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Rapid AIS PD surveys using a UAV

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SUMMARY

National Grid have operated a policy of radio frequency (RF) based partial discharge (PD) assessment in air-insulated substation (AIS) HV compounds for the past 38 years. Presently this policy is supported using hand-held RF spectrum sweeping equipment and radiometric PD trailers. Deployment of the hand-held equipment requires significant trained operator resources. The paper describes the results of a research project to investigate PD surveys from an unmanned aerial vehicle (UAV) platform. The UAV should yield more detailed PD information whilst reducing operator resource due to its ability to navigate rapidly around a substation, including areas where personnel are excluded. PD is widely used in factory testing but can be extended to in-service testing of HV equipment. In HV compounds the PD current pulse causes RF radiation from the PD site. Radiometric PD locators use highly accurate timing from an array of antennas to locate the origin of the PD source. Although radiometric PD trailers commonly use a four antenna array, the use of this technology on a UAV is restricted to two antenna arrays due to space and weight limitations. A two antenna radiometric PD recording system, weighing 1.6kg, has been designed to fit to the accessory rail of a six rotor UAV, capable of a payload of 5.5kg and flight times in excess of 18 minutes. The PD recording system autonomously records PD events during the flight, although real-time telemetry to an operator via Bluetooth allows changes to the gain and trigger level settings during flight. Testing in a variety of settings, including two operational 400kV substations, has demonstrated the viability of this approach and results demonstrate the location of an active PD source within a HV compound. Future proposals for further work on this project are presented including a programmed flight path of the UAV, automation of the recording system and PRPD measurements.

KEYWORDS

High Voltage, Substation Equipment, Unmanned Aerial Vehicle, Partial Discharge, Radio Frequency, Diagnostic.

1. INTRODUCTION

In 1984 the Central Electricity Generating Board (later to become National Grid following privatisation) experienced the catastrophic loss of a 400kV power transformer which required an extensive presence of the fire service. Whilst extending a courtesy to local householders who may have been affected by the fire, engineers learned that, far from upset by the previous events, residents where very gratefully to, once again, receive interference-free television transmissions: the inference being that the interference had been ongoing for a significant period before the fire. Many other HV equipment failures have been accompanied by similar stories of radio frequency (RF) interference episodes preceding the event.

Following a Board of Inquiry recommendation for this incident, and for the past 38 years, National Grid have operated a formal policy of RF based PD assessment in AIS HV compounds. The measurement equipment currently supporting this policy comprises of 60 hand-held spectrum sweeping RF receivers which are distributed around the transmission regions, backed up by 40 radiometric PD measurement systems fitted into trailers which can be easily transported to any substation. Trained operators deploy the hand-held RF receivers on a monthly basis in all 400kV, 275kV and 132kV compounds from a series of prescribed measurement positions. These surveys are focussed on very old and or very new HV equipment which, experience has shown, are the most problematic. In the event of significant measurements arising from the surveys, or from other pertinent information, the radiometric PD trailers are dispatched to the relevant site and positioned in the vicinity of the suspect HV equipment. Once installed, the PD trailers continuously measure and upload all results to a cloud server where the PD locations are superimposed on a substation map of the HV equipment assets. PD trailers require no intervention following installation and are typically deployed for periods lasting days through to months. By comparison, PD surveys using hand-held RF receivers consume significant staff time that limits the frequency of the surveys and the nature of the HV equipment being assessed. It is the latter issues that have acted as the motivation for exploring alternatives methods of performing regular PD surveys.

The drivers for this project are:

- RF based PD measurement is an effective and well-tested technology.
- The use of unmanned aerial vehicles (UAV) for the inspection of overhead lines (OHL) is a similarly accepted technology with more than 5 years' experience.
- A UAV can fly around all HV equipment within a substation far faster than can be achieved using ground-level manpower. Thus, if RF PD measurement could be incorporated into UAV technology, and shown to reliably and safely operate within an HV compound, then there are potential savings in staff costs and potential increases in the quantity of HV equipment that can be surveyed for PD activity.
- UAVs can reduce staff exposure to HV substations, especially in risk management areas where staff presence is either minimised or forbidden on safety grounds.
- Although initially expensive, the price of larger UAVs capable of payloads of greater than 2 kg is continually dropping, so this technology is likely to be cheap in the future.

This paper will describe the initial stages of a research project to incorporate a radiometric PD locator onto a UAV suitable for flight within a transmission HV compound. The following sections will describe RF based PD, the design of the UAV PD attachment, and the results collected to date.

2. PARTIAL DISCHARGE

2.1 Introduction

Partial discharge (PD) [1] is a phenomenon occurring in electrically stressed dielectrics that causes localised current flow to occur in regions not bridging high voltage electrodes. The current flow is in the form of pulses of duration < 0.1µs with amplitudes < 10mA. The presence of PD is usually indicative of some physical change in the dielectric, or the dielectric/electric field stress geometry, and can be an early warning of future failure of a high voltage (HV) asset.

The use of PD assessment in factory testing of HV equipment is widespread and is achieved by the use of measurement equipment that is capacitively coupled to the HV supply point. The combination of a direct electrical connection to the HV supply point and the electromagnetically shielded environment of the HV testing area allows for highly sensitive PD measurements. PD is normally measured in picoCoulombs (pC) to quantify the amount of charge transferred that is apparent during the current pulse. Although HV equipment should be PD-free when new, evidence of PD will be found if sufficiently sensitive measurements are made. In practice HV laboratory testing can achieve sensitivities of ~ 1pC and any PD below this level can be discounted.

For in-service assessment of HV equipment PD measurements can rarely, if at all, be made via a direct connection to the HV supply point. Consequently, PD measurement is made via an indirect sensing such as the use of high frequency current transformers (HFCT) on earthing leads, transient earth voltage (TEV) sensors fitted to equipment enclosures and the reception of radiated RF signals via antennas. Due to the electrically noisy environment of HV substations and the presence of external radio frequency (RF) communication signals, the assessment of PD is very challenging in this environment and results in significantly lower sensitivities than experienced in HV testing laboratories.

2.2 PD measurement using radiated RF signals

The use of radiated RF signal measurements – very relevant to this project - can be used both in air insulated (AIS) [2] and gas insulated substations (GIS) [3]. Assessment of PD using this approach relies on the initial current pulse radiating sufficient RF energy into the free space between the PD site and the receiving antenna. In GIS applications, this method is more commonly known as the ultra-high frequency (UHF) approach since PD defects produces RF signals within the range 300 – 1200 MHz which falls within the UHF band. The metal shielding provided by the gas enclosure provides good sensitivity of PD measurement when using purpose designed receiving antennas (sensors) which are installed within the GIS envelop. The repeatable, standardised nature of GIS gives rise to a relatively limited number of commonly encountered PD defects which can be distinguished via analysis of the incidence of the PD event as a function of the phase of the supply voltage: phase resolved PD (PRPD). Despite these favourable features, GIS PD measurement is still a challenging task since external signals can still enter the GIS enclosure via air bushings and gaps between tube flanges. Since the distance between PD sensors and PD sites can be variable in GIS installations, and due to the change in signal amplitude as a function of distance travelled, PD measurements cannot be directly related to pC levels without the use of a calibrating pulse.

In AIS PD measurement, the favourable features found in GIS do not apply: the lack of shielding prevents high sensitivity measurements, whereas a larger number of potential defects – not all malign – exist since it is now necessary to consider the surface discharge effects and a wider range of defects from many different types of HV equipment. Whilst this may appear to be adding complications to an already challenging environment, the use of radiated RF signals in AIS has one significant advantage in that the PD measurement system does not require any physical connection to the HV equipment and so is inherently portable and can be swiftly moved around the substation by the operator. This gives the ability to promote the preferential reception of PD signals, in relation to background RF substation noise, by moving the antennas closer to the PD source. This ability is complemented by the use of radiometric PD measurement equipment which can directionally determine the source of the RF radiation thus identifying a single item of HV equipment as the PD source. In this situation, it is only then necessary to determine whether the measured signals are indicative of internal PD, for which remedial action would be required, or external PD, which can be largely ignored. This is rarely a difficult task, although it usually requires further measurements over a longer time period. AIS PD measurement has proven sufficiently sensitive to determine a wide range of HV equipment defects including CTs, VTs [2].

Radiated RF signals from AIS HV equipment normally produce signals in the frequency range 10 – 1000 MHz. In general, it is the presence of metallic objects within close proximity of the PD site - such as busbar connections, earthing straps and internal nature of the HV equipment - that influences the amplitude and frequency content of the radiated signal since these objects can act as passive antennas for the PD signals. Since passive antennas are arbitrary due to the plethora of HV equipment and substation designs, the relationship between radiated signal strength and pC is highly complicated. Whilst there may be some merit in considering the frequency content when assessing PD signals, this is not an exact science and experience has shown that any impulsive signal in the 10 – 1000MHz range should be taken seriously if observed to radiate from HV equipment with explosive failure potential, i.e. CTs, VTs, bushings, surge arresters, capacitors, cable sealing ends. Note that corona effects are rarely detected within this frequency range. Figure 1 shows a typical radiated PD signal recorded from an antenna using wideband recording equipment. The PD signal is broadly impulsive in shape, but far from regular due to an intricate radiating structure close to the PD site in the HV equipment and a complex transmission path through the substation where the preponderance of steel supporting structures can reflect and cancel the initial signal. In this respect, similarly to the frequency content, the exact shape of the impulse contributes little to understanding the nature of PD effect that caused it. However, the initial start of the impulse indicates the fastest transmission time of the signal -which travels at the speed of light - between the PD source and receiving antenna; when measured using multiple antennas in a radiometric system, this timing information allows for the PD source to be identified.

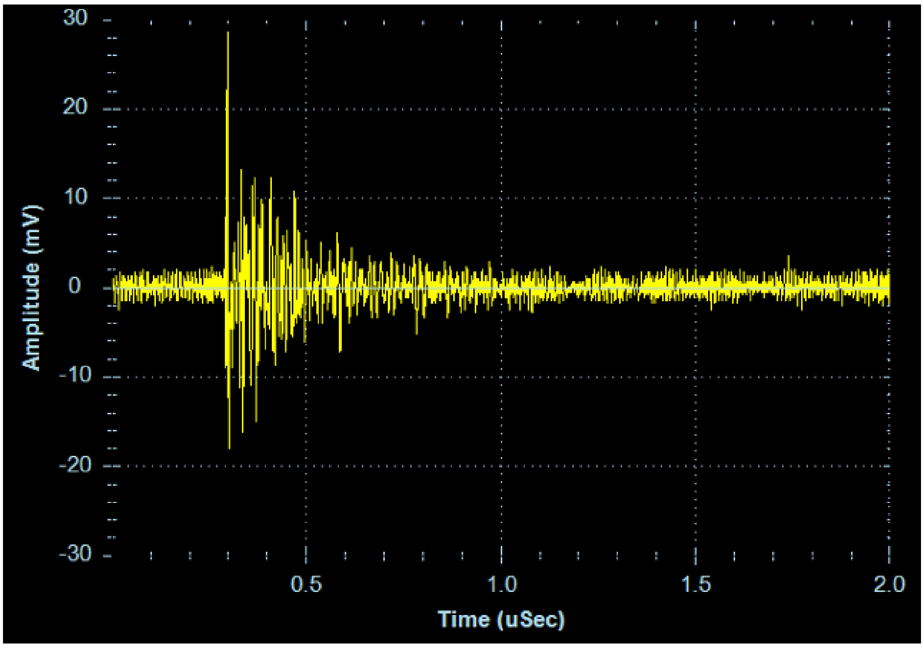

Figure 1 Typical radiated PD waveform

2.3 Radiometric PD locating systems

Radiometric PD locating systems [4] consist of multiple receiving antennas arranged in an array which are sampled by high speed, wideband recording equipment. Typical array configurations are rectangular with the spacing between antennas being in the region of 1m -2m. Although there is no restriction on the array size, the ability to fit the array on a vehicle which can be safely moved around a substation normally dictates the antenna spacing. The analogue bandwidth used for the antenna measurements must allow measurements in, or very close to, the 10-1000MHz region, as well as having a sufficiently high sampling frequency to allow calculation of the PD direction/location by tracking the passage of the PD wavefront across the array. In Figure 2 upper, an example calculation is shown for a PD source positioned ~10m distance from a 1×2m four antenna array. Although the time that the PD signal leaves the source is not known, the time differences apparent across the four antennas allow the PD source position to be calculated using an iterative procedure [4]. In the case of the UAV, fitting a four antenna system is not an option due to weight and space constraints, so a two antenna array is used. In Figure 2 lower, the directional bearing to the PD source is simply calculated using the time delay from the antennas and the antennas spacing. Note, however, there is an ambiguity since the array cannot distinguish between PD source positions either side of the antenna axis.

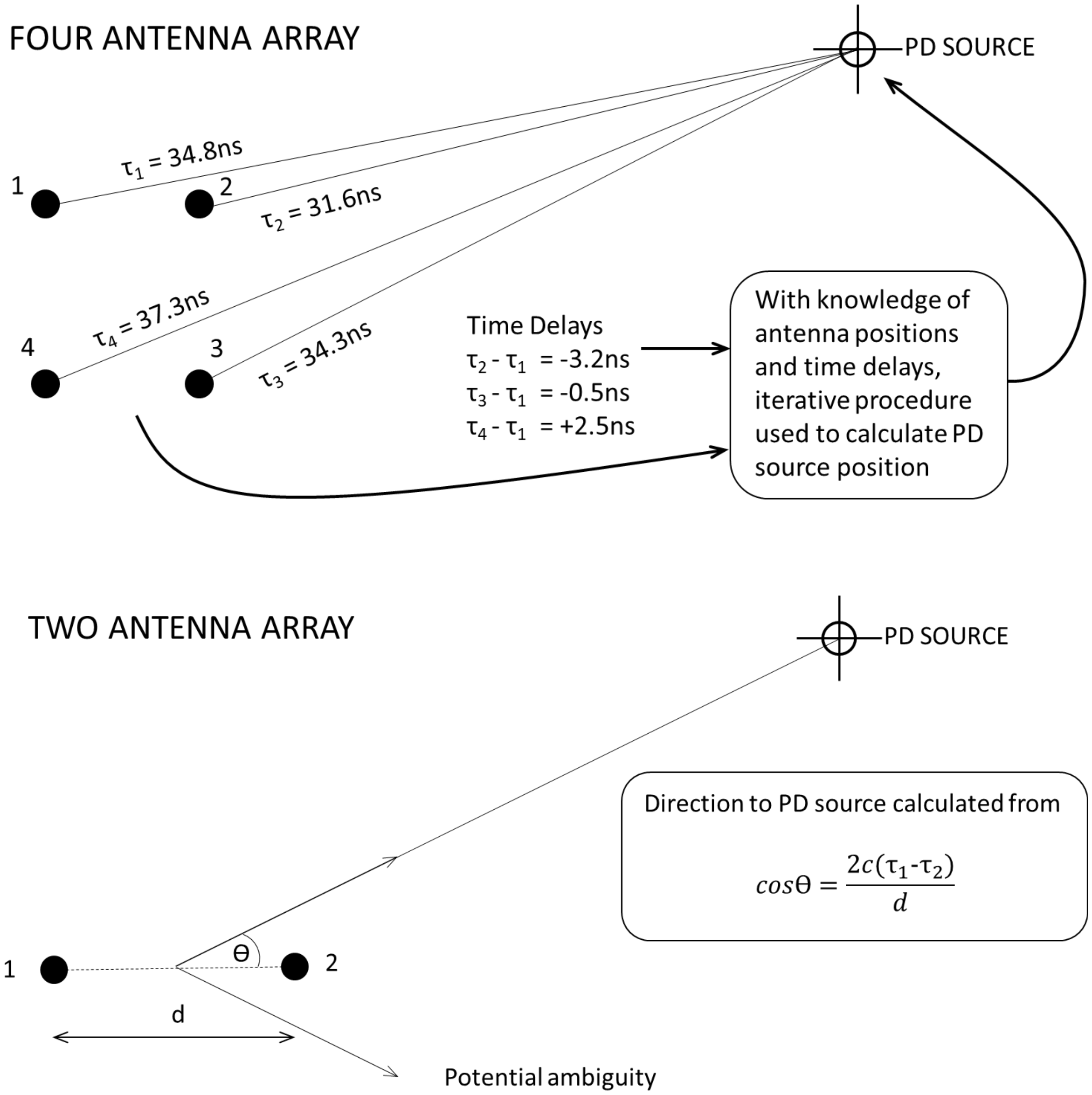

Figure 2 Antenna array PD source location methods, upper: four antennas, lower: two antennas.

3. DESIGN OF PD MEASUREMENT UAV ATTACHMENT

3.1 UAV

UAVs have attracted interest within the electricity supply industry for making visual inspections [5]. The UAV used for the trial was previously used for OHL inspections and is shown in Figure 3 with the PD system attached. The UAV has 6 rotors, retractable landing gear, is powered by 6 separate batteries, measures approximately 1.6×1.5m, weighs 10kg and has a maximum payload of 5.5kg. With fully charged batteries the UAV can fly for 18 minutes on full payload before the batteries reach 10%. The UAV has a triple redundant flight control system and incorporates multiple features to alert the pilot in the event of system failures that could lead to unexpected landings.

Figure 3 UAV used for the project with PD locator fitted.

3.1 Hardware design

Bespoke PD measurement hardware incorporating a two antenna array was designed for the UAV – the relevant features are described below:

- Digital hardware incorporating a microcontroller and field programmable gate array.
- Directly sampled RF inputs at 1.5 GSps provide the necessary resolution to calculate the time delay between the antennas.
- Fast RF waveform capture at a rate up to 7 recordings per second. RF capture is triggered by the inputs exceeding a set analogue level. All data recorded to a SD card.
- Variable gain and bandwidth RF amplifiers to cope with the wide variation of background signals encountered on site. The settings are adjustable during flight. The maximum bandwidth is 900 MHz.
- Time and positional data recorded from a GPS receiver every second.
- Bluetooth communications to allow real-time, in-flight telemetry via tablet PC.
- Powered by 50W/hr Lithium Ion battery pack with runtime >1 hour.
- Two bow-tie type, wideband antennas

The PD measurement system is housed within a shielded metal enclosure which was designed to clamp onto the UAV accessory rail (located underneath the main body). The enclosure also provides support for the antennas which were constructed from thin copper sheet and lightweight glass reinforced plastic tubes to avoid any significant changes to the moment of inertia of the UAV. The antennas, highly visible in figure 3 since they are coloured yellow, are mounted below the plane of the rotors and, although extending out beyond the UAV body, remain within the overall UAV dimensions. The entire PD attachment weighs 1.6 kg and is centre of gravity neutral with respect to the UAV. Note that unlike a fixed wing aircraft, the UAV has an arbitrary ‘forward’ direction and is able to fly with the antennas orientated at any angle with respect to the flight path.

4. RESULTS

A total of 29 test flights were flown from 3 separate locations, two of which were operational 400kV substations. In all test flights a highly experienced pilot was in charge of the UAV and had visual line of sight at all times, as well as the UAV telemetry. Similarly, an experienced engineer was in charge of the PD system. For all flights the UAV took off and landed at a designated area suitable for its use. Prior to the UAV starting up the PD system was powered and checks were made via the tablet that the recording system and GPS receiver had initialisation correctly. Use a battery powered PD impulse simulator – essentially a spark gap with attached antenna - the operation of the PD system was confirmed and suitable settings made for the gain and trigger. When flying above the busbars, the UAV was flown with a generous margin, typically at a minimum height of twice the busbar height above ground level. A post-flight desktop application to view the results from each flight was developed and allows the PD data to be superimposed on the plan view of the substation. A summary of the findings from the flights follows.

1. Early flights, made away from HV compounds, demonstrated that the PD attachment had little effect on the operation of the UAV with any changes to the aircraft dynamics being adequately compensated by the flight controller.
2. Similarly, the operation of the UAV, including RF emissions or in-flight motion, had no discernible effect on the PD locating system.

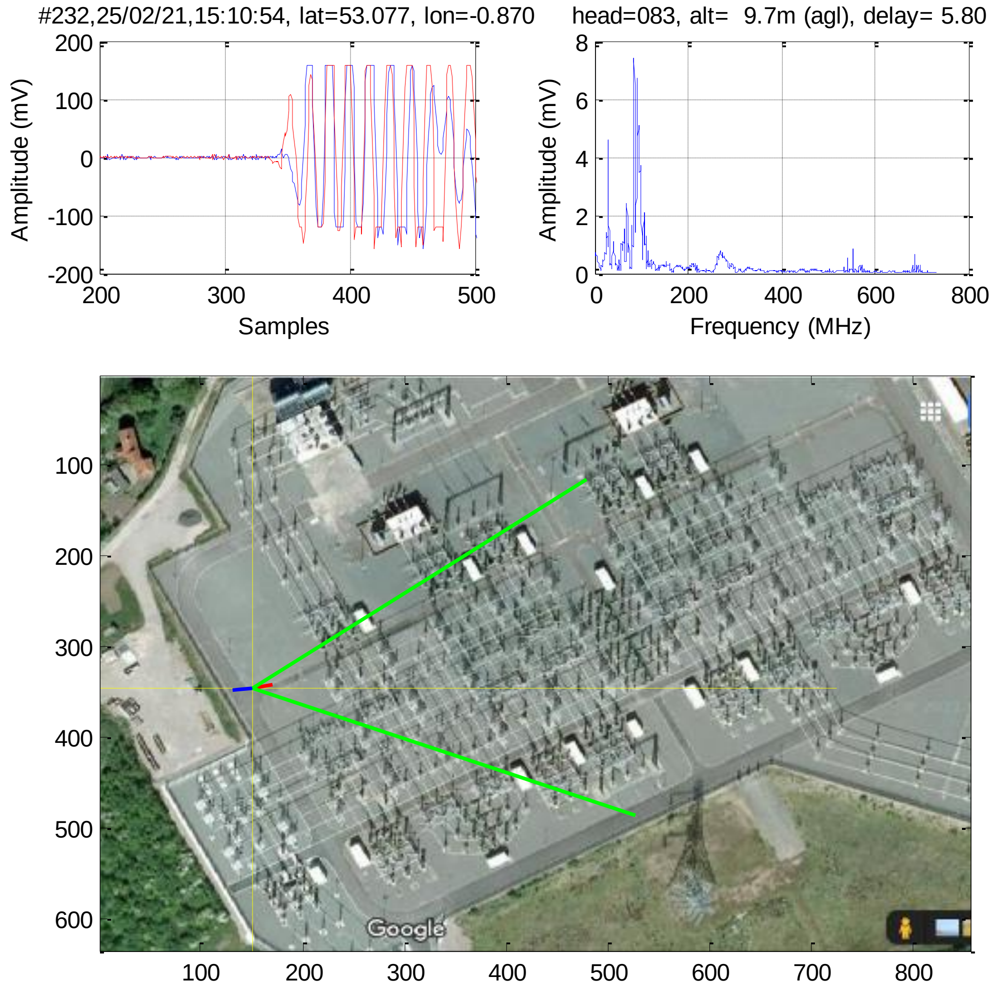

Figure 4 Typical post-flight result from PD analysis application – note that the PD source is the same as shown in Figure 6.

3. The measurement of HV equipment PD can be successfully achieved whilst the UAV is in motion within a substation. A typical screen-shot from the post-flight desktop application is given in Figure 4 which shows the UAV position at the intersection of the yellow lines, whereas the antennas are shown as red and blue lines, which correspond to the signals in the top left graph. The bearing of the PD locator is shown as the two green lines, taking account of the ambiguity described in section 2.3. This measurement is further described in point 7.
4. When significant line current was present in the busbars, the magnetic field occasionally affected the compass of the UAV. This effect generated a control system alert to the pilot, necessitating an immediate manoeuvre away from the busbars. The position at which this occurs – both a function of line current and proximity to the busbars – is not easy to predict and was resolved by maintaining a minimum 6 m distance from the busbars.
5. Similarly to point 4, flying too close to the busbars generated an internal PD within the UAV due to a high level of electric field. Figure 5 shows two consecutive triggers of the PD system taken within a 400kV compound where the upper graph shows the internal PD signal and the lower graph shows HV equipment PD; superficially, internal PD appears very similar to substation PD. An inspection of the UAV revealed that no equipotential bonding of the UAV structural components – predominantly carbon fibre – was present. An attempt to screen parts of the UAV with copper foil held at the same potential as the battery ground did not solve the problem. Instead, the UAV was flown at an increased distance from the busbars as described in 4. This reduced, but did not completely eliminate the internal PD effect. In practice an internal PD signal can be recognised by reference to its frequency response. In Figure 5, the frequency response of the internal PD is seen to be 'smooth' compared to substation PD since the UAV has far fewer *passive antennas* compared to the HV equipment (refer to section 2.2). This property allows the internal PD to be eliminated from the flight record.

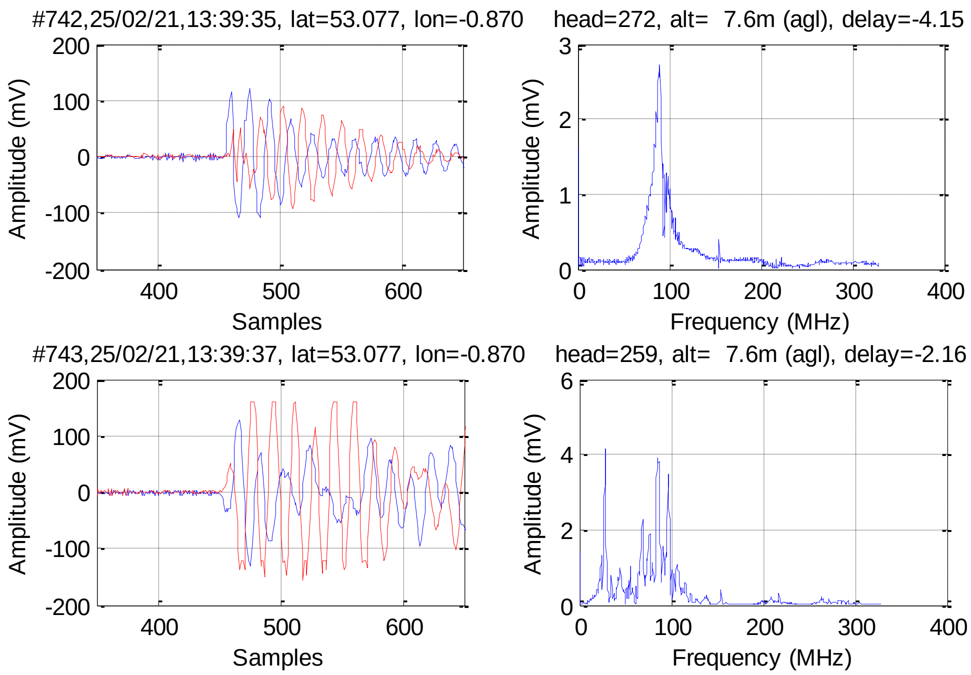

Figure 5 Internal PD caused by high electric field (upper) and HV equipment PD (lower)

6. The bearing calculation is prone to error, when viewed on the post-flight analysis application, due to the UAV and substation PD source not lying within the same 2-dimensional plane. It is difficult to compensate for this effect due to the variable nature of the relative height between the UAV and the PD source. In practice, the most useful position of the UAV is such that the antennas are equidistant from the PD source - the '0 degree position' – where the PD lies within a vertical plane that is perpendicular to the antenna axis, and no bearing error exists. An

additional benefit is that the ‘0 degree position’, coinciding with the position of highest timing accuracy with respect to the two antennas, is easily determined from the flight record.

7. Through the use of the ‘0 degree position’, the UAV was capable of uniquely locating PD sources within a HV compound. An example of this is shown in Figure 6 which, for brevity only shows the bearings to the same PD source for two different positions of the UAV. In this example, the PD source was a disconnector which are known to cause strong, yet totally benign, PD signals. Note that figure 4 also shows the same PD source as figure 6, but with the red antenna much closer to the PD source than the blue antenna. The error in the bearing calculation as described in point 6 is apparent by comparing these two figures.
8. The ability to fly the UAV above the busbars affords the PD locator a superior, line of sight view to a PD source than would be the case from the ground. In the latter case, the PD signal would propagate amongst the steel supporting structures with a consequent effect on its amplitude and signal quality. By comparison, PD source location using the UAV is rapid and simple if sufficient ‘0 degree position’ results can be recorded from differing locations.
9. Towards the end of the testing, as confidence in the equipment grew, the UAV was being flown along systematic routes above the HV equipment which sectioned the substation into a series of 40m squares. Whilst this was a successful strategy to fly the UAV close to all HV equipment, the UAV was flown with the antennas always *parallel to the busbars*. In view of the previous point, location of PD sources would have been far easier had the UAV flown with the antennas always *parallel to the direction of travel*, since this would have maximised the number of ‘0 degree’ positions.

5. CONCLUSIONS and FUTURE WORK

- This project has demonstrated that a RF-based PD locating system can be operated from a UAV platform whilst in flight within a transmission substation.
- The results show that unambiguous identification of HV equipment as the PD source can be achieved although, during the test flights conducted, only benign disconnector PD was observed.

The ultimate aim for this project is to provide for a completely automated system capable of autonomous flight, automatic data downloads and analysis. Whilst some of these aspirations will remain in the future for the time being, the next planned steps in this work include:

- Automation of the PD recording system firmware to remove the need for an operator during the flight.
- Programming of the UAV flight controller to allow the UAV to follow a prescribed route and antenna orientation within the substation. Whilst this will not remove the need for the pilot, it allows the pilot to concentrate only on the safety aspect of the flight.
- Following from the previous point, the investigation of strategies to generate routes within the substation that maximise the identification ability of the PD system as well as optimising the UAV battery usage. For example, the substation of Figure 6 (roughly 240m x 160m) requires 19 x 40m squares to cover the HV equipment. At an average forward speed of 2 m/s, the UAV would require nearly 32 minutes of flight time, which requires 2 changes of batteries (possibly only one change if the UAV is not flying at full payload). However, this could be improved by flying an optimised route which reduces unnecessary overlaps, as well as increasing forward speed over areas with fewer oil-filled HV assets. The ideal outcome would be the ability to survey a substation of this size on a single set of UAV batteries.
- Improvement of the post-flight analysis software to automatically identify the HV equipment as the PD source.
- Incorporation of PRPD results from the PD recording system through the external measurement of the phase of the busbar voltage.

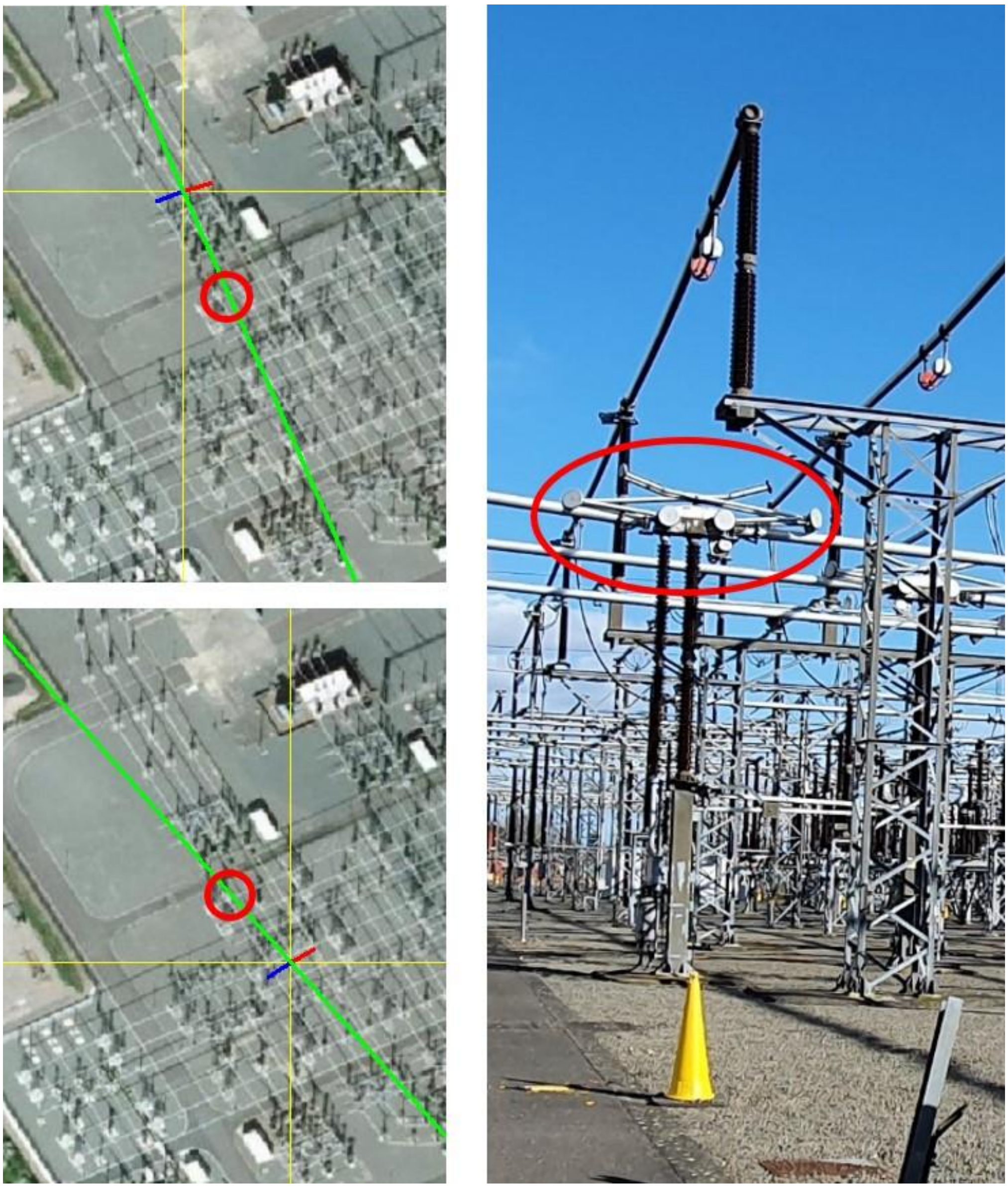

Figure 6 PD source identified on a disconnector – the red circles on the LHS images are the intersection points of the green lines.

BIBLIOGRAPHY

[1] Working Group D1.33 CIGRE. "Guide for electrical Partial Discharge Measurements in compliance to IEC 60270" (Technical Brochure, 2008)

[2] Portugues, I.E. et al, 'RF-Based Partial Discharge Early Warning System for Air-Insulated Substations', (IEEE Trans on PD, Vol 24, No 1, Jan 2009, pp 20-29).

[3] M D Judd et al, 'The excitation of UHF signals by partial discharges in GIS', (IEEE Trans. on Dielectrics and Electrical Insulation, Vol 3, No 2, April 1996, pp 213-228).

[4] Moore, P.J. et al, 'Radiometric Location of Partial Discharge Sources on Energised High-Voltage Plant', (IEEE Trans on PD, Vol 20, No 3, July 2005, pp 2264-2272).

[5] C Rozé et al, 'UAV Electromagnetic Field Compatibility and Tests Requirement for Use in OHL', (paper no. B2-308, CIGRE e-session, 2020).