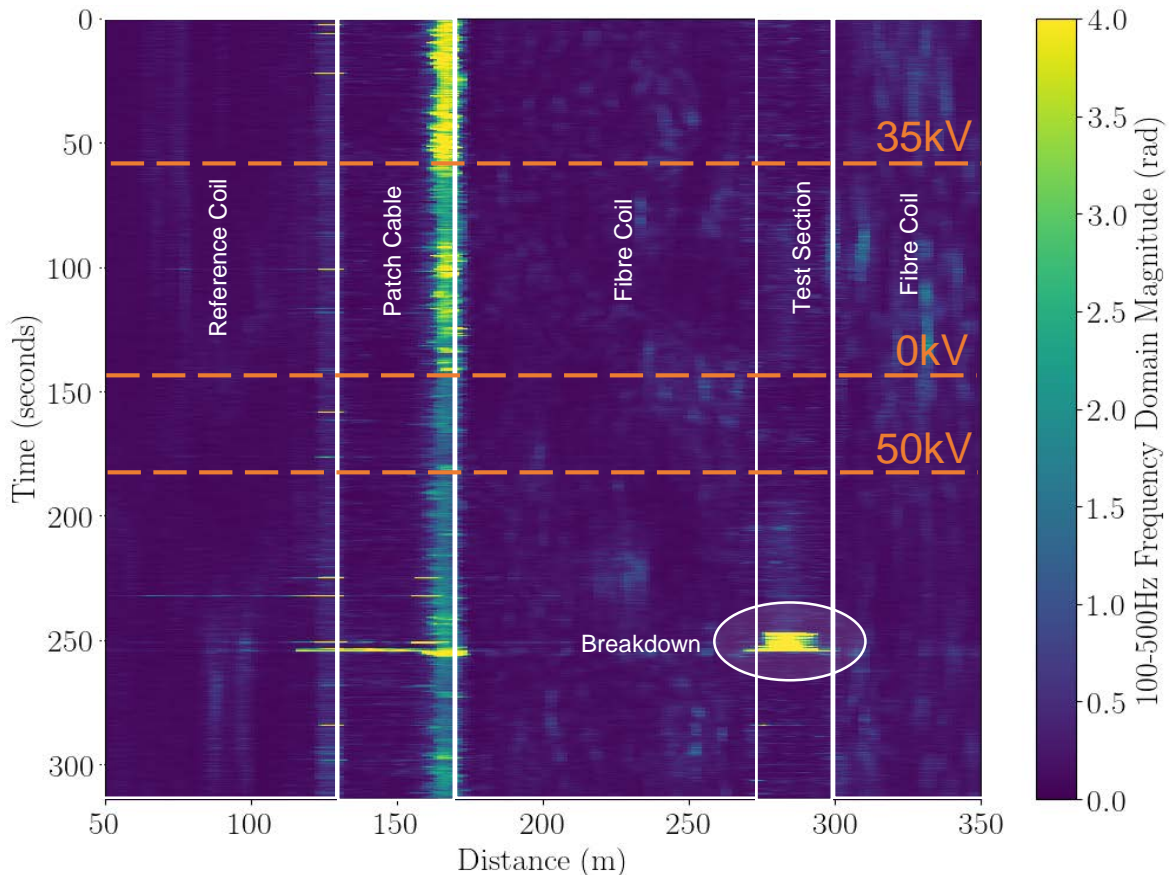
Figure 3: DAS 100-500Hz output with fiber in air at a distance of 30cms from insulator. Voltage ramped up at 70 seconds to 47kV, down to 0 at 150s. Ramped up again at 180s through to breakdown at 250s

to the insulator eventually up to the full in-air breakdown of the insulator at 69.1kV. At the location of the fibre near the discharge (275-300m), the decrease in detected vibrations is almost imperceptible; likely not extractable given no knowledge of the timing or position of the event. The nearby E2000 connector has a much more pronounced response due to a higher reflection. This reinforces the prediction from acoustic impedance previously calculated, showing that detection of small discharges through air is unlikely except in the worst case of discharges.

By comparing the different frequency bands of the build-up to the discharge, it was found that 100-500Hz output gave the best signal at the point of discharge of any frequency bands at the known sense fibre location. However, compared to the surrounding noise in any of the frequency bands it was extremely difficult to identify the discharge's acoustic emission.

By moving the fibre in contact with part of the insulator, vibrations are then directly coupled rather than attenuating through air and the boundaries into the fibre optic core. The bare single mode fibre was wrapped circumferentially around the outside of a PVC tube supporting the insulator.

As shown in Figure 4, there is a much greater signal and

when corona starts to occurs, the signal is clearly visible above all other noise in the same 500-1000Hz frequency bin with a SNR of up to approximately 60:1 or 17.8dB. This reflects an equivalent scenario with an embedded fibre optic in a cable where the fibre optic is coupled through solid insulation to the places where Partial Discharge may occur. The experimental setup due to its non-perfect mounting methods are likely reducing the signal more than what could be expected in a cable. Thus, it can be expected with this higher coupling ratio, a greater sensitivity can be achieved and therefore PD would be able to be detected.

Previously identified noise such as at the connector locations is still present, but the wanted signal is now at a much higher amplitude that within Figure 4 it is not visible.

Most of the energy is detected as broadband across the entire measurement spectrum with tail-off sub-500Hz and above 9kHz. 50Hz harmonics are very strong in the received data when corona discharge is occurring. From this, it can be deduced that the fibre is picking up the fundamental frequency of the discharge rather than the HF components that most AE sensors detect (usually greater
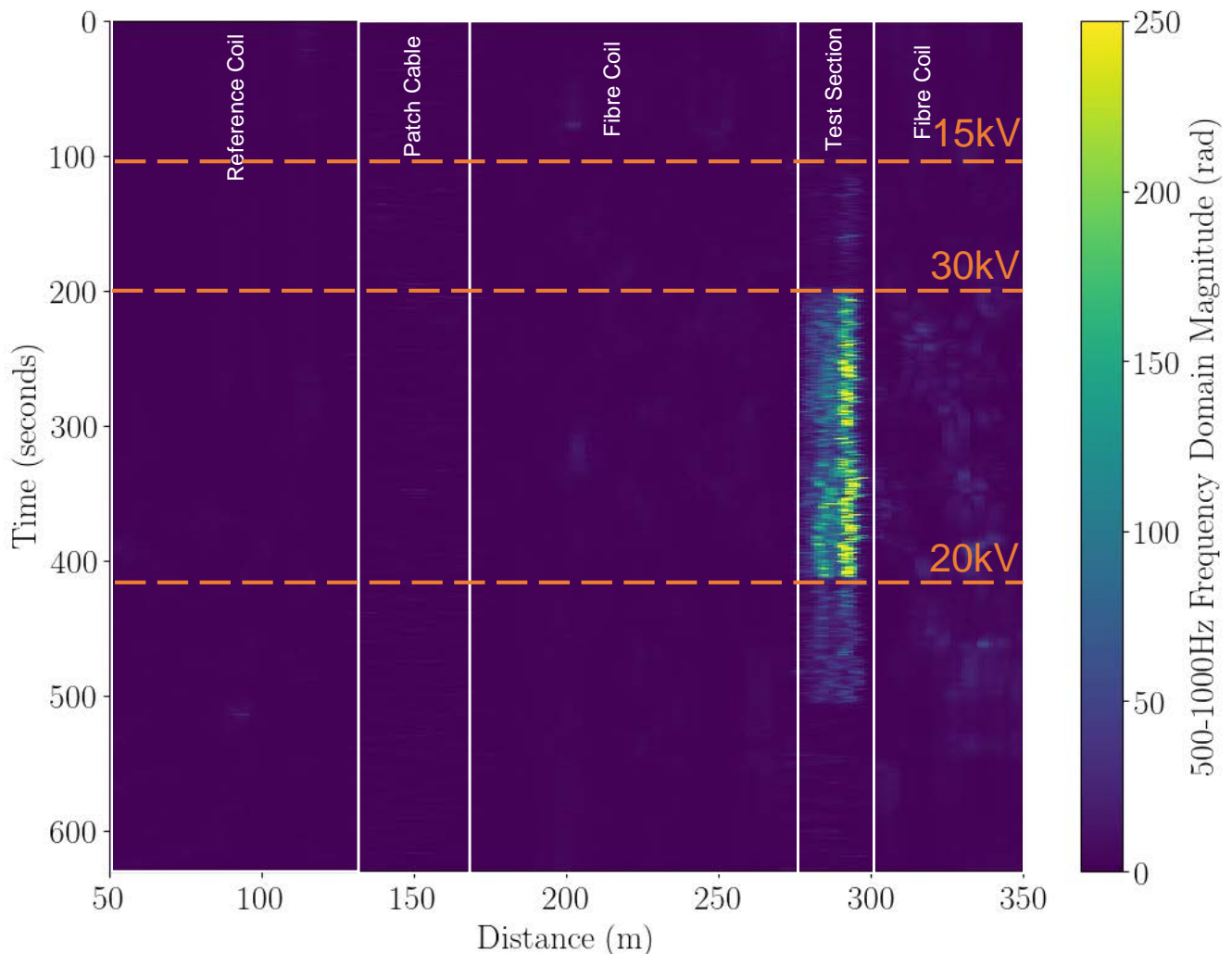
Figure 4: 500-1000Hz output with fibre vibrationally attached to insulator. Max amplitude increased to 250 Voltage increased at 100s up to 15kV, 30kV at 200s and 20kV at 420s.
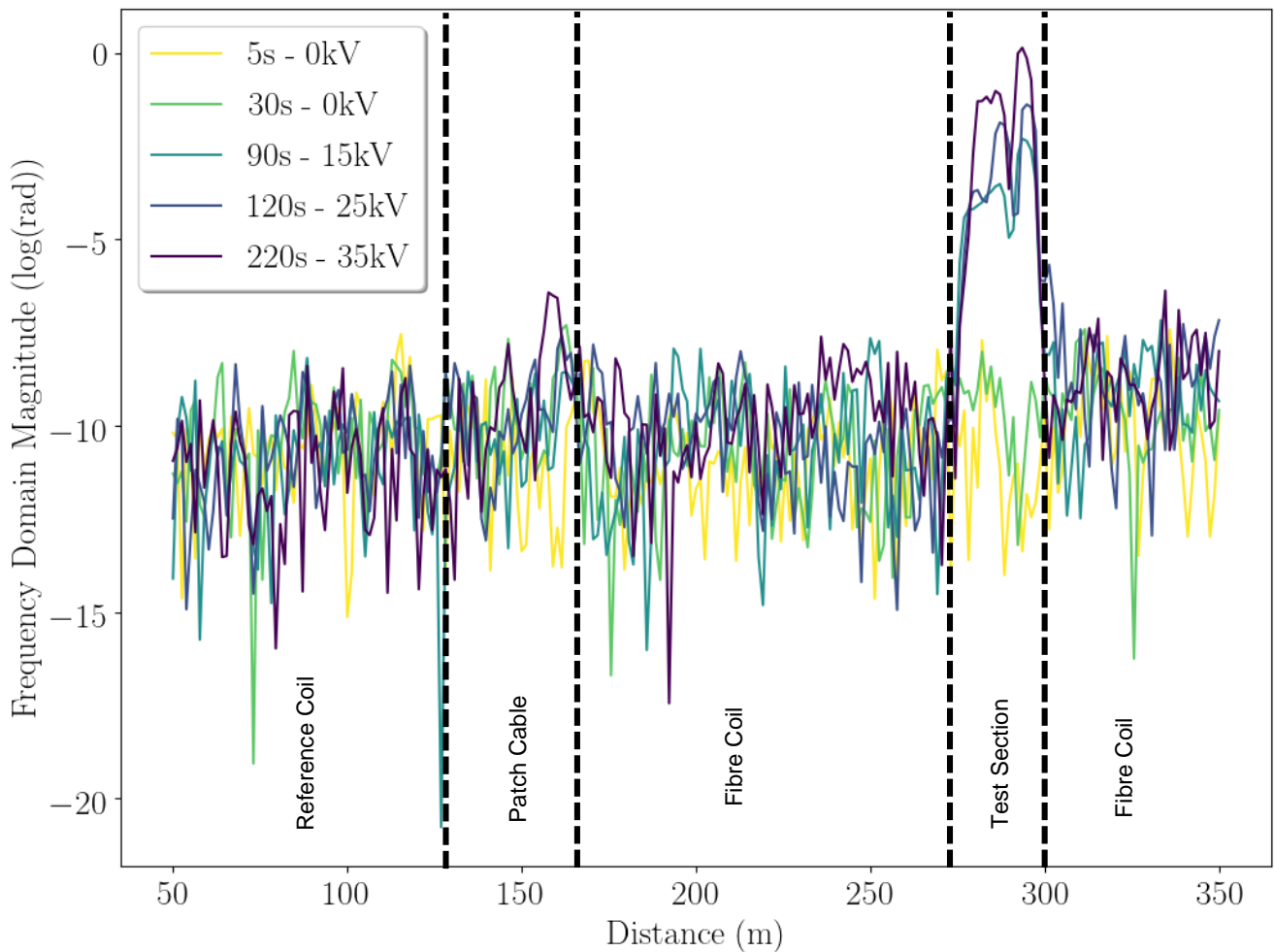
Figure 5: 50Hz intensity against distance for different discharge conditions. Fibre attached to insulator at 275-300m

than 5kHz). By looking at the 50Hz intensity along the length of the fibre in Figure 5, the location of the discharge can be easily found with a decent SNR considering no de-noising has been applied.

This is identified as an easy way of filtering out and automating the detection of discharge from a DAS system assuming a cable does not produce excess 50Hz vibrations that could swamp the desired signals. 50Hz is also well within the typical sample rate expected on a long length of fibre optic so no advancement on present detection methods would need to take place to implement this on existing cables. Fundamentals of the 50Hz signal (e.g. 100Hz, 150Hz, 200Hz etc.) were also examined and showed similar results but decreased in SNR above the 4th-5th harmonic. For isolation against default cable vibrations, these higher fundamentals may be useful. The fibre couplers that presented large reflections in previous measurements are present in the 50Hz signals, however they are much lower in amplitude than the discharge.

CONCLUSION

This report has shown that fibre in equivalent conditions to one mounted inside of a cable that experiences vibrations from partial discharges of reported values from literature, could be able to both detect and sense the amplitude of the discharges with a good signal to noise ratio. Due to the sense fibre being common single-mode communications fibre, DAS systems can be retro-fitted to any cables that already contain compatible and spare fibre optics. For cables installed in more ideal conditions where external vibrations are minimal e.g. subsea, the measured SNR may be further improved.

The fibre is also able to detect any large breakdowns external to the cable or other disturbances such as excavation activities along with the location. Due to vibrations transmitting along the cable, the precise location is hard to ascertain but within 25m localisation is considered adequate. Classification has not yet been achieved due to the low maximum sample frequency expected on long cable lengths. More research is required in this area for detection of PD types from data only in the low frequency spectrum.

Acknowledgements

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GLOSSARY

AE: Acoustic Emission
c-OTDR: Coherent Optical Time Domain Reflectometry
DAS: Distributed Acoustic Sensing
FDM: Frequency Division Multiplexing
HF: High Frequency
OTDR: Optical Time Domain Reflectometry
PD: Partial Discharge
PVC: Polyvinyl Chloride
SNR: Signal to Noise Ration