Remote Diagnosis of Overhead Line Insulation Defects

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***Abstract*—High voltage insulation defects cause partial discharges (PD) which can be detected through the reception of radiated radio frequency (rf) impulses. The paper describes a method of detecting insulation defects on overhead lines using vehicle mounted rf measuring equipment. The equipment is based on a 4 antenna array that is directly sampled using digital equipment with a bandwidth of 1 GHz. The results are analysed by firstly estimating the time delays apparent between the 4 antennas. Secondly, using the time delays, bearing and RMS time delay error information is calculated that allows identification of the PD source. The equipment has been tested in the field on a 132 kV overhead line defect that was initially reported to a radio spectrum management agency. The results show that equipment has the sensitivity to identify the defective insulator string.**

Index Terms **Overhead Lines, Partial Discharge, Radio Frequency**

I. Introduction

THE emissions of radio frequency (rf) signals from partial discharge (PD) effects in defective high voltage insulation has been widely investigated in the past. Recent work based on new developments in ultra-high-speed digital sampling technology [1] has shown that PD related rf emissions have impulsive waveforms. Since steep wavefronts in impulsive signals can be easily, and accurately, identified in time, it is now possible to identify the 3-dimensional position of PD sources on energized equipment [2].

This paper describes a field procedure for the identification of defective insulator strings on energised overhead distribution/transmission towers. Compared to the large body of literature related to PD effects and insulation defects in general, specific applications to overhead lines have received relatively little attention in recent years. It is accepted that PD rf emissions from overhead lines can interfere with radio and tv reception [3].

The standard method of monitoring overhead lines is via the use of a helicopter [4], this approach has the advantage of allowing close visual and field-sensing inspections of all components along the line route. However, the use of a helicopter is expensive in both equipment and manpower costs and, as a consequence, the amount of time spent on any individual component is likely to be short. In the investigation reported in this paper, the radiated rf field strength from a defective insulator string was observed at times (e.g. for 5 – 10 minutes) to be indistinguishable from background noise. It is, thus, conceivable that a helicopter survey would not have detected this defect.

A method for detecting line defects via measurements made at substations [5] has the potential to allow continuous monitoring, however, in view of the high attenuation of overhead lines at high frequencies, it is likely that low-level, incipient defects situated remote from the substation will not be detected.

A monitoring method based on measurements from stationary rf receiving equipment situated close to the line [6] will suffer neither of the shortcomings of the previous two approaches, but will be expensive since equipment has to be installed at every tower and provided with multiple fibre optic connections back to the control centre.

The technique described in this paper is based on equipment that can be vehicle mounted. This allows rf sensing of PD related line defects from ground level without the expense of a helicopter. However, it is necessary that the site to be surveyed is known to have a potential PD problem. In this case, use is made of information from a radio spectrum management agency; in general the low-level radiated field from an overhead line defect will be sufficient to degrade tv and radio reception to a point where a complaint is made to the relevant authority. This information is the starting point of investigation to be described in the following sections.

II. Measurement Apparatus

The equipment needed to remotely detect and diagnose defective line insulators is vehicle mounted as shown in figure 1. The equipment consists of a four channel antenna array which is directly sampled using an ultra-high-speed digital oscilloscope. A more detailed explanation of the equipment can be found in reference [1]. The salient features of the equipment are as follows:

- Digitisation: the oscilloscope supports real-time 2.5 GSps digitisation on all four channels simultaneously. A radio wave will propagate 12 cm within one sampling interval (0.4 ns).
- Bandwidth: the oscilloscope has an analogue bandwidth of 1 GHz; the antennas have a relatively flat frequency response between 100 MHz and 3 GHz.
- Segmented Memory: this feature allows the 2 Megasamples of memory for each channel of the scope to be segmented into 371 separate buffers, each of 5000 samples. A new buffer can be triggered immediately following capture of a

previous buffer. This allows simple and efficient recording of impulses with variable repetition frequency.

- Timestamping: Each trigger of the segmented memory buffer is recorded with a timestamp to 1 ps resolution.

Fig 1. Photograph showing the vehicle mounted antenna array. The sampling equipment is located within the vehicle.

The antenna array is fitted within two roof boxes which are mounted on a frame that attaches to the roof rail fittings on the vehicle. The coaxial connections to the four antennas are brought down the side of the vehicle and enter through a cable port. The oscilloscope (Tektronix TDS 7104) is rack mounted in an industry standard 19” rack fitted in the van interior. The rack has energy absorbing fittings to cushion the scope against mechanical shock during transport. The oscilloscope is powered with 220 Vac from a 700 W inverter that is supplied from the vehicle’s 12 V battery. During initial trials of this vehicle mounted arrangement, it was determined that the operation of the inverter or vehicle engine (diesel) did not affect recording of PD impulsive waveforms. It is possible to operate the impulsive recording equipment whilst the vehicle is being driven, although all results presented here were taken with the vehicle stationary and the engine off.

In the site measurements taken, it was relatively easy to locate the vehicle in relation to the tower by taking measuring tape readings between the van extremities and the tower base. It should also be pointed out that this investigation was also greatly helped by the provision of a car park around the base of the tower; this allowed the van to be sited at two separate positions with little difficulty. In general, to improve the quality of the recorded waveforms, it is advantageous to site the van at positions that maximise the impulsive signal from the PD source location. Although the use of a mobile antenna array simplifies this process by allowing the measuring position to be tested, the varying nature of the impulsive signal from this defect – occasionally the signal disappeared completely – complicated this procedure.

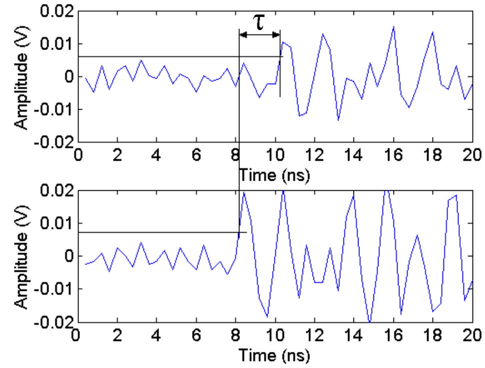

Fig 2. Time delay calculation. Initial wavefront of impulse arrives at the upper trace at 10 ns, and the lower trace at 8 ns.

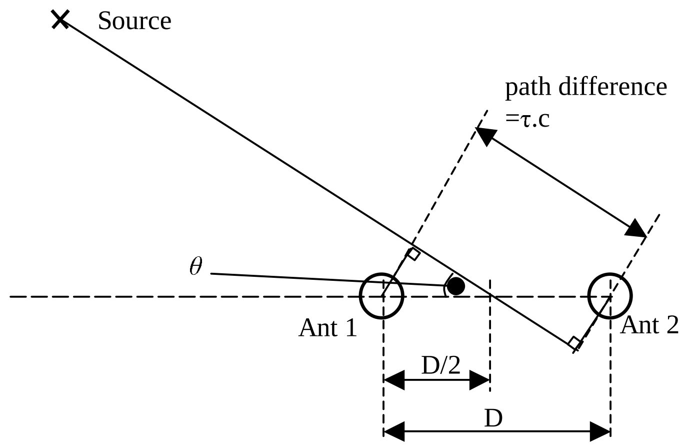

Fig 3. Bearing calculation.

III. Analysis of Recorded Data

Measurements of the PD impulse signal recorded on the antenna array can be used to identify damaged insulation components. This is achieved by determining if a component, e.g. insulator string, is acting as a source of impulsive noise via an analysis of the time delays of the signals recorded on the antenna array. Earlier work by the authors [2] has shown that it is only relevant to study the initial part of the impulse; this corresponds to the direct path of radio wave propagation between the source and the array. By comparison, information in the waveform following the initial impulse tends to be affected by the propagation environment due to reflections from metallic objects in the vicinity of the antenna array which significantly complicates the analysis.

In this investigation, the time delays are calculated by setting a threshold level based on the pre-impulse signal amplitude. Figure 2 shows an example of the time delays calculated using this approach; the time delay is evaluated to the nearest sampling interval.

The two techniques used for locating the PD source in this investigation are the *bearing*, and the *rms time delay error methods*:

A. Bearing Calculation

If an impulsive signal, radiating from an arbitrary direction, is incident on a two antenna array, it will cause a time delay,τ, that is related to the angle of incidence, θ, by:

$$\cos\theta = \frac{c\tau}{D}$$

where c is the velocity of propagation (3×10^8 m/s) and D is the spacing between the antennas in the array, as shown in figure 3. Thus, θ can be calculated with a knowledge of τ and D. However, with a two antenna array, the bearing is not uniquely found, e.g. it is not possible to evaluate whether the source lies above, or below the plane of the array. This ambiguity can be resolved using a four antenna array since four separate bearings are calculated – simple logic processing software can identify the true bearing of the source relative to the array. The bearing is useful to approximately identify defective plant.

B. RMS Time Delay Error

For more accurate identification, a 3-dimensional geometric technique has been developed. Let the 3-dimensional positions of the array antennas be denoted by (x_n, y_n, z_n) where $n \in \{1,2,3,4\}$, and the position of a potential PD source be denoted as (x_s, y_s, z_s). The theoretical propagation times for impulsive radiation between the source and the array are:

$$T_n = \frac{1}{c}\sqrt{(x_n - x_s)^2 + (y_n - y_s)^2 + (z_n - z_s)^2}$$

Since the time of impulse emission is not known, the impulse measuring equipment calculates the time delay differences, rather than the propagation times. Thus, it is more useful to calculate the theoretical time delay differences:

$$T_{21} = T_2 - T_1, \quad T_{31} = T_3 - T_1, \quad T_{41} = T_4 - T_1$$

where antenna 1 is taken as the reference. It is now possible to determine the error, ε, between a set of measured time delay differences, τ_{21}, τ_{31} and τ_{41}, and the theoretical values:

$$\varepsilon_s = \sqrt{\frac{(T_{21} - \tau_{21})^2 - (T_{31} - \tau_{31})^2 - (T_{41} - \tau_{41})^2}{3}}$$

By comparing the errors for different source positions, it is possible to determine the defective component. Note that this approach only works in situations where the PD source can be one of several clearly recognized possibilities.

IV. Field Measurements

The field investigation was conducted as a result of a complaint made to the UK Radiocommunications Agency (RA) regarding poor quality of tv reception in a house adjacent to an electrified railway line (25 kV overhead conductor) and a double circuit 132 kV overhead line, as shown in figure 4. The main purpose of the investigation was to ascertain whether either the railway or the distribution line were generating wideband radio frequency (rf) noise that could cause degraded tv reception. In the context of rf spectrum management, which is the RA's primary role, this information allows the relevant asset owner to be informed with a view to corrective action being taken. In the following, it will be apparent that the overhead line was responsible for the rf pollution. The results taken with the equipment however, go beyond discriminating between the railway and distribution systems' plant, and enable identification of the defective insulator string.

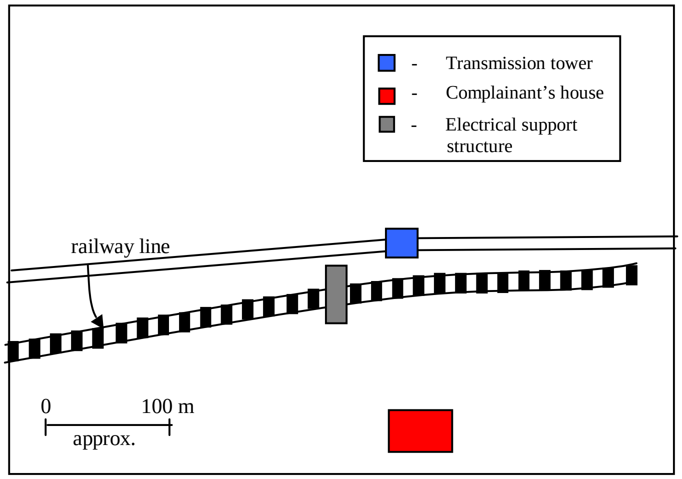

Fig 4. Schematic showing plan view of overhead line, railway line and complainant's house.

The vehicle was present at the site for a period of approximately 1 hour, during which time the vehicle was sited at two different positions, as shown in figure 5. At each position, the vehicle was measured in relation to the tower base, and 371 separate recordings of the impulsive signal were made. An example of the recorded signal is shown in figure 6; in general the signal amplitude varied considerably during the testing period.

A. Time Delay Results

Figure 7 shows a histogram of the time delays calculated from the signals recorded at position II using the method described in the earlier section. It will be apparent from this figure that the most likely time delays for τ_{21}, τ_{31} and τ_{41}, are -13, -17 and -1 samples respectively. Similarly conclusive results were obtained in respect of vehicle position I.

B. Bearing Results

Figure 5 shows bearing results, superimposed on the map, calculated from the two vehicle positions. This figure shows the overhead tower to be the source of the impulsive signal.

C. RMS Time Delay Error Results

This analysis was made with results from vehicle position II for 2 reasons: firstly, the vehicle was closer to the tower, and secondly, the vehicle had a direct line of sight to all the line insulator strings – see figure 8, which shows a site photograph of the vehicle with respect to the tower. This procedure identifies the defective insulator string.

To proceed, a dimensioned drawing of the tower type (PL4), figure 9, is required. This drawing is based on generic information of the PL4 tower and shows the cross-arm positions highly accurately. However, there are many tower base arrangements for this type and the height of the lower cross arm was not known – figure 9 shows the best estimate based on the photograph of figure 8. Figure 8 shows that each line conductor has two, horizontal insulator strings.

To calculate the time delay error, ε, 6 separate sources were considered corresponding to the end of each cross-arm, i.e. the positions A, B, C, a, b and c in figure 9. Figure 10 shows the variation in ε, as a function of height, for all 6 possibilities. It can be seen that, irrespective of the height, the phase labeled as 'C' in figure 9, has the lowest value of ε, and is consequently the mostly likely source of the PD. Note that the principal sources of error involved in the calculation of ε are: geometric measurement errors, errors in time delay estimation due to the presence of broadcast signals and quantization of the digitization process. These errors explain why ε is non-zero at the PD source.

With the defective phase of the overhead line identified, it is further possible to investigate which of the two insulator strings is responsible for the PD. In figure 11, at a constant height using the values of figure 9, the variation in ε as the source position is moved along each insulator string is investigated. The insulator furthest from the vehicle shows a lower value of ε and is thus the most likely site of the PD.

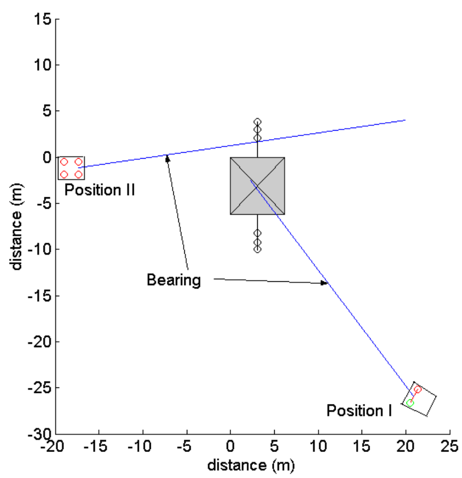

Fig 5. Plan view showing vehicle monitoring positions and bearing results.

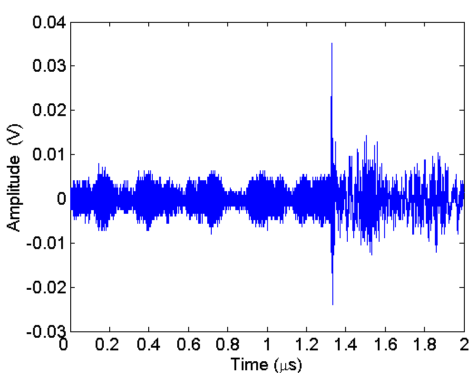

Fig 6. Typical RF impulse recorded from position II.

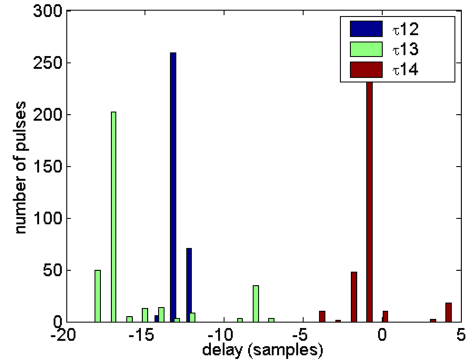

Fig 7. Histogram of time delays calculated from results recorded at position II.

Fig 8. Photograph showing vehicle position II in relation to tower.

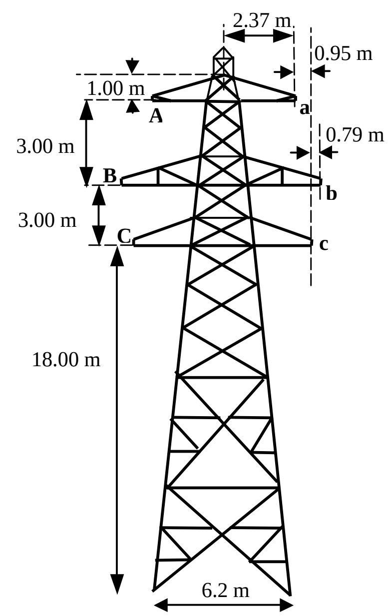

Fig 9. PL4 132 kV overhead double circuit tower with identifying phases.

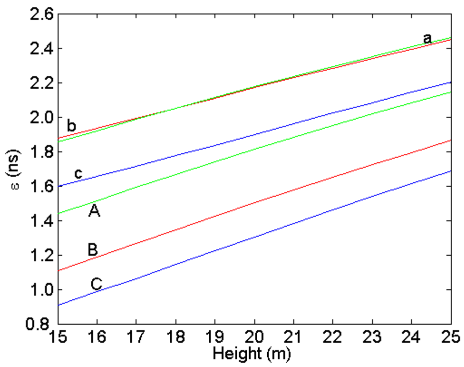

Fig 10. Variation in RMS time delay error, ε, as a function of height for each of the phases of figure 9.

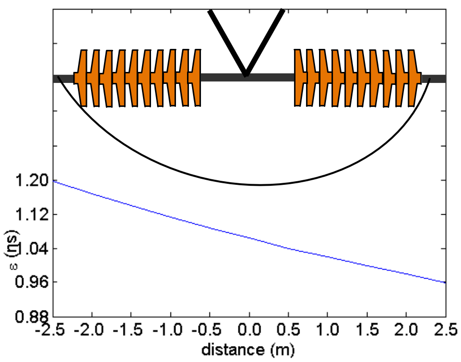

Fig 11. Variation in ε versus distance along insulator strings. X axis shows offset from centre of cross-arm; van situated in direction of decreasing x.

V. Conclusions

A technique for identifying defective overhead line insulator strings using vehicle-based rf measuring equipment has been described. Measurements are made using a directly sampled 4 antenna array. Two techniques for analyzing the measured impulsive PD waveforms for bearing, and RMS time delay error, information have been discussed. The former technique is useful for approximate indication of the defective region whereas the latter technique can more precisely identify the radiating component. This approach to insulation defect monitoring is cheaper in comparison to the traditional helicopter survey method. It is necessary that prior knowledge of the defect is required; it is suggested that information from a radio spectrum management agency is used to this effect.

VI. Further Work

The radiated signal from this defect is of a relatively low-level, unlikely to require immediate attention. It is therefore not possible to definitively state that the described approach has correctly identified the defective component until this is established by the utility-owner. This defect will be monitored in the future to establish any trend pattern.

VII. Acknowledgment

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VIII. References

[1] Moore P J, Portugues I E and Glover I A, "*A Non-Intrusive Partial Discharge Measurement System based on RF Technology*", Proceedings of IEEE Power Engineering Society General Meeting, Toronto, Canada, July 2003, ISBN 0-7803-7990-X, 6 pages.

[2] I E Portugues, P J Moore and I A Glover, "*Partial discharge localisation for efficient radio spectrum management*", Proceedings of 2002 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Cancun, Mexico, October 2002, pp 466-469.

[3] Giao Trinh N, "*Partial Discharge XX: Partial discharges in Air, Part II: Selection of Line Conductors*", IEEE Electrical Insulation Magazine, Vol. 11, No. 3, May/June 1995, pp 5-11.

[4] Jaensch G, Hoffman H and Markees A, "*Locating defects in high-voltage transmission lines*", Proc. of IEEE 8th Intl. Conf. ESMO 98, April 1998, pp 179-186.

[5] Jayasinghe J A S B, Aggarwal R K, Johns A T and Downes J, "*A new approach to condition monitoring of high voltage overhead lines using neural networks*", Proc. Of 11th Intl. Symp. On High Voltage Engineering, Vol. 1, August 1999, pp 33-36.

[6] Youssef M and El-Alayly A A, "*Remote monitoring of surface current over insulators*", IEEE/PES Transmission And Distribution Conference and Exposition, October 2001, Vol. 1, pp 113-116.

IX. Biographies

Philip Moore (M' and SM'1996) was born in Liverpool, England in 1960. He received his BEng in Electrical Engineering from Imperial College London in 1984 and his PhD in Power System Protection from City University London in 1989. From 1984 to 1987, he was a Development Engineer at Alstom Protection and Control, formerly GEC Measurements. From 1987 to 1991 he was a lecturer in Electrical Engineering at City University. He joined the University of Bath in 1991 where he is presently a Senior Lecturer. Dr Moore's research interests include harmonics, radio frequency emissions from power system plant, numeric protection, high voltage discharges, power system simulation and fault location. Dr Moore is a Chartered Engineer in the UK.

Iliana Portugués was born in Madrid, Spain in 1979. She graduated with a MEng degree in Electronic and Communication Engineering from the University of Bath in 2001. She was awarded a University Departmental prize for her work on harmonics measurement. She is currently employed at the University of Bath as a Research Officer in the Department of Electronic Engineering, investigating the characteristic radio frequency emissions from defective substation insulation.

Ian Glover trained, between 1975 and 1981, as a power engineer with the Yorkshire Electricity Board (UK) graduating from the University of Bradford (UK) in 1981 with a BEng degree in Electrical and Electronic Engineering. Between 1981 and 1984 he worked as a research student at the University of Bradford. Between 1984 and 1999 he was employed at the University of Bradford, first as a lecturer in Electronic and Electrical Engineering and subsequently as a senior lecturer. In 1987 he was awarded a PhD for a thesis on microwave cross-polarisation by the University of Bradford. In 1999 he moved to the University of Bath (UK) where he is currently a senior lecturer in telecommunications. Ian Glover is, with Peter Grant, the author of Digital Communications published by Prentice-Hall.