Partial Discharge Investigation of a Power Transformer Using Wireless Wideband Radio-Frequency Measurements

P. J. Moore, I. E. Portugues, and I. A. Glover

***Abstract*—The remote detection of a transformer internal partial discharge (PD) has been demonstrated using mobile wideband radio-frequency receiving equipment. The PD is externally detectable due to coupling within the transformer tank, causing impulsive signals to be radiated from external connections. A wideband direction-finding technique using a four-antenna array has shown the source of the radiation to be the tertiary winding connections; the radiated impulse has characteristics typical of this method of emission. No other external site of radiation from the transformer was detected. Due to the lack of coupling to the primary and secondary windings, it is believed that the PD is present between the tertiary windings and the core.**

***Index Terms*—Condition monitoring, location, partial discharges, power transformers, radiometric measurements.**

I. Introduction

Power transformers play a major part in electricity transmission and distribution. Their reliability affects both electric energy availability and the economic operation of the utility. The loss of a power transformer can be extremely expensive for a utility and so preventive tests and online monitoring are frequently used to predict incipient fault conditions. Accurate assessment of the transformer insulation condition is essential for safe and economic operation. The concept of detecting partial-discharge (PD) activity through radio-frequency (RF) measurements is not new and has been used for gas-insulated substations [1] and transformer applications [2] through the use of internal ultra-high-frequency (UHF) couplers. However, due to the metal tank surrounding a power transformer, free-space radiometric detection and location of PD has not been seriously investigated.

Using the results of tests carried out on a 400/275-kV, 1000-MVA power transformer known to be discharging [3], this letter improves the understanding of remote radiometric detection and the subsequent analysis of PD from a power transformer.

II. Methodology

PD measurements were made while the transformer was in service using impulsive noise direction-finding equipment [4], [5] in January 2004. The equipment simultaneously acquires four channels of RF energy radiating from the transformer. Earlier results [4] have shown the PD's radiate impulsive RF waveforms. Direct sampling from four wideband antennas connected to a high-speed digital scope of 1-GHz bandwidth and 2.5-GSamples/s sampling rate eliminates the need for demodulation and improves the ability to calculate time delays between the channels. The antennas are arranged in a rectangular-shaped array of dimensions 1.4×1.7 m, which is mounted on the roof of a vehicle to allow ease of movement and reduced installation time. A plan view of the arrangement is seen in Fig. 1.

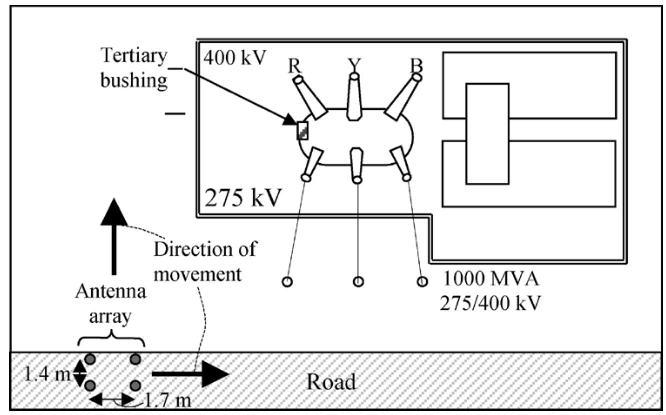

Fig. 1. Plan view of a transformer with initial positioning of antennas.

The objective of the investigation was to examine the radiated field from all possible positions on the transformer and to identify the position of the source. To achieve this, the antenna array was moved in steps of approximately 2 m around the transformer. At each step, the position and orientation of the array were recorded in addition to the impulsive signals. The small step size allows measurement redundancy and accounts for measurement positions that are not optimal due to obstruction between the radiating source and the array from metallic structures internal and external to the transformer. These metallic structures–the earthed transformer tank in particular–cause absorption, diffraction, and multipath effects which deteriorate the received signal. The higher frequencies responsible for the initial steep-fronted edge of the received impulse are usually attenuated by this process leaving a typical waveform as shown in Fig. 2. In general, a directional bearing of the radiating source can be found from waveforms of this type, provided that line of sight exists between the source and the array.

III. Bearing Algorithm

Analysis of the recordings is performed offline using an algorithm which calculates the bearing of the source of the PD from the array. The first step in determining this bearing is to calculate the angle of arrival of the impulse with respect to each pair of antennas in the array. This is achieved by estimating the time delay τ between the arrival of impulses at each pair of antennas. The start of an impulse is found using a threshold value calculated from 150% of the peak noise value in the preimpulse

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The authors are with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K.
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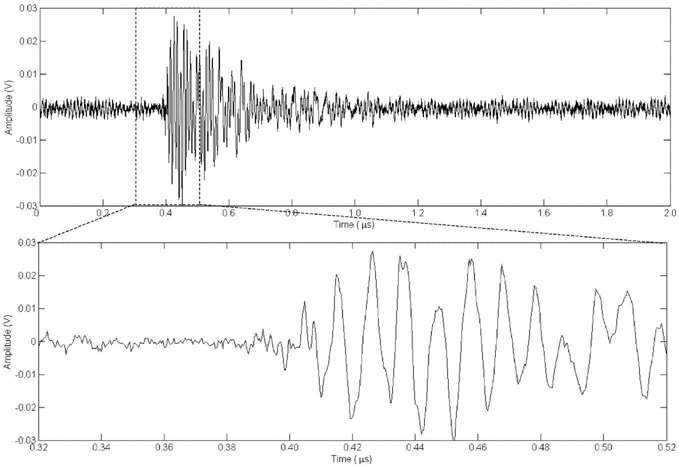

Fig. 2. Typical waveform recorded.

section of the waveform; in Fig. 2, the start of the impulse is calculated to occur at 0.398 μs. The angle of arrival is then found from

$$\cos\varphi = \frac{c\tau}{d}$$

where d is the antenna spacing and c is the velocity of light. Note that the angle of arrival φ is only unique within the range 0–180°; when combined with the orientation of the antenna pair with respect to the array, two possible bearings are produced. For a four antenna array having six antenna pairs, a total of 12 possible bearings are produced in this way. The correct bearing, which is common to all antenna pairs, is found from a least-squares approach that identifies the six bearings, one from each antenna pair, that are closest in value. The final bearing is calculated as the mean of these six values. Additionally, the standard deviation of the six selected values from the mean is calculated to allow elimination of results where the time delays cannot be correctly resolved; this is a particular problem where the impulses are small in magnitude.

IV. Background Noise

From Fig. 2, it will be apparent that the measurements were made with a relatively high level of background signal, which is predominantly due to television and frequency-modulation (FM) radio carriers. The impulse of Fig. 2 represents one of the larger PD waveforms recorded; however, for smaller impulses, the additive background signal can result in an error in the calculation of the time delays, the error becoming higher as the impulse amplitude diminishes. In some cases involving very small impulses, no reliable bearing information can be found, but, in general, the effect of the background signal is to "dither" the time delay. Since broadcast radio signals have a symmetrical probability density function, this effect can be compensated by taking a large number of measurements and finding the mean of the distribution. At each recording position, more than 100 separate measurements of the PD impulse were made using the antenna array. These measurements were then processed, as described previously, to yield a range of bearing angles–an example is shown in the histogram of Fig. 3. Due to

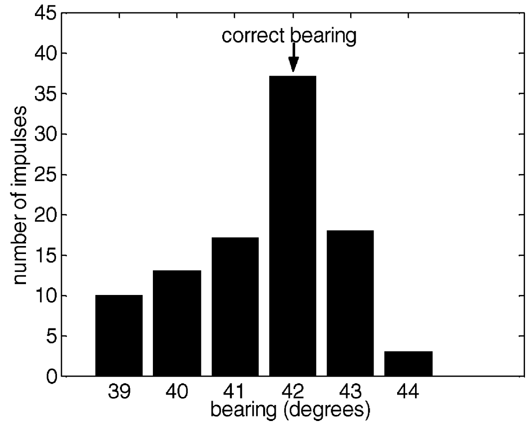

Fig. 3. Correct bearing determination.

the cosine function used in calculating the bearing, the distribution of Fig. 3 has become skewed. The correct bearing is then selected from the peak of the distribution. At the end of this procedure, confidence in the accuracy of the bearing result is very high. There is little incentive to improve the bearing resolution beyond one degree due to limitations in the vehicle positioning accuracy.

V. Transformer

The plant is an autotransformer, rated at 400/275/13 kV, 1000 MVA and was manufactured in 1965. The primary and secondary windings are Yy0 connected, the tertiary is delta connected. External tertiary connections, as indicated in Fig. 1, are brought out on a horizontal row of three porcelain bushings which are commonly connected. Two of these connections serve to close the tertiary delta windings between the yellow and blue phases, while the third grounds the tertiary connection to the lower end of the "a" phase main winding which is star connected to ground elsewhere within the transformer. This transformer has a known, though unidentified, source of internal PD and has been the subject of considerable investigations in the past using a variety of test methods including oil analysis, internal UHF measurements, ultrasonic, and fiber-optic transducers [3]. No conclusive agreement regarding the internal fault has been presented, although all test methods agree that a fault is present. Oil analysis has shown a buildup of hydrogen and a gradual degradation of the paper insulation. Taken in totality, this has proved insufficient evidence for the utility concerned to take the transformer out of service.

VI. Results

Fig. 4 shows a plan view of the transformer overlaid with bearing results from some of the recording positions. Some results are omitted for clarity, but some positions did not allow recording of PD impulses large enough to calculate the bearing. It is apparent from Fig. 4 that the single source of PD radiation from the transformer is from the region of the tertiary bushings. Although the array was circumnavigated around the transformer, only positions that allowed line of sight to the tertiary bushings yielded a bearing result.

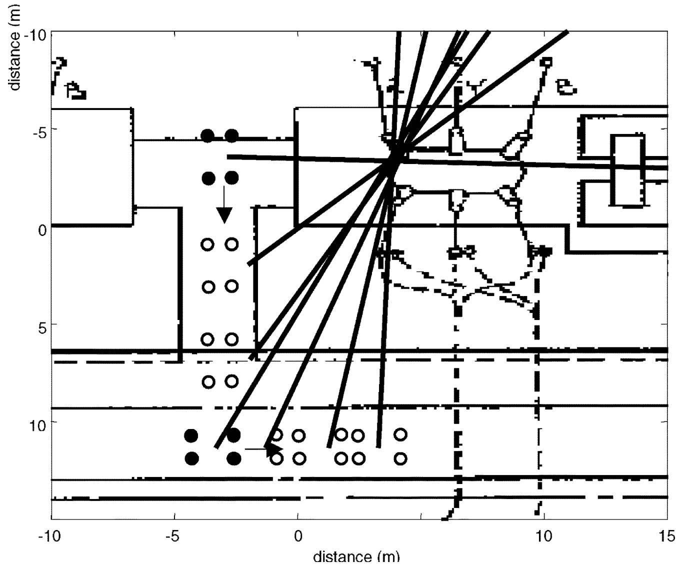

Fig. 4. Bearing results superimposed on the site plan.

The dominant frequency of the received PD impulse is in the region of 95 MHz. This corresponds to a wavelength of 3.1 m, which is approximately twice the length of the tertiary external connection arrangement. It is hypothesized that the radiation is caused by excitation, due to the internal PD, of the tertiary connection which resonates as a half-wave dipole.

VII. Discussion

An earlier investigation (May 2002) on this transformer using similar equipment had determined that the internal PD was causing radiation from the tertiary bushing. However, at that time, it had not been possible to move the array around the transformer perimeter and so it could not be concluded as the only source of radiation. A comparison of the results taken on the two measuring campaigns shows that the PD has remained constant with approximately 20 waveforms per second being recorded. The transformer has been in continuous service during this period.

The ability to detect remotely internal PD within transformers is potentially beneficial to asset managers since a risk assessment can be made without taking the transformer out of service, or making any physical connections. Experience of using this equipment on other 400-kV transformers not suspected of any internal discharge has shown that virtually no impulsive signal is radiated under healthy conditions. Considering the results from this investigation, it should be appreciated that internal transformer PDs can only radiate from structures attached to the transformer that are not earthed, these are essentially the primary, secondary, or tertiary connections. In view of the readily measurable signal radiating from the tertiary connections, it is not unreasonable to suspect that the insulation defect responsible for the PD is located in close proximity to the internal tertiary windings. Since no signals were measured from the primary or secondary connections, it may further be concluded that the defect lies between the tertiary winding and the core, which would explain the absence of coupling with the higher voltage windings. Since the tertiary winding is delta connected and, consequently, links with all three limbs of the transformer core, it is unlikely that these measurements can identify which phase of the transformer contains the defect.

VIII. Conclusions

The remote detection of a transformer internal PD has been demonstrated. Mobile wideband RF receiving equipment situated approximately 10 to 15 m from the transformer identified the tertiary winding connections as the source of the impulsive radiation. Although limited in its diagnostic ability, the measurement method allows a simple, low cost, and noninvasive assessment of potential insulation defects in transformers of this type. The method can be used as a screening approach for the application of more sensitive, contact-based PD measuring systems.

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