THE USE OF RADIOMETRIC PARTIAL DISCHARGE LOCATION EQUIPMENT IN DISTRIBUTION SUBSTATIONS

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INTRODUCTION

This paper describes a vehicle mounted radiometric system consisting of an array of four antennas connected to broadband, high-speed recording hardware capable of locating the source of partial discharges (PD). The significant advantages of the system lie in its ease of application, not requiring any electrical plant interface, and its ability to monitor emissions from several items of plant simultaneously. The system has been widely used at transmission level.

This paper explains the application of the locator to distribution substations. It describes the method of use and the added difficulties of radiometric PD location at lower voltage levels. The paper presents and analyses the results obtained from site trials in a 33 kV substation which revealed PD in the vicinity of an air break isolator.

RADIOMETRIC PD MEASUREMENTS

Partial discharges are a precursor of high voltage insulation deterioration. Their measurement has proven to be an effective method of condition monitoring the state of plant. For this reason, various on-site diagnostic methods have been developed [1,2], however, they all require physical contact to the equipment under investigation. Non-invasive substation inspections for this condition may be made using radio frequency interference receivers although this approach can be time consuming and inaccurate. The researchers have developed a vehicle mounted system, based on an array of four antennas and ultra-high-speed sampling technology, which is capable of locating the source of partial discharges in substations. Whilst the concept of detecting partial discharge signals using radio frequency (rf) equipment is not new, a technique for locating the PD source within a substation using wave arrival time differencing has never been previously reported.

HARDWARE

The measurement system is based on the synchronous acquisition of four channels of radio frequency (RF) radiation. Four wideband, disk-cone type antennas are mounted on the roof of the vehicle inside two separate plastic roof boxes creating a rectangular array of approximately 1.5m x 1m in dimension. Direct sampling from the antennas to a Tektronix TDS7104 oscilloscope with 1 GHz bandwidth and 2.5 GSps sampling rate removes the requirement for demodulation and down-conversion to a smaller frequency range; the PD signals are consequently recorded using the full 1 GHz bandwidth. The oscilloscope is fitted within an EMC hardened, 19” racking system which is installed within the vehicle. The entire assembly contains a suspension system to prevent damage to the electronic equipment when in transit.

All metallic parts of the van are electrically bonded to a common point that can be connected to a safety earth connector. This prevents the build-up of static charge allowing prolonged measurements to be taken within a substation if required. The oscilloscope can be supplied from an external supply if the vehicle is stationary, or through the use of a battery-fed inverter, allowing measurements whilst the vehicle is mobile. The battery is charged from the vehicle alternator. To reduce unwanted rf impulsive noise the vehicle is powered by a diesel engine. A photograph of the vehicle whilst in the process of monitoring is shown in Figure 1 below.

SUBSTATION SURVEYS

The surveying procedure consists of moving the van around the substation. Initially, by circumnavigating the whole substation slowly, any plant with major defects can be identified for further, more detailed analysis. Once this has been accomplished, individual plant items are inspected by positioning the vehicle at various locations around the item. At each position, the measurements taken by the system allow an accurate bearing to the partial discharge source to be calculated. The orientation of the van with respect to the power system equipment is measured manually at each position to allow for an accurate frame of reference.

The surveying method used for each substation is voltage dependant; most of the operating experience of this equipment has been gained within transmission substations. At 275/400 kV voltages, the safety distance is 2.3 metres above ground, which is higher than the total height of the vehicle. This means the vehicle can be driven around most bays, creating a wider choice for positioning equipment at the time of recording. The most accurate results from the equipment occur when there is line-of-sight between the PD source and the antenna array. Line-of-sight is important since metallic structures can cause absorption, diffraction and multipath effects which deteriorate the PD signal at the point of reception. Multipath effects are due to the constructive and/or destructive summation of reflections produced from the same PD signal. This causes the signal from the source to arrive at the receiving antennas from a multiplicity of directions and propagation paths which are added to the original waveform at the point of measurement. Consequently each antenna receives a virtually unique representation of the emitted impulsive signal composed of an unpredictable set of reflections each with its own degree of attenuation and delay. Hence, accuracy of location is related to the relative positions of the PD source and antenna array, and any metallic structures in between or near them. If there is line-of-sight with respect to the PD source from the faulty plant, the initial part of the signal contains a fast high rising edge indicative of direct path propagation. If, on the other hand, there are obstacles impeding this direct propagation, a slow rising waveform is generally observed which has a direct effect on the location accuracy.

Figure 1. Photograph of the van during recording process

Due to the wide separation between bays and individual phases at transmission voltages, lower locating accuracies are required to determine the individual phase of defective equipment. At distribution voltages however, substations are much more compact and safety distances are smaller. The substation roadways on which the vehicle operates are very restricted and distances between phases are reduced from around 4.5 metres at 400 kV to approximately 1.5 metres at 33 kV. The accuracy necessary to obtain a confident PD location doubles. In order to obtain the precision required more measurements are essential.

LOCATION CALCULATION

Due to the accuracy required, analysis of the recordings is performed off-line using an algorithm which calculates the bearing of the source of discharge, marked as θ in Figure 2. The first step in determining this bearing is to calculate the individual bearings between each possible pair of antennas, an example of which is marked φ in Figure 2. This is achieved by estimating the time delay, τ, between the signals arriving at each of the two antennas. The time delay is measured from the initial wavefronts of the recorded signals. The method used, described in detail in [3], is possible due to the fact that partial discharges emit impulsive radio frequency signals having fast-rising wavefronts (e.g. Figure 3) that may be used to accurately estimate the time-difference of arrival between synchronously sampled signals. The bearing is then calculated from:

$$\cos\varphi = \frac{c \cdot \tau}{d} \qquad (1)$$

where d is the antenna separation and c is the velocity of light. In this way twelve possible individual bearings between each pair of antennas can be calculated. Due to their symmetry, each pair of antennas gives two bearings. By subtracting each bearing from other corresponding antenna pairs, the correct angle of the pair is obtained. An example is shown in Table I. The minimum difference is achieved by the subtraction between both values in the right-hand column yielding this as the correct bearing. A least-squares analysis is then performed on the remaining correct set of six bearings to determine the bearing of the array with respect to the source.

One of the biggest signals recorded is shown in Figure 3. In general high-levels of background noise encountered at site can make the initial wavefront difficult to determine. Instead of a steep, fast rising, high amplitude front, small peaks just above the trigger level are recorded. The signal of figure 3 represents a waveform from which the arrival time of the wavefront can be readily determined.

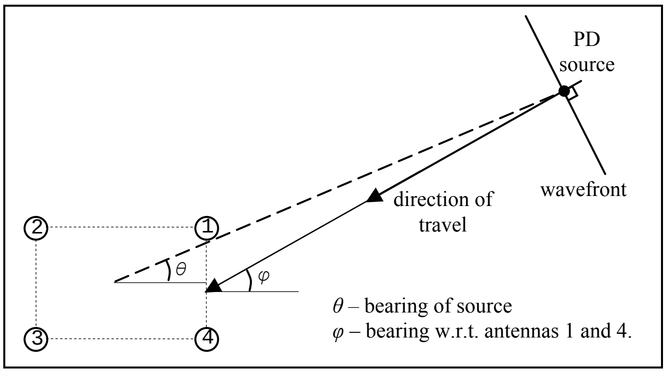

Figure 2. Relationship of bearing between two antennas and bearing with respect to the array.

TABLE I: BEARING VALUES FOR TWO ANTENNA-PAIR COMBINATIONS (CORRECT BEARING SHOWN IN BOLD)

Antenna-pair	Angle 1	Angle 2
1 – 2	60.1	**209.9**
2 – 3	150.1	**209.9**

Due to the large number of signals emanating from the source, a statistical distribution of the bearings from similar waveforms may be calculated from which the peak is obtained. This peak of the distribution, as shown in Figure 5, provides the most accurate bearing of the source of discharge.

RESULTS

In order to test whether the PD locator can be successfully employed within distribution substations a site trial was conducted in a 33 kV substation. After an initial patrol around the substation roadways, radio frequency impulses (a typical waveform is shown in Figure 3) were discovered to be present in the vicinity of an air break isolator (ABI). A detailed analysis was conducted by taking measurements at four different positions around the ABI. Each position was accurately measured with respect to the ABI (see Figure 8).

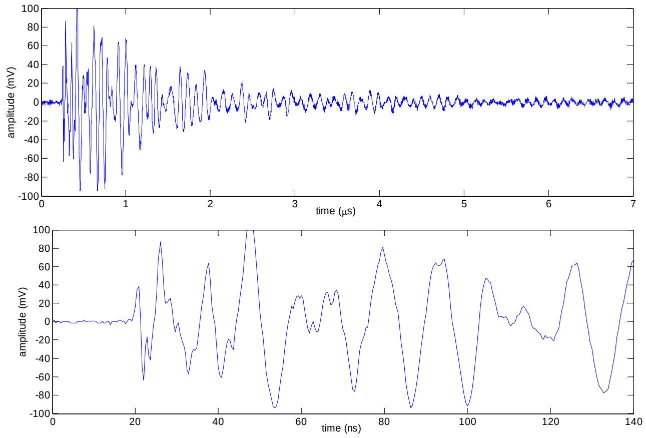

Figure 3. (a)Typical impulsive waveform originating from ABI (b)Wavefront of impulsive signal

The range of bearings calculated from the site results are shown below in Figures 4-7. Figure 4 shows a histogram of the bearing estimations taken from position 1 as shown in Figure 8. The distribution is relatively symmetrical around the peak value of 159°. This contrasts with Figures 5 and 6 which show distributions slightly skewed to one side. This is due to the cosine function in Equation 1 used to calculate the bearing.

Figure 7 shows a histogram of the bearing results taken from position 4. This distribution is much more spread apart with the most common bearing occuring at 11°. This spread is due to the presence of a substation building between the ABI and the van and shows the effect that obstacles can have on the accuracy of the bearing. However, by recording over 350 separate wavefroms, the true bearing is clearly shown as the peak of the distribution.

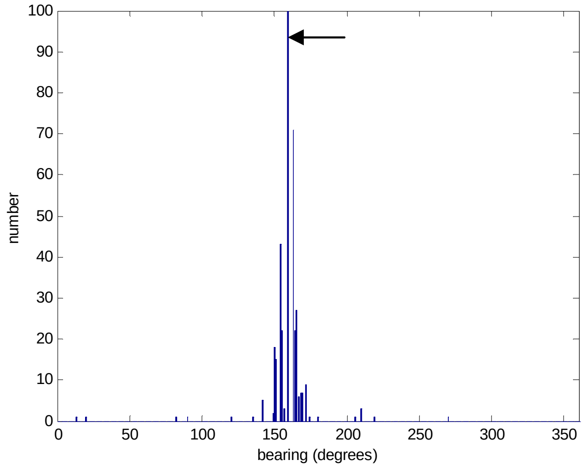

Figure 4. Histogram of bearings from position 1 (bearing used = 159°)

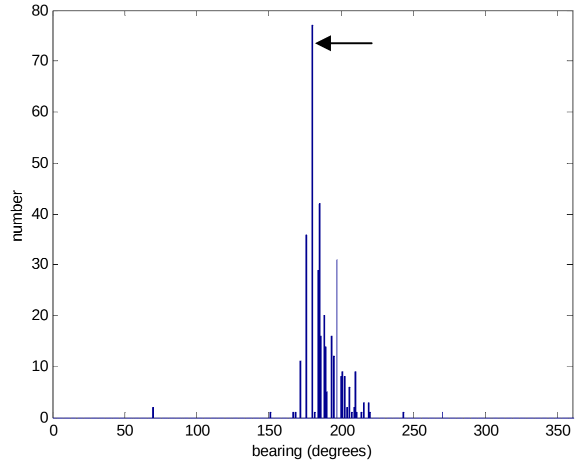

Figure 5. Histogram of bearings from position 2 (bearing used = 180°)

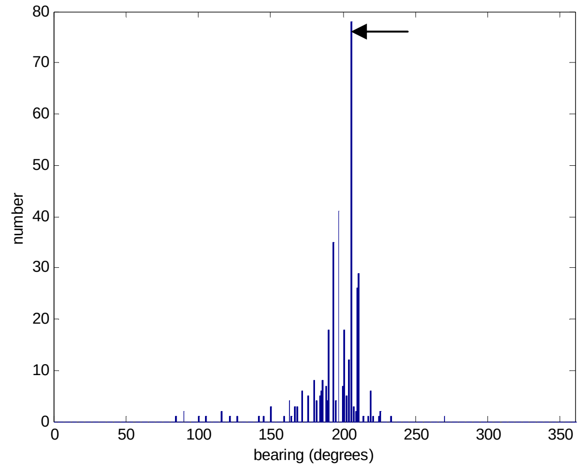

Figure 6. Histogram of bearings from position 3 (bearing used = 206°)

The results of the investigation are shown in Figure 8 with the four bearings superimposed on a scaled drawing of the ABI and the associated vacuum circuit breaker. An expansion of the ABI area shows the positions at which the bearings intersect confirming the source of partial discharges as originating from the red phase of the ABI.

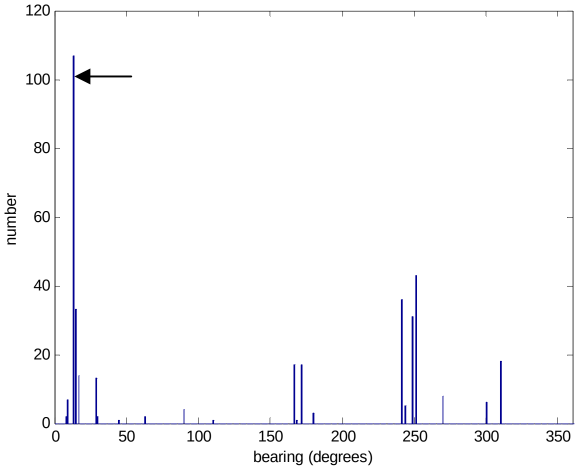

Figure 7. Histogram of bearing from position 4 (bearing used = 11°)

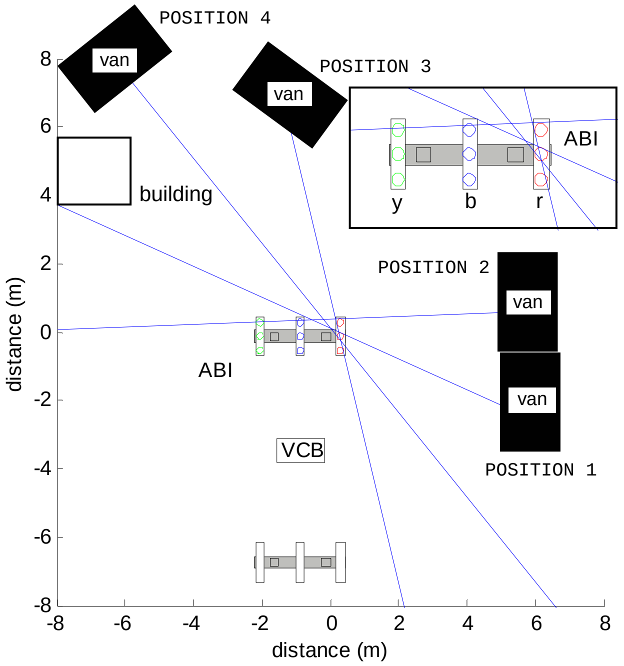

Figure 8. Plan view of the plant and various van positions and bearings

Figure 9. Side photograph of the ABI, VCB and substation building

DISCUSSION

The results of Figure 8 show very clearly that a defect is located on the red phase of the ABI. This is the first experience of using the PD locator in a 33 kV substation and the first time a defect in an ABI has been measured. The ABI will shortly be removed from service and a forensic examination on the cause of the PD will be performed.

Although a high degree of accuracy is required for locating PD sources in distribution substations, this trial has shown that the equipment can be successfully employed at this voltage level. The advantages of this method of PD investigation include:

- No requirement to remove the equipment from service.
- No physical or electrical connection required.
- Ability to monitor all energized plant within a substation.
- Relatively fast procedure: a typical 33 kV substation can be surveyed within one hour.

ACKNOWLEDGEMENTS

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