A Non-Intrusive Partial Discharge Measurement System based on RF Technology

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***Abstract*—Conventional electrical measurements of PD are performed with detectors connected to the plant. This paper describes research conducted in conjunction with the National Grid Company and the Radiocommunications Agency for the radiometric detection of partial discharge sources via a novel non-contact digital method. The equipment uses an antenna sensor and reference voltage inputs which are directly sampled at 2.5 GHz. Results for hv laboratory tests involving air, SF6 and oil discharges are presented. The results include the waveform, average frequency spectrum and pulse count distribution. A proposal is made for the characterisation of the recorded impulses from these different breakdown effects based on analysis of the spectra and pulse count distributions.**

Index Terms **Partial Discharge, Radio Frequency**

I. Introduction

THE area of partial discharge (PD) measurement and diagnosis is accepted as one of the most valuable non-destructive means for assessing the quality and technical integrity of high voltage (HV) power apparatus and cables. It is well known that PDs in different insulating systems produce varying physical effects and may represent different discharge mechanisms. During recent years, the correlation between PD and the type of defect has become of fundamental importance in the quality control tests of HV components. Hence, methods differing either in the representation of PD data (PD pulse shape data, statistical parameters of these data and pulse density distribution) or in the classification methods (statistical algorithms or neural networks), have been proposed to automate the identification of defects through pattern recognition. Nonetheless, up to now, the problem of identification and classification of partial discharge phenomena occurring on insulation systems has been based on a contact measuring system. Though PD monitoring systems are presently being introduced to specific plant equipment during the production process, retrofitting of such equipment can be economically unviable. Therefore, the possibility of distinguishing between such discharges remotely would be a great advantage since no interruption to system operation is required. In addition, due to the possibility of continuous supervision, remote monitoring allows deteriorating tendencies to be identified in advance, thus reducing costs by allowing period-oriented maintenance to reliably change to condition-oriented maintenance.

The study of radio frequency (RF) emissions arising from high-voltage equipment is not new [1]. Recent studies have shown that radiation from PDs is impulsive in nature and consists of individual high-energy, wide-band impulses of a few microseconds in length. These individual pulses arise, in the case of corona, because once a discharge is initiated, the electrons are quickly depleted in the gap, either by striking the point electrode or by attachment to gas-phase molecules. The space charge so created reduces the electric field near the point, quenching the discharge and inhibiting any new discharge until the space charge dissipates [2]. Only recently, with the advent of high-speed digital recording equipment, is it possible to make wideband recordings of typical breakdown events that occur within the power system on a regular basis. Research conducted by the authors has concentrated on the location of these impulses [3]. However, under certain circumstances, the location might not have sufficient resolution or range so as to determine the exact location of the source of discharge. Under such circumstances the possibility of characterization of the discharge as a means to determine the origin becomes invaluable. It is therefore timely to consider the detailed nature of impulses generated during common electrical discharge phenomena.

II. Impulsive radiation from partial discharges

Partial discharges occur due to a displacement of charge. This produces of a rapid rate of change of current that occurs as the dielectric begins to breakdown. This rate of change, predominantly determined by both the nature of the dielectric and applied electric field, is subject to a limiting value established by the dielectric as shown in figure 1(a). Empirical evidence suggests that the frequency spectrum is bounded for a specific dielectric as shown in figure 1(b). Results taken by the authors, and others [4], indicate that air discharges radiate the majority of their energy at frequencies below 200 MHz, whereas discharges in oil or SF_6 - stronger dielectrics - have a broader spectrum extending up to 1 GHz.

In addition to the generation of radio frequency currents, the radiation efficiency of the connected metallic structure needs to be considered [1]. To fully predict the impulsive noise result of, say, a flashover across the coordinating gaps on an overhead line insulator, the frequency response (i.e. frequency dependent radiation efficiency) and radiation pattern of the entire overhead tower would need to be considered, Figure 1(c). This effect applies equally well to partial discharges occurring in, say, a grid transformer in which case the frequency response and the radiation pattern of the connecting busbars should be considered. Therefore, the final spectrum of a given discharge radiation is the product of the current waveform spectrum and frequency response of the connected radiating structure, Figure 1(d). For this reason, and also due to multipath effects (discussed later), it is difficult to characterize PD effects based on the detailed nature of the radiated waveforms since these are substantially affected by attached metalwork.

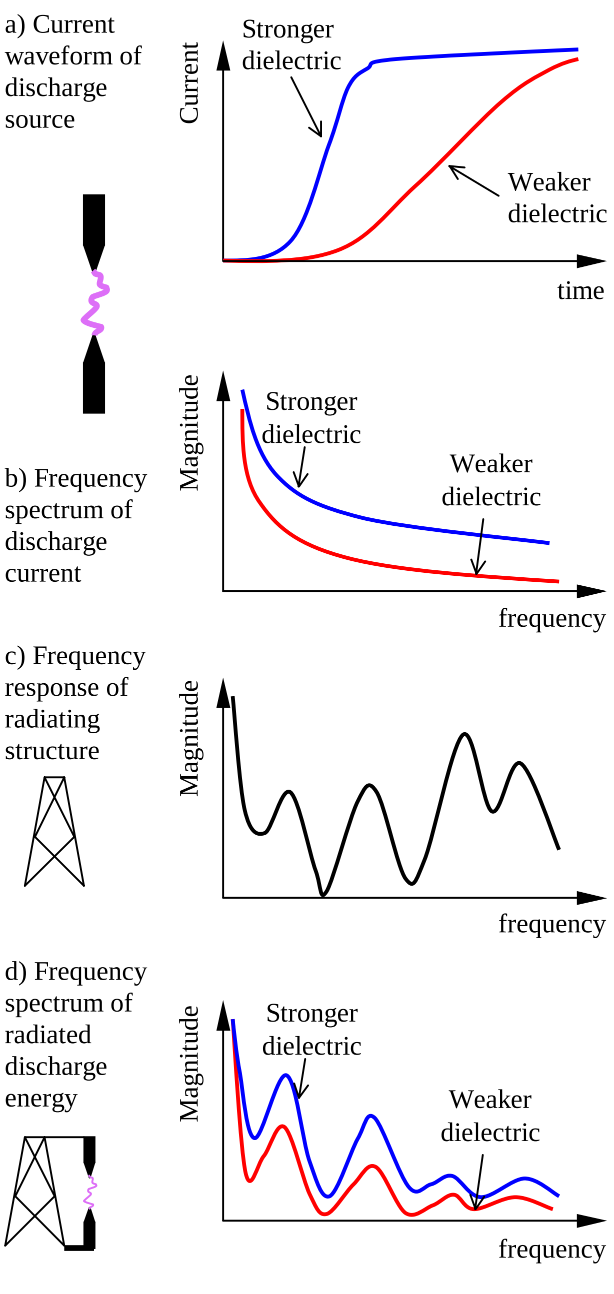

Fig 1. Schematic illustrations of discharge energy radiating from power system plant.

III. Measurement System

The equipment used for capturing and recording PD induced impulsive waveforms consists of a disk-cone antenna, sampling scope and personal computer. For measuring and locating impulsive noise, the disk-cone antenna is ideal: the design shown in figure 2 provides a relatively flat frequency response, shown in figure 3, of the vertical electric field in the range 0-2.5 GHz, with a constant impedance of 50 Ω.

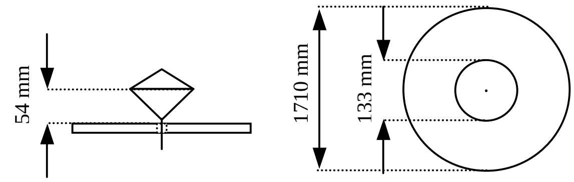

Fig 2. Disk-cone antenna. The cone section was machined from solid aluminium. The base plate was fabricated from 2 mm thick aluminium sheet.

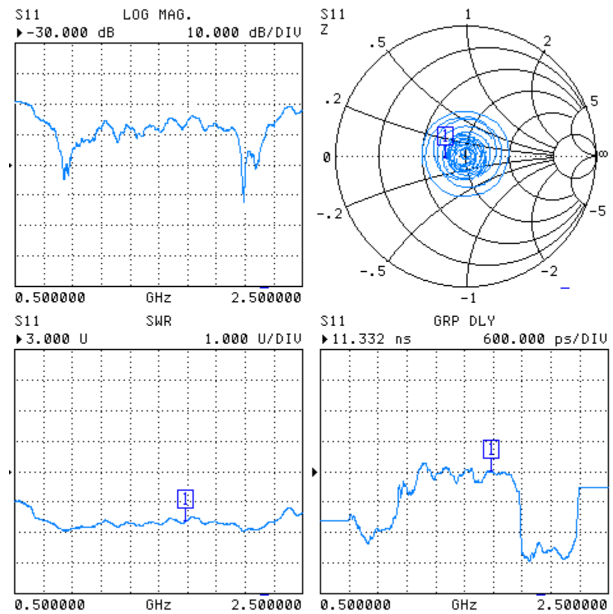

Fig 3. Antenna characteristics.

The antenna is directly connected to a sampling scope. Direct sampling is used since previous studies [5] have shown receiver down-conversion distorts the signal. The sampling scope used was a 4 channel Tektronix TDS 7104, that has an analogue bandwidth of 1 GHz and simultaneous sampling of four channels at 2.5 GSps. Conventional amplitude triggering of the scope was used. Due to the high electric field environment in which this system works, minimising any possible coupling introduced through the connections between the antennas and the oscilloscope is vital. This is achieved via the use of Quickform© coaxial cable, which provides outstanding screening capabilities, ensuring that the signals recorded by the scope are due solely to the antennas. To allow unattended operation of the scope, the oscilloscope was interfaced via the IEEE-488 port to a personal computer (PC). Considering the frequency of impulsive noise and the required sampling rate, continuous recording of the signal is impractical and an alternative solution is required. In order to achieve this, the RAM of the oscilloscope is fragmented into multiple memory slots in a method developed by the manufacturer allowing the storage of individual pulses. In addition, the connection of a high capacity hard disk to the oscilloscope prolongs the capturing time permitting the system to capture unattended for weeks. A block diagram of the full acquisition system is shown in figure 4. During tests described, all waveform analysis was performed offline.

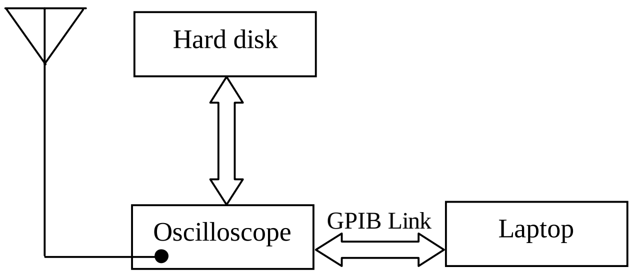

Fig 4. Schematic of acquisition system.

In addition to the RF measurement system, the reference voltage and its derivative are also recorded by the scope in order to determine the phase distribution of signals emitted from the impulsive noise source. The size of each record triggered by the scope corresponds to 2 μs, which is adequate for the average length of a typical impulse, but is too short to allow assessment of the reference voltage gradient. Hence, the derivative of the voltage is additionally recorded. By looking at the signs of the waveforms, the quadrant may be distinguished as appreciated in figure 5. With a knowledge of the reference voltage peak value, the angular position of the captured impulse with respect to this waveform may be determined.

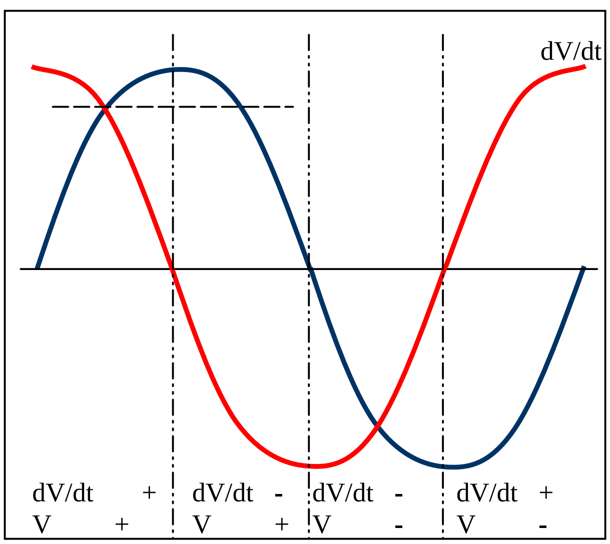

Fig 5. Schematic to show how point-on-wave values may be determined by the acquisition of the voltage waveform and its derivative.

IV. Characterization Procedure

Distortion of the true impulse waveform due to multipath effects and background noise means characterization parameters need to be chosen accordingly. This distortion may be appreciated in figure 6, which shows an impulsive signal captured using 2 spatially separated antennas. In order to illustrate the multipath effect the signals have been adjusted to eliminate the time delay. The impulse reflects from metallic structures in the neighborhood of the discharge source increasing the number of paths taken to reach the antenna.

At the antenna, the waveforms from each of the various paths, each having differing delays due to the different path lengths, summate to produce a distorted representation of the original impulse. In addition, different paths distort the impulse differently due to the reflection of differing structures. In figure 6, the part of the waveform occurring before point A in time, known as the direct path, comes straight from the source and is therefore identical in both cases. After this point, multipath effects cause the two waveform to be dissimilar, rendering the waveform largely unusable for waveform characterization.

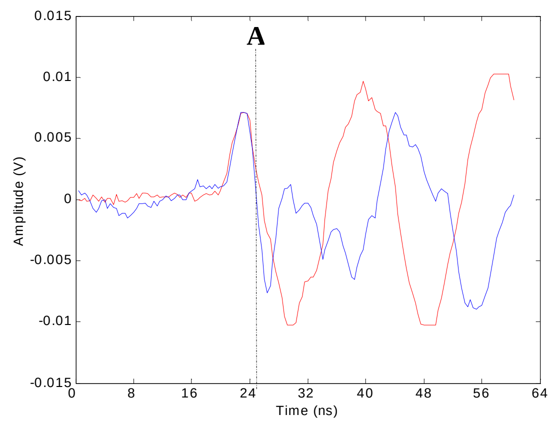

Fig 6. Schematic showing the start of an impulse produced by a partial discharge measured from two separate locations.

Figures 7, 8 and 9 show typical waveforms for the cases of air, oil and SF_6 discharges respectively. It will be apparent from figures 7(a), 8(a) and 9(a), that intricate processing is required if time domain characterization of these waveforms is to be reliably achieved. From the impulse emission process explained in section II, the recorded impulse waveform should decay with time. However, it may be observed from these figures how multipath effects may cause the constructive addition of the waveforms to cause a rise in magnitude of the waveforms after the initial pulse. It is apparent from all the figures that the peak amplitude of the impulse follows its beginning. In some situations, multipath may cause several peaks to be present as in the case for oil, in which the impulse recorded due to the discharge has two distinct peaks. One method in which characterization unaffected by the surroundings may be achieved is in the phase domain. By statistically processing a large amount of similar pulses for a definite period of time, a pulse count distribution, $H_n(\varphi)$ may be created, showing the number of discharges captured at a given point-on-wave reference.

V. Results

The supply of electrical power relies upon the use of specially designed insulation systems, coordinated throughout the range of voltages used in transmission and distribution. The most frequently used insulation media for high-voltage applications are air, oil, sulphur hexaflouride gas (SF_6) and polymers. Unlike the former three materials, polymeric insulators are restricted mainly to cable applications which, in general, do not generate significant amounts of discharges. The present study has therefore concentrated on the three previously mentioned dielectrics: air, oil and SF_6. Impulses of this type, caused by partial electrical breakdown, consequently show a point on wave dependency related to the power system frequency.

The differences between the three dielectrics have been initially studied in order to produce the basis for a future database of digital recordings of impulse emissions caused by a wide variety of common substation insulation defects. All results have been obtained within a high-voltage laboratory.

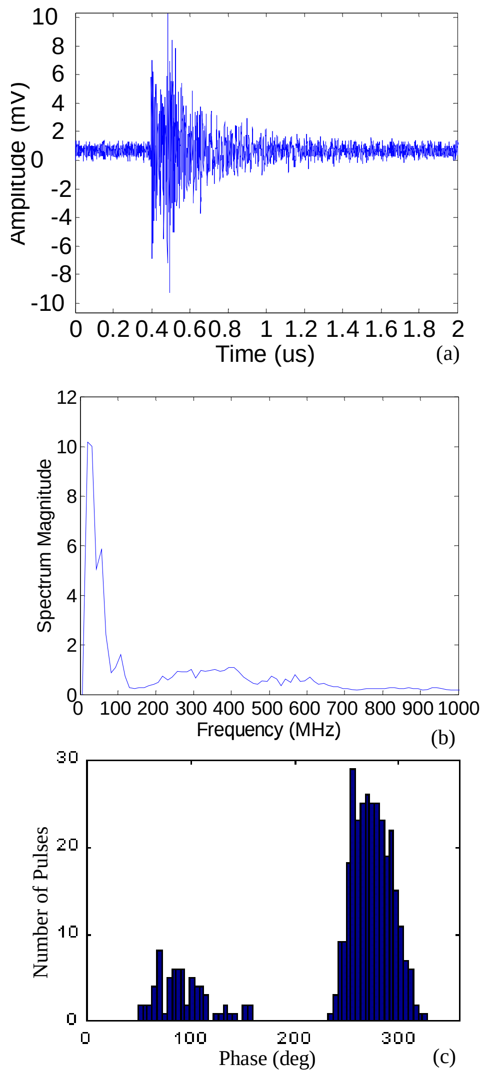

Fig 7. (a) Typical RF impulse produced by air breakdown. (b) Frequency Spectrum of impulse. (c) Pulse count distribution for air breakdown.

Figure 7(a) shows a typical impulse recorded during the measurement of corona. All discharges were obtained via the energization of a test cell containing a point-plane gap. Figure 7(b) shows an averaged frequency spectrum. The averaged frequency spectra shown for the three cases were obtained by averaging 200 impulses captured from the same source and additionally averaging the resulting spectrum over a 25 MHz range. It may be observed how most of the energy is concentrated within the initial 150 MHz band in accordance with previous research mentioned earlier. Figure 7(c) shows two clear areas of activity separated by 180°: this is a classical pattern for a partial discharge occurring in air. The greater activity at approximately 270° is due to discharges occurring at the negative voltage peak since negative partial discharges occur at a lower voltage than for positive discharges.

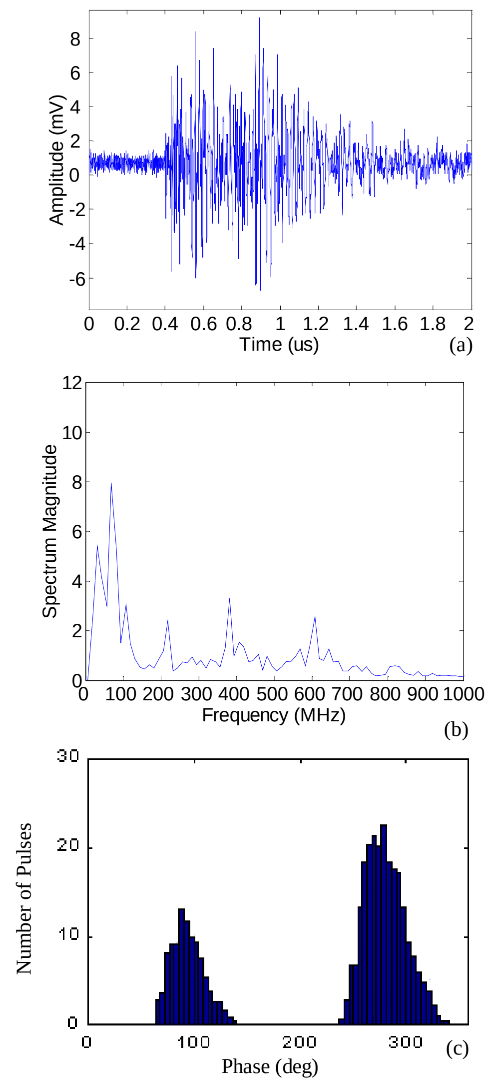

Fig 8. (a) Typical RF impulse produced by oil breakdown. (b) Frequency Spectrum of impulse. (c) Pulse count distribution for oil breakdown.

The graphs represented in figure 8 were obtained by immersing the test cell in oil. The frequency spectrum of this discharge is distributed across a wider spectral range than those of air. Three peaks, at around 200 MHz, 400 MHz, and 600 MHz are the most noticeable. The variation between negative and positive peak values observed in the pulse count distribution graph is less than that observed in air. However, the tail of each half is more pronounced increasing the asymmetry of each distribution. This is related to the liquid nature of the insulator.

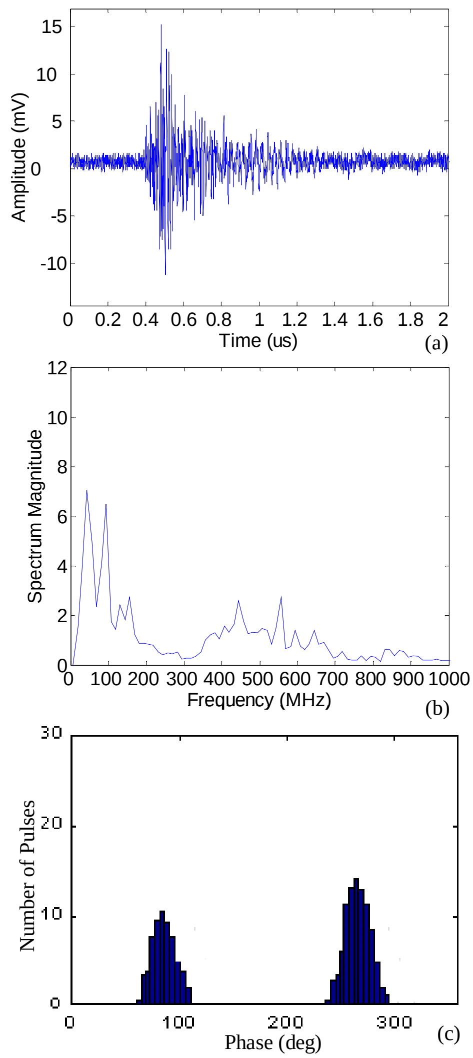

Fig 9. (a) Typical RF impulse produced by SF_6 breakdown. (b) Frequency Spectrum of impulse. (c) Pulse count distribution for SF_6 breakdown.

The results of figure 9(c) were obtained by filling the test cell with SF_6. The symmetry of both positive and negative pulse count distributions is very distinctive and additionally the variation in peak values is reduced even further compared to the air or oil results. The frequency spectrum of SF_6 discharges is wider in content than air, and shows similarities with oil.

VI. Conclusions

Partial discharges caused by electrical insulation breakdown can be detected radiometrically using a directly sampled antenna system. The lack of requirement for physical connection to plant has significant advantages when applied to energized equipment in a substation, although a reference voltage is needed to calculate the pulse count distribution.

Due to the effects of metallic structures within the substation, which modify both the emission and propagation of partial discharge impulses, the recorded waveforms can vary greatly. Any attempt to relate the nature of the defect to the waveshape of the recorded impulse is unlikely to succeed for this reason. However, characterization between the three studied breakdown effects could be achieved through analysis of both the frequency spectrum and pulse count distribution. The results show that air discharges can be distinguished between oil or SF_6, via analysis of the frequency spectrum: air discharges are less represented in frequency components above 200 MHz compared to oil or SF_6. Similarly, oil and SF_6 discharges can be distinguished via analysis of the pulse count distribution which is symmetrical for SF_6, but skewed for oil.

VII. Further Work

Further work is needed to examine all possible sources of partial discharges; it is anticipated that future results will be recorded from substations.

Further analysis of the data is needed to confirm the proposed characterization method. Additionally, it is intended to analyze this data to allow noise amplitude distribution curves [6] to be derived. Presentation of the results in this way will facilitate their application to substation environment modeling.

Further study of the effect of environmental conditions – temperature, pressure and humidity - on the emission of PD induced impulses is being conducted. This is required to assess whether environmental conditions will affect the proposed characterization procedure.

VIII. Acknowledgment

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IX. References

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X. 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.

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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. Until his move to the University of Bath he was an active member of the Radio Environments Work Group in the Mobile Virtual Centre of Excellence and was the Academic Coordinator of the Terminals Work Group.