Electromagnetic Radiation due to Partial Discharge and Fault Detection Method for Overhead Distribution Lines

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Electromagnetic Radiation due to Partial Discharge and Fault Detection Method for Overhead Distribution Lines

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Sahan Chathura Fernando

30th November 2012
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To my son,
Sanuth.
Publications


Abstract

Partial Discharge (PD) is a major problem in aging electrical power systems. It exists in most components of a power system, including transformers, switch gear and power lines. Partial discharge causes damage to electrical hardware, power losses, and issues with power quality. It also creates electromagnetic (EM) interference that may couple into communication systems. PD activity can be an indicator of impending power line insulator failures, leading to catastrophic events such as pole top fires, bush fires and power outages, potentially causing damage to power infrastructure worth of millions of dollars and put the safety of people at risk. The prevention, detection and eradication of PD are hence vital to avoid such failures and consequences. Real time monitoring of overhead power lines for the EM radiation signatures emitted by PD can be employed for this purpose.

The four main types of PD are investigated in this thesis: cavity discharge, corona discharge, dry-band arc discharge, and surface discharge. EM radiation due to cavity discharges has been examined with respect to an increase in the number of cavities in defective Perspex and Epoxy insulator samples. Cavity discharges in Perspex exhibit EM radiation significantly above the noise level in the 10 – 170MHz and 760 – 1120MHz bands, whilst the high voltage Epoxy nano-composite insulators show similar radiation increases in the 30 – 140MHz and 840 – 1120MHz bands. Furthermore the average voltage spectral density in these bands was seen to escalate as more cavities were introduced in the tested samples.

The EM radiation characteristics of corona discharge between water droplets and the dry-band arc discharge resulting from extensive levels of corona discharge and the loss of hydrophobicity of the surface of the insulator have also been investigated. An electromagnetic identification of the transition from corona to dry-band arc discharge has been discovered, which indicates an escalation of the severity of the PD. For uniform water droplets, the transition from corona discharge to dry-band arc discharge can be identified via EM sensing in the 800 – 900MHz and 1.25 – 1.4GHz bands. The average detected voltage spectral density was shown to be higher for dry-band arc discharges at 800 – 900MHz, whilst corona discharge exhibited stronger levels in the 1.25 – 1.4GHz band. This finding was observed to be independent of water droplet volume and separation.

Monitoring of the insulator degradation level due to extensive levels of discharge activity is also possible via electromagnetic techniques. Damage to the insulator surface caused by
discharge activity causes the deformation of water droplets, primarily due to a reduction in hydrophobicity. For an extensively damaged surface it is difficult to observe the transition from corona discharge to dry-band arc discharge as the water droplets immediately wet the surface, eradicating corona. It is notionally possible to monitor the degradation of the insulation surface by sensing the reduction of the voltage spectral density due to dry-band arc discharges in the 800 – 900MHz band.

An EM detection mechanism to monitor the variation of contamination level of a polluted insulator is proposed. By studying the EM radiation spectrum of surface discharge/creeping discharge activity, variations in salt concentration of a pollution layer on nano-composite epoxy insulator samples can be electromagnetically monitored in part or all of the 520 – 600MHz, 700 – 740MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz frequency bands. A link between the pollutant salt concentration, breakdown voltage, surface conductance and the magnitude of the electromagnetic radiation has been identified.

The propagation and radiation characteristics of the UHF frequency components of a PD signal along an uninsulated Aluminium power lines have been numerically evaluated. Bare Aluminium overhead cables show very low attenuation levels, even at GHz frequencies. Hence high frequency components of a PD signal will travel for a significant distance along a cable, allowing for remote real-time detection. The radiation patterns for the high frequency components of PD propagating on single wire and three phase systems exhibit travelling wave radiation patterns analogous to a long wire antenna. High directivity values were recorded at 550MHz, 700MHz, 800MHz, 900MHz and 1.1GHz, which are in the high radiation bands for different PD types.

An initial practical methodology and demonstration of PD detection and localisation was implemented on live power distribution lines. The results and findings gathered from field trials conducted with a pilot PD detection and localisation system have demonstrated the success of the PD monitoring system in identifying faults on heavily contaminated areas of line, as well as observing random events.
# Table of Contents

**Chapter 1 : Introduction and Literature review** ................................................................. 1  
1.1 Introduction......................................................................................................................... 1  
1.2 Literature review ................................................................................................................ 2  
  1.2.1 PD characteristics ......................................................................................................... 2  
  1.2.2 Types of PD ................................................................................................................. 3  
  1.2.3 PD detection technique ............................................................................................... 4  
  1.2.4 EMI from PD ............................................................................................................... 5  
  1.2.5 Direct connection PD sensing systems .................................................................... 5  
  1.2.6 Contactless PD sensing systems ............................................................................. 7  
  1.2.7 UHF PD characteristics and propagation ............................................................... 8  
1.3 Thesis Overview ............................................................................................................. 9  
  1.3.1 Introduction .............................................................................................................. 9  
  1.3.2 The novel partial discharge detection and localisation system ......................... 9  
  1.3.3 Research approach .................................................................................................. 10  
  1.3.4 Summary of chapters .............................................................................................. 11  
1.4 Original contribution .................................................................................................... 12  
  1.4.1 Publications from this research .............................................................................. 12  
  1.4.2 Contribution to the field .......................................................................................... 13  

**Chapter 2 : Electromagnetic Radiation due to Cavity Discharge** ......................... 15  
2.1 Introduction ................................................................................................................... 15  
  2.1.1 Relationship between cavity discharge and EM radiation .................................... 15  
2.2 Experimental Method .................................................................................................. 17  
  2.2.1 PD excitation and detection ..................................................................................... 17  
  2.2.2 Perspex Samples ......................................................................................................... 18  
  2.2.3 Epoxy nano-composite samples ............................................................................. 19  
  2.2.4 Noise floor of the test setup ..................................................................................... 19  
  2.2.5 Calculated charge inside the samples ................................................................... 20  
2.3 EM radiation from cavity discharges in Perspex Samples ........................................ 21  
2.4 EM radiation from cavity discharges in Epoxy samples .......................................... 24  
2.5 Comparison between calculated and measured charge for sample with cavities .... 29  
2.6 Summary ....................................................................................................................... 30
Chapter 3: Monitoring of corona discharge between water droplets and the resultant insulator degradation

3.1 Introduction

3.1.1 Contact angle of a water droplet

3.1.2 Initialisation of Corona Discharge between two water droplets

3.2 Experimental Method

3.3 EM radiation due to Corona discharge between water droplets

3.3.1 EM radiation versus the distance between droplets

3.3.2 EM radiation versus the volume of the water droplets

3.3.3 EM radiation due to corona discharge for different insulator materials

3.4 Detection of the transition from Corona to Dry-band arc discharge

3.5 Detection of Insulator Degradation due to Repetitive Corona and Dry-band arc Discharges

3.6 Summary

Chapter 4: Detection of contamination level of the insulator surface using electromagnetic radiation due to partial discharge

4.1 Introduction

4.2 Experimental Method

4.3 Analysis of the Partial Discharge from polluted insulator samples

4.4 Partial Discharge radiation from polluted insulator samples

4.5 Summary

Chapter 5: Partial Discharge transmission, detection and localisation on uninsulated power distribution lines

5.1 Introduction

5.2 PD pulse propagation on uninsulated power distribution cables

5.2.1 Simulation Technique

5.2.2 Simulation Setup

5.2.3 Investigation on PD pulse propagation

5.3 EM Radiation from a Single Overhead Power Line due to Partial Discharge

5.4 Electromagnetic Radiation from typical electrical discharges
5.5 EM Radiation from an 11 kV three phase cable system .......................................................... 79
5.6 Detection and localisation of Partial Discharge activity .............................................................. 87
  5.6.1 Partial discharge detection and localization system .............................................................. 87
  5.6.2 Field trials with SP AusNet and results ................................................................................. 88
5.7 Summary ..................................................................................................................................... 93

Chapter 6: Conclusion and Future Work ....................................................................................... 94
  6.1 Conclusion ................................................................................................................................. 94
  6.2 Future work ............................................................................................................................... 96

Bibliography .................................................................................................................................. 99
Chapter 1

Introduction and Literature Review

1.1 Introduction

Partial Discharge (PD) is a major problem in the aging electrical power systems. Extensive levels of partial discharge will degrade the condition of electrical insulation and hence may cause failures in power systems [1]. PD exists in most components of a power system, including transformers, switch gear and power lines. PD in transformers and switch gear leads to electromagnetic interference, power losses, and issues with power quality. PD on power lines can also cause electromagnetic interference that may couple into communication systems. Furthermore, power line insulator failures due to PD activity often lead to catastrophic events such as pole top fires and bush fires. Hence extensive levels of PD activity cause damage to power infrastructure worth of millions of dollars and can potentially affect the safety of people. Prevention, detection and eradication of PD are hence vital to avoid such failures and consequences.

The reliability of High Voltage (HV) insulators has been improved by the introduction of epoxy and silicon-rubber nano-composite insulating materials, and tight control of insulator manufacturing. However due to environment factors such as exposure to Ultra-Violet rays, wet weather and insulator pollution, PD activity on power line systems is still a relevant and serious problem.

Power industries have employed various PD detection techniques such as visual inspection, corona cameras, infrared thermography, and measurement of acoustic emission. Visual inspection is a pre-emptive way of determining the insulator condition that does not require special equipment. However it is necessary to take the insulator out of the service to conduct a proper visual inspection. PD activity produces UV radiation, heat and acoustic emission. Corona cameras, infrared thermography and acoustic emission measurement techniques use these by-products of PD to evaluate insulator condition. Acoustic emission measurement is highly vulnerable to background noise and hence is an ineffective method to determine PD activity. The other methods (corona camera and IR thermography) are used widely in the industry. However, all four methods have the following drawbacks in common:
- Capable of detecting only large defects. Therefore they cannot detect PD activity at its early stage;
- Can be only used for spot measurements;
- Cannot be used for automated sensing in a real time detection system; and
- Unable to detect defects located away from the direct line of sight of the sensing device.

For the prevention and eradication of PD activity, power companies have scheduled costly manual cleaning regimes in areas where high levels of insulator pollution have been reported. Hence the integration of a cost effective, automated early detection and localisation system for PD into the existing grid would be a significant advance in power system monitoring technology, to avoid damages to the power grid due to sudden insulator failure.

1.2 Literature Review

1.2.1 PD characteristics

The inception and characteristics of PD have been investigated widely in the open literature. Morshuis presented an extensive investigation and explanation of partial discharge mechanisms which lead to breakdowns [2]. Three stages of the breakdown due to partial discharge activity were identified. The stages are:

- Stage I: Streamer like discharge stage;
- Stage II: Townsend like discharge stage; and
- Stage III: Pitting discharge stage.

As explained by Morshuis, Streamer like discharge stage presents in the first 10 to 60 minutes of the discharge activity. The discharge generated in this stage can be characterised as a short discharge current pulse with a pulse width of about 1ns, and the magnitude of the single discharge is approximately constant for a constant void height. Morshuis also showed that the area affected by the discharge in the Streamer like stage is restricted to a small part of the void surface. Discharges in Townsend like stage are dominant after 10 to 60 minutes of discharge activity and last for a period of several days. The discharges observed in this stage can be characterised by a broad current pulse width proportional to the height of the void and the peak of the pulse will grow with an increase in the diameter to height ratio of the void. Crystals of oxalic acid are formed due to the discharge activity in the Townsend like stage.
Morshuis describes the final stage of the discharge activity as the Pitting stage due to the creation of pits caused by the discharge activity as the dielectric degrades. This stage starts several hours after the inception of discharge activity, initially in parallel with the Townsend like stage. The Pitting stage can be characterised by a high repetition of pulses with pulse width of several milliseconds and very small pulse height. Discharges initiated in this stage are located at a specific location of the void surface.

Morshuis also studied the above discharge stages using a mathematical model. A relationship linking the difference between applied voltage and minimum breakdown voltage to a coefficient defining the discharge stages was proposed. These seminal studies have laid down a strong foundation for current research on PD activity. Boggs described signal generation due to PD and its detection sensitivity in electrical systems in a series of publications [3-5]. Current PD measuring techniques such as the Bridge measuring configuration and its limitations were highlighted. The effect of background noise on PD measurements was also discussed. The papers propose conducting PD testing in shielded rooms with power line filters, PD free transformers and PD free capacitors to mitigate noise. SF\textsubscript{6} insulated substations should be tested using a metal enclosed test transformer coupled to a metal enclosed test chamber. However, these suggestions can only be practically implemented under laboratory conditions and are not suitable for real time PD detection and localisation methods. The EM radiation signals generated by PD activity can be used for the detection and localisation of PD activity [6-9]. These publications discuss different PD detection mechanisms using EM sensors, and will be described in detail in Section 1.2.3.

1.2.2 Types of PD

Common types of PD found in insulator systems are:

- Cavity Discharge;
- Corona Discharge;
- Dry-band arc Discharge; and
- Surface Discharge (Creeping Discharge) due to insulator pollution.

Cavity discharge occurs in a cavity or void inside a faulty insulator due to the movement of charges. These types of discharges are common in ceramic insulators.
Corona discharge occurs due to the ionisation of fluid, and hence it commonly occurs between water droplets on insulators. Extensive levels of corona discharge can cause degradation of the insulation material.

Dry-band arc discharges initiate between two wet areas on an insulator surface, through a dry zone created by the leakage current transmitting through a wet insulator surface. These discharges are more damaging to the insulator than corona discharges due to the high leakage current at the time of creation of the wet and dry zones.

Surface discharge (or Creeping discharge) generates due to a reduction in potential across the insulator due to the increase in the surface conductivity caused by pollution. These type of discharges are mainly observed in coastal and desert areas due to salt, dust and moisture deposits on the insulator.

1.2.3 PD detection techniques

In the mid-90s, the detection of PD activity inside Gas Insulated Substations (GIS) using UHF (300MHz – 3GHz) signals generated from PD was investigated [10, 11]. A UHF coupler design was proposed to detect PD activity in GIS which is attached to the body of the GIS using a dielectric window [7]. Disc shaped sensors operating in the UHF band have also been proposed to detect PD in GIS [12]. Unlike the PD detection sensor proposed in [7], this sensor needs to be installed inside the GIS in order to detect the PD activity effectively. The detection of partial discharge in transformers using the same UHF coupler proposed for GIS was discussed in [13, 14]. In both [13] and [14] the use of a pair of UHF sensors attached to the transformer body to distinguish multiple PD sources inside the transformer was proposed. However these sensors need to be attached to the body of the transformer or GIS, and hence cannot be used as a non-contact sensor.

The frequency characteristics of EM waves radiated from GIS apertures was discussed in [15]. In this study a log periodic antenna was used as a sensor. The antenna was placed 6m away from the model GIS, and the electromagnetic waves radiated from a spacer aperture of the model GIS was analysed up to 2.7GHz. The electromagnetic wave in the frequency range from 500MHz to 1.2GHz was shown to radiate from GIS due to parallel resonance between the inductance of the connecting bolts and the capacitance of spacer aperture. Radiometry techniques using an array of diskcone antennas operating in the UHF band have been proposed to locate PD sources in energised high voltage plants in [8]. The system is proposed
for two different case studies, one of which is an investigation on 132 kV overhead power line. The system in [8] was not able to define the exact PD location. Further works were conducted, focussed on the detection and localisation of faults in transformers and switch gear [16-18]. The detection system using antenna technology for locating faults on power lines was not pursued. Other than the work discussed in [8], the use of radiated electromagnetic (EM) waves to detect and locate PD sources on overhead power lines has received little attention.

1.2.4 EMI from PD

There have been several investigations into Electromagnetic Interference (EMI) to common communication networks due to PD activity on power lines [19-22]. The majority of these studies were based on corona discharges occurring on power cables during wet weather [19-22]. In [19], measured EMI at 900MHz on 230kV and 500kV transmission lines using a high gain parabolic antenna and a low noise pre amplifier was presented. EMI was detected in the 800 – 1000MHz band during foul weather. A study of EMI characteristics of distribution lines located in desert lands was undertaken in [24]. The research shows that the EMI generated due to PD activity on the distribution lines is caused by pollutant on the surface of the conductors, insulators and hardware. EMI measurements in the 0.2 – 30MHz band concluded that unlike the PD on distribution lines in wet weather, PD on distribution lines in a desert area produced a significant level of Radio Interference and minimal level of Television Interference due to the lack of gap discharges. However, these studies do not provide a detailed analysis of the radiated frequency spectrum from different forms of PD on power lines.

1.2.5 Direct connection PD sensing systems

In the past, many direct connection PD sensing systems have been proposed. Power line fault detection and localisation for medium voltage underground cables is discussed in [19]. A Rogowski coil is used as the sensor, which is directly attached to the underground cables. A bank of match filters is employed to identify the type of discharge [26]. This PD detection and location system uses time of arrival (TOA) method to localise the fault. Rogowski coils have also been proposed as a PD detection sensor for overhead insulated cables [27]. Recently, a multi end correlation passed PD location technique for medium voltage covered overhead conductor lines was discussed which again used a Rogowski coil as its PD detecting sensor [28]. The proposed use of a VHF capacitive coupler to detect PD in insulated cables is given in [29].
Australian Work Health and Safety (WHS) regulations place strict restrictions on conducting maintenance on overhead power lines, and other regular day to day activities around power lines to ensure the safety of the general public [30]. As shown in Figure 1.1, Table 1.1 and Table 1.2, the area around the power line has been divided into three zones [30]. The power grid network operators’ pre-approval is required to do maintenance work in the ‘No go zone’ (Figure 1.1). It is necessary to get access to ‘No go zone’ to install directly attached sensors to the existing power grid, and disruptions to power supply may be required in order to get access to this zone. Power disruptions cost significant amounts of money (up to millions of dollars) to the power industry. Due to these WHS and financial reasons, directly attached sensors such as Rogowski coils and the VHF capacitive coupler proposed in [29] are not seen as viable sensors for overhead power lines (especially for un-insulated overhead distribution cables). A contactless sensing method (such as an EM sensing technique) is likely to be a financially viable alternative, and easier to implement into an existing power network. Therefore to further understand contactless sensing methods, it is important to gain a detailed understanding of the radiated EM spectrum of different types of discharges, and how a PD signal propagates along and radiates from overhead power cables.

![Figure 1.1. Approach distance and work zones near overhead power lines](image-url)
Table 1.1. Approach distances for work performed by Ordinary Persons [30]

<table>
<thead>
<tr>
<th>Nominal phase to phase A.C. voltage</th>
<th>Approach distance ($D_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to and including 132 kV</td>
<td>3.0m</td>
</tr>
<tr>
<td>Above 132kV up to and including 330kV</td>
<td>6.0m</td>
</tr>
<tr>
<td>Above 330kV</td>
<td>8.0m</td>
</tr>
</tbody>
</table>

Table 1.2. Approach Distances for work performed by Accredited Persons, with a Safety Observer [30]

<table>
<thead>
<tr>
<th>Nominal phase to phase A.C. voltage</th>
<th>Approach distance ($D_1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated low voltage cables up to 1kV, including LV ABC</td>
<td>0.5m</td>
</tr>
<tr>
<td>Un-insulated low voltage conductors up to 1kV</td>
<td>1.0m</td>
</tr>
<tr>
<td>Above 1kV up to and including 33kV</td>
<td>1.2m</td>
</tr>
<tr>
<td>Above 33kV up to and including 66kV</td>
<td>1.4m</td>
</tr>
<tr>
<td>Above 66kV up to and including 132kV</td>
<td>1.8m</td>
</tr>
<tr>
<td>Above 132kV up to and including 220kV</td>
<td>2.4m</td>
</tr>
<tr>
<td>330kV</td>
<td>3.7m</td>
</tr>
<tr>
<td>500kV</td>
<td>4.6m</td>
</tr>
</tbody>
</table>

1.2.6 Contactless PD sensing systems

Wong proposed the use of VHF antennas to detect the radiation from faults in Ceramic insulators [31], and detection of PD on Polymer ZnO surge arresters [32]. Both [31] and [32] suggested that the possibility of use of VHF sensor to differentiate defects in HV insulators. It was also suggested in [32] that the condition monitoring of HV overhead insulators could be implemented using a system which consists of EM sensors and advanced digital signal processing. An international patent was filed on this method of PD detection and localisation in 2007 [33]. Due to the sensed frequency range, VHF antennas can be quite large (up to several meters in size) and could pose complications in deployment. Therefore the size of the EM sensor is a primary concern which arises during the practical use of EM sensors for overhead power lines. Hence sensing in the UHF band is advantageous as a compact EM
sensor can be designed, alleviating safety and aesthetic issues. Also, an investigation of the UHF band may unlock further information about PD radiation that would enable discrimination between the different types of discharges described in Section 1.2.2.

### 1.2.7 UHF PD characteristics and propagation

Studies of various partial discharge mechanisms such as cavity discharge, corona discharge between water droplets, dry band arc discharge and creeping discharge on the polluted surface has been carried out by various researchers [5, 34-41]. The close proximity electric field variation due to corona discharge between water droplets and insulator pollution has also been discussed [42-45]. However the EM radiation characteristics due to different types of PD activities from HV overhead line insulators, and the differences between their EM spectra (particularly in the UHF band) has not been considered by these previous investigations.

A method of fault location for power transmission lines, based on current travelling waves was proposed in [46]. The investigation utilises an EMTP/ATP and MATLAB based circuit simulation model. In this research the PD signal propagation up to 200kHz is analysed. The propagation of higher frequency components in XLPE cables up to 30MHz is given in [47], again using an EMTP/ATP based simulation model and experimental results. Frequency components over 30MHz could not be considered due to limitations with EMTP/ATP based simulation technique, and it was suggested that the use of a FEM based model could overcome this. The propagation and attenuation of frequency components of PD up to 100MHz when travelling along an insulated power line has been studied in [48, 49]. To date, the majority of the research in this area has been focused on XLPE cables, up to a maximum frequency of 100MHz. Therefore it is important to evaluate the characteristics and propagation of PD frequency components higher than 100MHz in order to realise a contactless UHF PD detection and localisation system.
1.3 Thesis Overview

1.3.1 Introduction

The end goal of this research is to propose a novel partial discharge detection and localization system for overhead power lines using EM sensors. This monitoring system will detect the fault by sensing a PD pulse travelling on the power lines, and will use Time of Arrival (TOA) method to determine the fault location. To achieve this, knowledge of the high frequency EM radiation characteristics from different types of PD activity, and the behaviour of the PD along the power lines is required. However, a basic-science level understanding of the relationship between partial discharge and the resulting electromagnetic signals is still unknown. Hence this research aims to study and understand the EM radiation due to various types of PD activity on high voltage insulators. An investigation of PD pulse propagation and radiation along un-insulated Aluminium overhead cable systems will also be undertaken. These studies will provide vital insight into the information required for the design of a novel EM partial discharge detection and localization system for overhead power lines. The outcomes of this research will further advance the fundamental understanding of electromagnetic radiation from partial discharge, which can be applied to develop an inexpensive and accurate means of identifying deteriorating insulation in high voltage overhead insulator systems.

1.3.2 The novel partial discharge detection and localization system

Figure 1.2 shows the proposed novel method of PD detection and localisation. The overhead line sensing system employs a set of EM sensors attached to monitoring stations. These monitoring stations are placed at predetermined distances (up to several km’s) along a HV distribution line. The EM sensors detect the UHF signal generated by PD that propagates along and radiates from the overhead line. Matched filters tuned to PD radiation signatures will be used in the monitoring systems to eliminate false PD detection due to background noise and interference. The Time of Arrival (TOA) method will be applied to the detected PD signal data collected by each monitoring station to precisely locate the fault.
1.3.3 Research approach

This research has been divided into two main phases:

- The investigation and classification of the electromagnetic radiation due to various types of partial discharge; and
- The implementation of a partial discharge detection and localization system.

The existing knowledge on the EM radiation characteristics from partial discharge on high voltage overhead line insulators is minimal. Hence the first phase of the research is focused on the study of the characteristics of EM radiation of the four basic types of PD:

- Cavity Discharge;
- Corona Discharge;
- Dry-band arc Discharge; and
- Surface Discharge (Creeping Discharge) due to insulator pollution.

The research in the first phase will investigate:

- The effect on EM radiation due to cavity discharges with an increase in the number of cavities in defective insulator samples.
The EM radiation characteristics of corona discharge between water droplets and the dry-band arc discharge resulting from extensive levels of corona discharge and the loss of hydrophobicity of the surface of the insulator. The investigation will also aim to electromagnetically identify the transition from corona to dry-band arc discharge, and to monitor the insulator degradation level due to extensive level of corona discharge activity.

The EM radiation spectrum of surface discharge/creeping discharge activity due to insulator pollution. An EM detection mechanism to monitor the variation of contamination level of a polluted insulator is the intended research outcome.

Findings from the first phase of the research will provide an understanding of the UHF frequency bands where PD activity is strong. These results will inform the second phase of the research, where focus is placed on:

- A study of the propagation and radiation of the UHF frequency components of a PD signal along an uninsulated Aluminium power line. Due to practical complications, experimental investigations using a physical overhead power line system are not possible. Hence simulations approach based on Finite Integral Technique (FIT) is used for this investigation. FIT is capable of simulating large high frequency structures in time domain.

- The construction and field testing of a partial discharge detection and localisation system.

1.3.4 Summary of chapters

- Chapter 2 discusses the measured EM radiation due to cavity discharges. This chapter identifies increases in the magnitude of the EM radiation due to the introduction of cavities in a HV insulator, and the influence of the number of cavities in the sample. Cavity defects are common in older ceramic insulators.

- Chapter 3 studies the EM radiation from corona and dry-band arc discharges when HV excitation is applied to two water droplets. The variation in EM radiation due to corona discharge with the change of contact angle, the distance between water droplets, and the change of the high voltage insulator material is investigated. Techniques to identify the transition from corona to dry-band arc discharge, and to
Chapter 4 discusses the variation in EM radiation due to partial discharge activity with the increase in salt concentration of a polluted high voltage insulator. The frequency bands which can be used to monitor the pollution level of an insulator efficiently are determined.

Chapter 5 analyses the transmission, detection and localisation of PD on un-insulated overhead power distribution lines. PD pulse propagation along uninsulated cables is numerically evaluated, with the power line attenuation and radiation of different line configurations explored in depth. A novel detection method of PD activity on overhead lines using EM radiation from excited power lines is proposed. The Chapter concludes with experimental results from a demonstrator PD monitoring system collected during field trials, demonstrating the success of the method in detecting and localising PD activity on overhead power lines.

1.4 Original Contribution

1.4.1 Publications from this research.


1.4.2 Contribution to the field

- EM radiation generated by PD at insulator defects has not been discussed widely in the literature, particularly in UHF band from 300MHz to 2.5GHz. Chapter 2 proves the existence of EM radiation due to cavity discharge in the 0 – 2.5GHz frequency band. It is also shown that the 760 – 1120MHz band can be effectively used to track the number of cavities in a HV insulator by examining the increase in EM radiation. Chapter 2 is based on the publication [C1].

- Previous research has discussed the detection of differences between corona and dry-band arc discharges by measuring the leakage current. However this method can only be applied in the laboratory. The research in Chapter 3 ascertains the EM signatures of corona and dry-band arc discharges between two water droplets in the 0 – 2500MHz band. It also enables the detection of the transition from corona discharge to dry-band arc discharge by monitoring spectral levels in the 800– 900MHz and the 1.25 – 1.4GHz bands. Furthermore, Chapter 3 identifies the degree of insulator degradation by examining the EM radiation from corona and dry-band arc discharge activity. The Chapter concludes that detecting the degradation of an unpolluted insulator due to high level of corona and dry-band arcing activity can be achieved by measuring 800 – 900MHz radiation. This chapter is based on publications [J1], [C3] and [C4].
Leakage current measurements are also common practice to test high voltage insulators for pollution levels, which pose a major problem in coastal areas. For this test, the insulator needs to be taken out from the system and measured offline. Chapter 4 shows that the surface discharge activity due to insulator pollution actively radiates in the 0 – 200MHz and the 500 – 1600MHz bands. A qualitative assessment of the pollution level, and hence the prediction of impending insulator failure is shown to be possible by monitoring the EM radiation level in 520 – 600MHz, 700 – 740 MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz bands. This chapter is based on the publication [J3].

Partial discharge signal propagation along an uninsulated overhead power cable and its resulting radiation are important parameters for the novel partial discharge detection and localisation system proposed in this thesis. Chapter 5 shows that the uninsulated aluminium overhead power cables have a very low level of attenuation in UHF band and hence the UHF components of the PD signal can travel a long distance. This chapter also presents the radiation pattern characteristics for single and three phase cable systems, which instruct the design of suitable EM sensors and their orientation to detect the PD activity accurately. The Chapter 5 presents field tests for a practical implementation of a demonstrator PD detection and localisation system. This chapter is based on publications [J2] and [C2].
Chapter 2

Electromagnetic Radiation due to Cavity Discharges

2.1 Introduction

Cavity discharge has been discussed widely as one of the primary types of Partial Discharge (PD) [2]. Cavities can be formed during the manufacturing process of insulators due to improper process control during epoxy casting, or over a lifetime of operation as a result of environmental stresses [50]. Early detection of cavity discharge is important to avoid electrical treeing, and hence insulator breakdown [50]. Cavity discharge is generated due to the electron flow inside a cavity, caused by the electric field across it [6, 51]. This transition of electrons gives rise to Electromagnetic (EM) Radiation. Previous research suggests that the physical properties of the discharge source are related to the flow of current [5]. Therefore the various speeds of electrons within the dielectric, the recombination process, and the discontinuities in the discharge current may all affect the frequency radiated [6, 51]. EM sensors play a major role in remote detection and localisation of PD activities [7, 52, 53]. It is crucial to know the EM radiation spectrum due to cavity discharge and other forms of PD activity so that efficient EM sensors for overhead power line PD detection and localisation systems can be designed. To date, the EM radiation from cavity discharges has not been discussed for HV insulation materials. This chapter experimentally identifies EM radiation frequency bands within 0 - 2.5 GHz range which can be used to detect the presence of cavity discharge activity in HV insulators. Variations in the power density of the EM radiation with respect to the number of cavities in the insulator sample are also identified. Focus is placed on the UHF band (>300 MHz) to ensure the EM sensor required for detection remains highly efficient at a workable size of less than 1 metre. The experimental investigations conducted in this chapter are based on Perspex and Epoxy nano-composite materials.

2.1.1 Relationship between cavity discharge and EM radiation

A build up of charge occurs inside a cavity in an insulator when it is subjected to a certain electrical stress, which leads to the electrical discharge [54]. The required electrical stress for the inception of discharge decreases with an increase in the size of the cavity [55]. The maximum charge inside the cavity can be represented by equation (1), where ‘a’ is the radius of the cavity in meters, ‘\( \varepsilon_r \)’ is the relative permittivity of the dielectric material used in the insulator, ‘d’ is the thickness of the insulator or the distance between electrodes in meters, and ‘p’ is the pressure inside the cavity [5]. When the cavity filled with air, ‘p’ is equal to the
atmospheric pressure. As per equation (2-1), the increase in the size of the cavity will result in a greater amount of charge stored before the onset of PD activity.

\[
Q = \frac{1.64 \times 10^{-8} a^{5/2} \epsilon_r p^{1/2}}{d} \quad (2-1)
\]

\[
J = \rho v \quad (2-2)
\]

The current density ‘\(J\)’ due to moving charges inside the cavity is defined in equation (2-2), where ‘\(\rho\)’ is the volumetric charge density inside the cavity, and ‘\(v\)’ is the velocity of the moving charges. Thus an increase in the total charge inside the cavity results in a higher volume charge density, and hence current density, as per equation (2-2). Kadish and Maier have demonstrated the relationship between the current density and the EM radiation using Maxwell equations [51]. Bojovschi et al. showed that EM radiation due to cavity discharge increases with the radius of the cavity inside the insulator sample, using simulations based on Maxwell equations [56]. Hence by using equation (2-1), (2-2) and the results shown in [51] and [53], it can be deduced that the power density of the EM radiation from cavity discharges increases with the level of charge stored inside the cavity before the discharge. Hossam-Eldin et al. have shown that vertically aligned cavities increase the volumetric charge density which leads to the cavity discharge [34]. This increase in charge inside the faulty insulator results in a reduction in breakdown voltage [34]. However the results shown by Bojovschi et al. and Hossam-Eldin et al. are simulation based, using Finite Difference Time Domain and Boundary Element Method techniques, respectively. Therefore this chapter will define an experimental method of confirming the existence of EM radiation due to cavity discharge activity in the UHF frequency band. The influence of a single and multiple vertically aligned cavities in Perspex and Epoxy nano-composite insulator materials is explored. The UHF frequency bands that exhibit the strongest radiation variation with respect to the introduced cavities will also be identified.
2.2 Experimental Method

2.2.1 PD excitation and detection
The experimental setup utilises a point to plane excitation, as depicted in Figure 2.1. The point (with flat end surface) is connected to a single phase high voltage 50 Hz AC power supply, while the plane is connected to the ground. The electrical stress on the sample has been limited to the area where the cavity is placed, by using the flat edged point and metallic plate electrodes.

![Diagram of Point to Plane Excitation](image)

*Figure 2.1. Point to plane discharge excitation*

A double ridged waveguide horn antenna with a very wide frequency response (up to 18 GHz) is employed as the electromagnetic radiation sensor. The antenna is placed 1 m away from the discharge source, as shown in Figure 2.2. A Tektronix TDS5104 real-time oscilloscope with a 5GS/s sampling rate and 1GHz bandwidth was used to collect and analyse the measured signal. Due to the stochastic nature of partial discharge, twenty discharge data samples were collected for each insulator sample under test. The recorded data was then converted via a Fast Fourier Transformation (FFT) to the frequency domain over the range of 0 - 2.5 GHz for each data sample, and then averaged at each frequency to get the average voltage spectrum. The charge magnitude of the discharge (Q) in pC was also measured using a Presco AG PD-4 partial discharge detector in accordance with the IEC60270 standard, and again twenty data samples were collected to calculate the average charge transferred from one electrode to another. It also should be noted that the measured discharge magnitude is expected to be always smaller than the true discharge magnitude of the cavity discharge inside the sample, as it has been measured by the charge coupled into the coupling capacitor. However, differences in the measured discharge level can be used to understand the variation in the cavity discharge magnitude with an increase in the number of cavities.
2.2.2 Perspex Samples

Due to unavailability of HV epoxy insulator samples, Perspex plates were used to create samples shown in Figure 2.3. The Perspex plates were stacked on top of each other to create thicker samples without cavities. Small holes were machined into the surface of the plates to form the samples with cavities. The thickness of each plate was constant at 6mm, and each cavity had a 5mm lateral diameter with 2mm height. For these experiments the thickness of each sample has been increased, as has the number of cavities.

![Diagram of experimental configuration](image_url)

**Figure 2.2. Experimental configuration for detecting cavity discharge radiation**

**Figure 2.3. Perspex samples under test (a) Two plates without cavities (b) Two plates with one cavity (c) Three plates with no cavities (d) Three plates with two cavities (e) Four plates with no cavities (f) Four plates with three cavities**
2.2.3 *Epoxy nano-composite samples*

Epoxy nano-composite insulator plates cut from an epoxy high voltage distribution line insulator were also used to create experimental samples. As shown in Figure 2.4, the epoxy nano-composite insulator plates were stacked on top of each other to create a sample without cavities, and samples with an increasing number of cavities. The total thickness of all constructed samples is 60mm, and each cavity had a 5mm lateral diameter with 2mm height.

![Figure 2.4](image.png)

*Figure 2.4. Epoxy samples under test (a) Sample with no cavities (b) Sample with one cavity c) Sample with two cavities (d) Sample with three cavities (e) Sample with four cavities (f) Sample with five cavities*

2.2.4 *Noise floor of the test setup*

The background noise inside the laboratory was measured using the experimental setup shown in Figure 2.2. The noise floor displays the classic random fluctuations of white Gaussian noise and typically appears below -90dBV. Hence any frequency component below -90dBV can be automatically considered as noise affected. This noise boundary of -90dBV has been used to determine the frequency bands in which the radiation from cavity discharges can be detected.
2.2.5 Calculated charge inside the samples

The maximum charge inside a sample with one cavity can be calculated using Equation (2-1) presented in Section 2.1.1. This equation has been constructed for samples with single cavity. Hence it has been assumed that the maximum charge stored inside the sample will increase linearly with the number of cavities. The maximum charge inside each sample has been calculated using this method as shown in Table 2.1 and Table 2.2.

Table 2.1. Calculated charge inside Perspex samples (Figure 2.3) with cavities

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Calculated charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two plates with one cavity</td>
<td>459.19</td>
</tr>
<tr>
<td>Three plates with two cavities</td>
<td>612.25</td>
</tr>
<tr>
<td>Four plates with three cavities</td>
<td>688.78</td>
</tr>
</tbody>
</table>

Table 2.2. Calculated charge inside Epoxy samples (Figure 2.4) with cavities

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Calculated charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample with one cavity</td>
<td>108.04</td>
</tr>
<tr>
<td>Sample with two cavities</td>
<td>216.09</td>
</tr>
<tr>
<td>Sample with three cavities</td>
<td>324.13</td>
</tr>
<tr>
<td>Sample with four cavities</td>
<td>432.18</td>
</tr>
<tr>
<td>Sample with five cavities</td>
<td>540.22</td>
</tr>
</tbody>
</table>
2.3 EM radiation from cavity discharges in Perspex Samples

Each of the Perspex samples shown in Figure 2.3 were loaded into the point to plane setup of Figure 2.2, and measurements were taken with the antenna located at a distance of 1m away from the excitation source. The experiment has been conducted to observe the EM radiation due to PD activity inside the cavity, which will eventually lead to flashover. The supply voltage is set to a level where the initiation of PD will occur, but is much smaller than that required for flashover (breakdown of air). Since PD is dependent on the voltage across the sample, a constant voltage stress (field strength) of 2.08kV/cm was applied across the electrode during all measurements. Hence, the supply voltage of the test setup was varied between 5kV, 7.5kV and 10kV when the number of Perspex plates used in each sample was 2, 3 and 4 respectively, due to the variation in the thickness of the sample. However, it is a known fact that the electrical stress across the sample may not be uniform, leading to uneven electrical stress across each cavity in the sample. Whilst cavity defects in modern high voltage insulators are extremely rare, older insulators still in service are likely to contain multiple cavities (rather than just one) if there were imperfections in manufacture. Therefore it is important to study the variation of the EM radiation with the increase of the number of cavities to determine any escalation in PD activity which may lead to catastrophic insulator failure.

Figures 2.6 to 2.8 present the average voltage spectrums for the six Perspex samples of Figure 4. When PD occurs the average voltage spectrum within certain frequency ranges rises above the noise floor. Figures 2.6 to 2.8 show that PD activity has been observed for all six samples. The sample with no cavities has also shown PD activity due to air gaps between each plate. The frequencies components inside the 10 – 170MHz and 760 – 1120MHz bands show a significantly higher amplitude than that of the noise floor (taken as -90dBV). The 250 – 650MHz range also show radiation levels above the noise floor, but typically at lower amplitude than the other bands mentioned. As mentioned in Section 2.1 this investigation is focused on identifying UHF radiation from PD, and hence particular attention will be paid to the 760 – 1120MHz band. Higher signal amplitudes are seen for samples with cavities present as compared to their analogous sample without cavities in this band, in excess of 5 dB greater in some instances.
Figure 2.6. Average voltage spectrum of EM radiation due to partial discharge from samples with two Perspex plates

Figure 2.7. Average voltage spectrum of EM radiation due to partial discharge from samples with three Perspex plates
Figure 2.8. Average voltage spectrum of EM radiation due to partial discharge from samples with four Perspex plates

Figure 2.9 plots the difference in the average voltage spectral density of the EM radiation over the 760 – 1120MHz band between samples with artificial cavities and those without cavities. The difference value increases logarithmically with the number of cavities in the sample. An increment of 2.95x10^{-12} V/Hz is seen when the number of cavities is increased from one to two, and a 3.86x10^{-13} V/Hz increment when increasing number of cavities from two to three. Charge levels from the PD activity of all six samples were measured using the PD detector. Higher levels of charge are observed for the samples with cavities compared to the sample without cavities. The difference in charge between samples with and without cavities is displayed in Figure 2.10. The charge difference increased by 162.15pC when the number of cavities in the sample went from one to two, and by a further 86.66pC from two to three cavities.

Regression analysis on the results in Figures 2.9 and 2.10 show that R^2 value the trend line (dashed lines) for Figure 2.9 is 0.93 and Figure 2.10 is 0.99. Both R^2 values are close to one. Therefore these trend curves shown in Figure 2.9 and 2.10 are good representations of the data collected during the experiment. Furthermore, the EM radiation difference in Figure 10 for the 760 – 1120MHz band shows a similar logarithmically ascending trend to that observed for the charge level difference. This implies that the sensing of EM radiation in the 760 – 1120MHz band could effectively be used to monitor cavity discharge levels from the samples depicted in Figure 2.3.
2.4 EM radiation from cavity discharges in Epoxy samples

The same experimental method used in Section 2.3 for Perspex samples has been employed to observe the PD activity from the six different Epoxy nano-composite samples shown in Figure 2.4. The total thickness of the assembled Epoxy samples was constant at 60mm, and hence a 7kV AC voltage, which is just enough for the inception of PD, was supplied to each sample to create a 1.167 kV/cm electric field strength between the electrodes.
Figure 2.11. Average voltage spectrum of the EM radiation due to partial discharge from Epoxy nano-composite sample with no cavities

Figure 2.12. Average voltage spectrum of the EM radiation due to partial discharge from sample with one cavity
Figure 2.13. Average voltage spectrum of the EM radiation due to partial discharge from Epoxy nano-composite sample with two cavities

Figure 2.14. Average voltage spectrum of the EM radiation due to partial discharge from Epoxy nano-composite sample with three cavities
Figures 2.11 to 2.16 show the EM radiation in the 0 – 2.5GHz band due to PD activity in the six Epoxy nano-composite samples of Figure 2.4. The sample without cavities in Figure 2.12 exhibits PD activity due to microscale air gaps in between each plate, as solid plates of the same thickness did not display any PD behaviour. The average amplitude of the voltage spectrum due to PD activity is significantly higher than the noise floor in the 30 – 140MHz and 840 – 1120MHz bands. Once again, the variation in radiation level identified in the UHF band from 840 – 1120MHz is of primary interest to this research.
In Figure 2.17, the average voltage spectral density of the EM radiation in the 840 – 1120MHz band increases from -225.8dBV/Hz for the sample without cavities to -224.2dBV/Hz for the sample with five cavities. An ascending trend line is also plotted as the dashed line in Figure 2.17. Figure 2.18 shows the variation in the charge level of the PD activity inside the sample measured using a PD detector. This variation again shows an increasing trend with the number of introduce cavities similar to Figure 2.17. The charge level of the discharge ranges between approximately 27.2pC and 215.6pC for the samples with zero and five cavities, respectively. Regression analysis of the trend curves shows that R² values of 0.87 and 0.81 are observed for Figure 2.17 and 2.18 respectively, indicating they
are reasonable representations of the data collected during the experiments. These results confirm similar findings to those in Section 2.3 for Perspex samples: monitoring EM radiation in the 760 – 1120MHz provides an indication of the cavity discharge levels in the Epoxy nano-composite samples depicted in Figure 2.4. It can also be concluded that the logarithmic increase of the discharge level associated with additional cavities can be observed as a corresponding elevation of the EM radiation in the 840 – 1120MHz band.

### 2.5 Comparison between calculated and measured charge for sample with cavities

The Table 2.3 and Table 2.4 show the measured and calculated maximum charge inside each sample due to cavity discharge. As shown in Table 2.3 and 2.4, the difference between calculated and measured values for the sample with single cavity is minimal. However the calculated and measured values for samples with multiple cavities show significantly different values. Equation (2-1) discussed in Section 2.1.1 assumes constant field distribution across the sample. However when multiple cavities are located next to each other, the field in each void is affected by the others around it [57]. This effect is significant when cavities are placed vertical to the ground (the cavity orientation which is shown in Figure 2.3 and 2.4) [57]. This causes an uneven electric field across cavities inside the sample. Therefore an assumption of uniform electric field distribution across the sample cannot be used, and leads to the significant differences between calculated and measure values when multiple cavities are present. Further investigation is necessary to modify the Equation (2-1) to accommodate the electric field variation due to multiple cavities.

### Table 2.3. Calculated charge inside Perspex samples with cavities (Ref Figure 4.2)

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Calculated charge (pC)</th>
<th>Measured charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two plates with one cavity</td>
<td>459.19</td>
<td>418.67</td>
</tr>
<tr>
<td>Three plates with two cavities</td>
<td>612.25</td>
<td>1350.81</td>
</tr>
<tr>
<td>Four plates with three cavities</td>
<td>688.78</td>
<td>3360.78</td>
</tr>
</tbody>
</table>
**Table 2.4. Calculated charge inside Epoxy samples (Ref Figure 4.3) with cavities**

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Calculated charge (pC)</th>
<th>Measured charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample with one cavity</td>
<td>108.04</td>
<td>127.13</td>
</tr>
<tr>
<td>Sample with two cavities</td>
<td>216.09</td>
<td>146.2</td>
</tr>
<tr>
<td>Sample with three cavities</td>
<td>324.13</td>
<td>142.9</td>
</tr>
<tr>
<td>Sample with four cavities</td>
<td>432.18</td>
<td>137.22</td>
</tr>
<tr>
<td>Sample with five cavities</td>
<td>540.22</td>
<td>215.64</td>
</tr>
</tbody>
</table>

**2.6 Summary**

This chapter has observed EM radiation in the UHF band from cavity discharges through experiments conducted on Perspex and Epoxy nano-composite insulator samples. Cavity discharges in Perspex exhibited EM radiation significantly above the noise level in the 10 – 170MHz and 760 – 1120MHz bands. In the high voltage Epoxy nano-composite insulators the voltage spectra from 30 – 140MHz and 840 – 1120MHz displayed heightened levels during cavity discharge. The average voltage spectral density in these bands was seen to escalate as more cavities were introduced in the tested samples. Comparisons between the discharge activity results focused on UHF frequencies (>300 MHz) with the view that an EM monitoring system would require an efficient sensor with practical dimensions.

The cavity discharges were also monitored for both types of insulator using a PD detector as the number of cavities in the sample was incremented. A logarithmic increasing trend was observed for both the charge level associated with the cavity discharge and the average voltage spectral density measured from the resulting EM radiation for both insulator types. The results indicate that the increase in the level of cavity discharge activity in Epoxy and Perspex insulators can potentially be monitored by a non-contact EM sensor working in the UHF band. For the specific samples analysed, the monitored bands of 840 – 1120MHz for Epoxy nano-composite insulators and 760 – 1120MHz for Perspex can be used.

Due to the quality control methods used in high voltage insulator manufacturing processes, cavity discharges are not a common type of partial discharge in modern power networks. They are generally not observed during normal operation, except in very antiquated insulators. Corona discharges, dry-band arc discharges and surface discharges due to
insulator pollution are more common types of partial discharge which are commonly observed in practice. Hence it is also vital to study the EM radiation due to these more common types of PD in power distribution networks, to enable a non-contact and continuous fault identification and localisation system for overhead power lines to be realised. These other forms of discharge will be explored in the following chapters.
Chapter 3

Monitoring of corona discharge between water droplets and the resultant insulator degradation

3.1 Introduction

Insulator manufacturing has evolved to mitigate partial discharge in insulators. Ceramic materials have been used in the past for high voltage (HV) insulator manufacturing. However manufacturers now commonly use nano-composite materials due to their hydrophobic properties and high durability [58]. Quality control methods used in the insulator manufacturing process have rendered cavity discharges from nano-composite insulators almost non-existent. However some forms of surface discharges such as corona and dry-band arc discharges are still common, particularly when the surface of the insulator is wet. Insulators can degrade due to insulator pollution, ultraviolet radiation, acid rain and surface discharges. Of these causes, surface discharges have a high impact on insulator degradation [59]. Corona discharge initiates when a water droplet on the surface of an insulator starts to change the shape under electrical stress [60]. Under heavy corona discharge, the insulator will degrade and lose its hydrophobicity [61]. This loss of hydrophobicity leads to imminent dry-band arcing. Extensive levels of dry-band arcing are also detrimental to insulator condition due to the significant amount of current transmission, potentially leading to catastrophic failure [1, 62].

The use of leakage current characterization for estimating the condition of the insulators, and hence detecting the dry-band arc discharges has previously been reported [63, 64]. Measuring the charge magnitude of the PD has also been discussed as a possible method of detecting the transition from corona discharge to dry-band arcing on the insulator [65]. This detection method must be performed inside a laboratory, meaning the insulator needs to be removed from the electrical power grid. Due to the lack of an online, non-contact detection method to identify failing insulators caused by dry-band arcing, power companies cannot identify a damaged insulator until the insulator has completely failed. It has been proposed that EM sensors can be used for online PD detection [66].

A UHF technique to identify the discharge initiated by a liquid droplet on epoxy nano-composite insulation material was proposed in previous studies [67]. Discharges using a single NH\textsubscript{4}Cl droplet under AC voltage were investigated of nano-composites with different
percentages of composition. The corona discharge between two water droplets has been studied previously [68-70]. However, the experiments in [68-70] did not investigate the radiated UHF signal caused by corona discharge between two water droplets, dry-band arcing, and the differences between the two.

This chapter measures and evaluates the radiated frequency spectra ranging from 0 - 2.5 GHz due to corona discharge between two water droplets, as well as the resulting dry-band arc discharges. Parameters such as the droplet size and separation are varied to examine their influence on the resulting radiation. The potential for the detection of the transition between corona and dry-band arcing based on the differences in the frequency spectrums generated by both discharges is also explored. The condition of the HV insulator is assessed using the EM radiation from successive sets of discharges on the same insulator location. The results will highlight the potential of this EM sensing technique for insulator condition monitoring.

### 3.1.1. Contact angle of a water droplet

The contact angle $\theta$ of a water droplet is measured with respect to the surface it is sitting on, as shown in Figure 3.1. The contact angle is dependent on the hydrophobicity of the material the water droplet is sitting on. Hence it is often used to define the hydrophobicity of the material. Epoxy and Silicon-rubber are common materials use for nano-composite HV insulators. Silicon-rubber nano-composite has a higher hydrophobicity than Epoxy nano-composite insulator surfaces. Therefore water droplets on Silicon-rubber insulators show a higher contact angle than droplets on Epoxy surfaces.

![Figure 3.1. Contact angle of the water droplet.](image)

### 3.1.2. Initialisation of Corona Discharge between two water droplets

Water droplets formed on the surface of electrical insulators result in a disturbed electric field distribution around the insulator [42, 71]. The electric field surrounding the water droplets was discussed in [43, 71-73]. Electric field distributions along the lines of equal distance from the insulator surface ($E_1$ to $E_n$ in Figure 3.2) are defined. The variation in electric fields is
described as an electric field enhancement factor ($E_{efn}$), relative to each line (equation (3-1) and (3-2)). Corona discharge will initiate where $E_{efn}$ is maximum [72]. However the value of $n$ for maximum $E_{efn}$ will change with the contact angle of the water droplet and the distance between water droplets [43]. Hence the spatial path of the discharge also varies with the contact angle and the distance between water droplets, as shown in Figure 3.3.

\[ E_{efn} = \frac{E_n}{E_o} \]  

(3-1)

$E_{efn}$ = Electric Field Enhancement Factor at $n^{th}$ line  
$E_n$ = Electric Field along the $n^{th}$ line 

Where

\[ E_o = \frac{V}{d} \]  

(3-2)

$V$ = Applied voltage  
d = Distance between electrodes

Figure 3.2. Electric field distribution lines to explain the initiation of corona discharge.

Figure 3.3. Discharge between (a) 0.4mL water droplets on Epoxy surface (approximate contact angle of 71 degrees) (b) 0.4mL water droplet on Silicon-rubber surface (approximate contact angle of 90 degrees) [10].
3.2 Experimental Method

Two water droplets of Melbourne (Australia) tap water of the same volume were placed on an insulator sample, as shown in Figure 3.4. The water droplets were connected to metal electrodes, one was grounded whilst the other was connected to a 5kV 50Hz AC voltage supply as shown in the experimental setup of Figure 3.5. Radiation emitted from corona and dry-band arcing were observed using a wideband horn antenna located 1m away from the discharge source. The 1m distance was chosen to ensure that adequate signal strength was received by the antenna [74]. A Tektronix real-time oscilloscope with a 5GS/s sampling rate and 1GHz bandwidth was used to capture the detected signal. Due to the stochastic nature of high voltage discharges, twenty radiation data samples were collected from each of seven different discharge locations on an insulator sample for each experiment. The recorded radiation data was then converted via a Fast Fourier Transformation (FFT) to the frequency domain over the range of 0 - 2.5GHz. Unlike in the experiment setup discussed in Section 2.2.1, the Presco AG PD-4 partial discharge detector has not been used for this investigation. The sudden increase in leakage current at the time of the creation of the water bridge leading to dry band arc discharge could potentially damage the discharge detector.

![Figure 3.4. Two 0.4mL water droplets on the epoxy nano-composite sample before corona discharge](image_url)
Figure 3.5. Experimental setup of the high voltage discharge between two water droplets

In practical scenarios, water droplets formed on a high voltage insulator are likely to be of different volume and have varying distances between each other. Therefore, a set of results was collected for 0.4mL water droplets having a distance between electrodes of 1.5cm, 2cm and 2.5cm. A second set of data was observed by varying the size of the water droplets from 0.2mL to 0.8mL in 0.2mL steps, providing a wide coverage of droplet contact angles with the insulator surface, whilst keeping the distance between electrodes at 2cm. To monitor changes to the frequency spectrum due to the degradation of the insulator, radiated signals were observed for repeated discharges at the same physical location on the insulator sample surface.

3.3 EM radiation due to Corona discharge between water droplets

3.3.1 EM radiation verses the distance between droplets.

In real life scenarios a HV insulator is under constant AC voltage and the distance between two adjacent water droplets is random. An investigation into the effect the distance between water droplets on the surface of Epoxy nano-composite insulator sample has on the EM radiation from corona discharge was performed. The distance between water droplets is linked to the magnitude of the electric field when the applied voltage is constant. The electric field magnitude applied was 3.3kV/cm, 2.5kV/cm and 2kV/cm for corresponding distances between electrodes of 1.5cm, 2cm and 2.5cm respectively.
Figure 3.6 shows three spectra for the examined distances between electrodes. The electric field strength between the electrodes has reduced when increasing the distance between them. Therefore a decrease in the overall magnitude of the corona discharge between the two water droplets was observed. Consequently, the level of radiated energy due to corona discharge has reduced for the whole frequency band from 0 – 2.5GHz, as shown in Figure 3.7. This magnitude reduction is clearly visible in 600MHz – 750MHz, 1.2GHz – 1.3GHz and 1.4GHz – 1.6GHz bands.
Previous research has shown that the water droplets under constant electrical stress will enhance the nearby electric field [72]. To understand the extent of this effect on the EM radiation due to corona discharge, droplets with different volumes were investigated whilst the distance between electrodes was kept constant at 2cm. Epoxy nano-composite insulator samples were used in this investigation. Each water droplet on the surface of the Epoxy nano-composite insulator sample was photographed (Figure 3.7) to observe changes to the contact angle with the volume of water.

The contact angle of the water droplet (and hence the shape of the droplet) changes with the increasing volume of the droplet [73]. It also changes with the hydrophobicity level of the material. A change in droplet volume also alters the radius of water droplet footprint. Hence the distance which separates two water droplets in the experimental setup of Figure 3.1 changes from approximately 1.2 cm to 0.5cm for volumes of 0.2mL to 0.8mL respectively. This also results in a reduction in the time taken for breakdown to initiate. Table 3.1 shows the approximate contact angle measured using the photographs of the water droplets shown in Figure 3.8 and image processing software, and the time taken until breakdown occurs.

![Average Voltage Spectral Density for Corona and Dry-band arc discharges for different distances between electrodes for frequency spectrum of 0 – 2.5GHz](image-url)
Figure 3.8. Water droplets of different volumes on epoxy nano-composite insulators (a) 0.2mL (b) 0.4mL (c) 0.6mL (d) 0.8mL.

Table 3.1. Approximate contact angle of the water droplets and the time until breakdown

<table>
<thead>
<tr>
<th>Volume of the droplets (mL)</th>
<th>Contact Angle (Degrees)</th>
<th>Time until breakdown (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>89</td>
<td>14.50</td>
</tr>
<tr>
<td>0.4</td>
<td>71</td>
<td>9.36</td>
</tr>
<tr>
<td>0.6</td>
<td>52</td>
<td>6.26</td>
</tr>
<tr>
<td>0.8</td>
<td>23</td>
<td>4.17</td>
</tr>
</tbody>
</table>
Figure 3.9. EM radiation due to corona discharge versus volume of the water droplets when electrode distance is 2cm.

Figure 3.9 displays the frequency spectra for corona discharge, when changing the volume of both water droplets between 0.2mL, 0.4mL, 0.6mL and 0.8mL. As mentioned above the distance which separates the two water droplets changes from approximately 1.2 cm to 0.5cm for volumes of 0.2 mL to 0.8 mL respectively. This change has contributed to the increased amplitude of the radiated signal in 1.1 – 1.8GHz band.

Figure 3.10. Average Voltage Spectral Density for Corona discharge for different water droplet volumes over 0 – 2.5GHz
Guan et al. [72] has shown using an electromagnetic simulation model that when increasing the contact angle of the water droplet by changing its volume, the electric field enhancement due to corona discharge first increases, and then decreases, reaching a peak value between 40 to 60 degrees. The total energy radiated from both corona and dry-band arc discharges shown in Figure 3.10 displayed a rapid increase when the droplet volume decreased from 0.8mL to 0.6mL, corresponding to an increase in contact angle from 23 to 52 degrees. As the droplet volume changed from 0.6mL to 0.4mL the radiated energy is held relatively constant, and a further decrease in volume to 0.2mL showed a noticeable drop in radiation, particularly for corona discharge. Hence the experimental results for corona discharge shown in Figure 3.10 bear reasonable resemblance to the findings of [72].

3.3.3. EM radiation due to corona discharge for different insulator materials

A water droplet on different insulator material surfaces shows different contact angles. Therefore, corona discharges between two 0.4mL water droplets placed on both epoxy and silicone-rubber samples were investigated, whilst keeping the electrode distance constant at 1.5cm.

Figure 3.11. EM radiation due to corona activity on Epoxy and Silicone-rubber insulators

Figure 3.11 shows the frequency spectrum observed from the EM radiation due to corona discharges on epoxy and silicone-rubber insulators. The EM radiation from corona activity is dominant in the 500 – 1500MHz range for both cases. However the frequency spectrum for corona activity shows dissimilarity between the epoxy sample and the silicone-rubber sample.
The highest amplitude peak of the frequency spectrum from corona discharge on epoxy was at 625MHz, whilst for silicone-rubber it was at 825MHz. Also, the silicone-rubber case shows lower amplitude than epoxy for the frequency range between 1 and 1.5GHz. The overall magnitude of the discharge for the corona discharge on the epoxy sample is 26% higher than on silicone-rubber sample, as depicted in Figure 3.12.

![Figure 3.12. Average voltage spectral density for corona discharge.](image)

Silicone-rubber has higher hydrophobic properties than the epoxy insulator. As shown in Figure 3.13, the same size water droplets (0.4mL) on epoxy and silicone-rubber surfaces have clearly different shapes. The contact angle of the water droplet on the epoxy surface is around 70 degrees, whilst the water droplet on the silicone-rubber surface is close to 90 degrees.

![Figure 3.13. Pictures of 0.4mL water droplets on the surface of different insulation materials (a) Epoxy (Approximate contact angle: 70 degrees) (b) Silicon-rubber (Approximate contact angle: 90 degrees)](image)
As explained in Section 3.1.2, variation in the electric field distribution will result in variation in the discharge path, as seen in Figure 3.3. The lower contact angle in Figure 3.3(a) shows a discharge that takes an arc shaped path through the air. The larger contact angle in Figure 3.3(b) depicts the discharge largely confined between the two droplets. This discharge confinement could explain the lower levels of radiation from corona discharge from droplets on silicone-rubber as compared to an epoxy insulator.

Guan et al. explained that the water droplets under constant electrical stress will enhance the electric field nearby [72]. However the enhancement level of the electric field will vary with the contact angle. When the contact angle is increased for the same volume of water droplet, the electric field around the water droplet is reduced. In this study, the water droplet contact angle is higher for silicone-rubber than epoxy insulators. Using [72], there is less electric field enhancement between the two water droplets in the silicone rubber case, hence causing the reduction in magnitude of the corona discharge between water droplets. Consequently, the lower level of radiated energy due to corona discharge on a silicone rubber insulator is seen in Figure 3.12.

### 3.4 Detection of the transition from Corona to Dry-band arc discharge.

Corona discharge between water droplets causes a change in the shape of the water footprint, consequently creating a water bridge between water droplets. The leakage current travelling through this water bridge initiates dry-band arc discharges. Extensive levels of dry-band arcing are also detrimental to insulator condition due to the significant amount of current transmission, potentially leading to catastrophic failure [1, 62]. Therefore finding a method to detect the transition from corona discharge to dry-band arc discharge using the variations in the frequency spectrum of EM radiation due to corona and dry-band arc discharges could provide an effective, non-contact means of averting insulator failure. The experiments discussed in Sections 3.3.1 and 3.3.2 were continued until the occurrence of dry-band arc discharge. The same data collection and analysis method used for results shown in Sections 3.3.1 and 3.3.2 were used for dry-band arc discharges. The frequency spectrums for both corona and dry-band arc discharges were compared to identify the frequency band(s) that clearly illustrate the transition from corona to dry-band arc discharge using their EM radiation.
The local electric field distribution and level of enhancement has been shown to vary with the changes to the applied electric field and the shape of a water droplet [43]. This, along with the contact angle and the distance between the two water droplets may have an effect on the water droplet deformation, hence affecting the creation of dry bands [75] and the number of dry bands created. Consequently the overall magnitude of the radiated energy pattern from dry-band arc discharge follows a similar trend as from corona discharge as seen in Figure 3.14.

Figure 3.14. Average Voltage Spectral Density for Corona and Dry-band arc discharges for frequency spectrum of 0 – 2.5GHz, for (a) different distances between electrodes (b) different volumes of water droplets
Figure 3.15. Average corona and dry-band arcing spectrum between two 0.4mL water droplets for different distances between electrodes (a) 1.5cm (b) 2cm (c) 2.5cm.
Figure 3.16. Average corona and dry-band arcing between two water droplets of different volumes for a constant distance (2cm) between electrodes (a) 0.2mL (b) 0.4mL (c) 0.6mL (d) 0.8mL.
Figure 3.15 and 3.16 show the frequency spectra for EM emission due to both corona and dry-band arc discharges when the distance between HV electrodes is changed, and variation in volume of the water droplet. As per Figure 3.15 and 3.16, there is a notable difference between the EM frequency spectrums for corona discharge and dry-band arcing for each of the electrode separation and droplet volume combinations. This variation can be clearly observed in the 750 – 1500MHz region. Of particular note is the region around 800 – 900MHz, where dry-band arc discharges show a higher amplitude of EM radiation as compared to corona discharge. The opposite scenario can be observed in the 1.25 – 1.4GHz band, where corona discharge emits higher EM radiation. This phenomena is examined in more detail in Figure 3.17 and 3.18, where the average voltage spectral density within these bands is portrayed. Sensing the radiated energy in these bands could potentially provide a non-contact method of discriminating between corona discharges and dry-band arcing on HV insulators.

Figure 3.17. Average Voltage Spectral Density for Corona and Dry-band arc discharges for different distances between electrodes (a) 800 – 900MHz (b) 1.25 – 1.4GHz.
Figure 3.18. Average Voltage Spectral Density for Corona and Dry-band arc discharges for different water droplet volumes (a) 800 – 900MHz (b) 1.25 – 1.4GHz.
3.5 Detection of Insulator Degradation due to Repetitive Corona and Dry-band arc Discharges

Repetitive corona and dry-band arc discharges cause damage to an insulator surface and reduces its hydrophobicity [76]. This has an impact on the contact angle and the footprint of the water droplet. An experimental investigation was conducted to analyse the relationship between EM radiation due to discharge activity, and the associated degradation of the surface of the insulator. Seven sets of corona and dry band arc discharge experiments were conducted at the same location on a nano-composite epoxy sample using two 0.4mL water droplets 2cm apart.

The radiated EM frequency spectra from the seven experimental stages are shown in Figure 3.19 and 3.20. For the first four stages, both corona and dry-band arc discharges have been observed whereas only dry-band arc discharges were observed from the 5\textsuperscript{th} to 7\textsuperscript{th} stages. The frequency spectrum for dry-band arc discharges for stages from 5 to 7 (Figure 3.20) remain similar to the dry-band arc discharge at the 4\textsuperscript{th} stage (Figure 3.19(d)). The absence of the corona discharge in these latter stages is due to the loss of hydrophobicity of the insulator surface. This creates water bridging between the two droplets even before the AC voltage is applied. As was seen previously, the most significant variation between EM signature for corona and dry-band arc discharge in Figure 3.19 can be observed between approximately 750MHz – 1500MHz.
Figure 3.19. Spectrum of Corona and Dry-band arc discharge at the same position on the insulator surface (a) 1st Stage (b) 2nd Stage (c) 3rd Stage (d) 4th Stage

**Average Corona Discharge**  **Average Dry-band arcing**
Figure 3.20. Spectrum of Dry-band arc discharge at the same position on the insulator surface  
(a) 5th Stage  
(b) 6th Stage  
(c) 7th Stage
The detected radiation for corona and dry-band arc discharges in 800 – 900MHz and 1.25 – 1.4GHz bands are shown in Figure 3.21. In the 800 – 900MHz frequency band of Figure 3.21(a), Stage 1 and 2 show higher average voltage spectral densities from dry-band arc discharge, while Stage 3 and 4 show a higher level from corona discharge. In the 1.25 – 1.4GHz frequency band of Figure 3.21(b), Stage 1, 2 and 4 show higher level of radiated energy for corona discharge while Stage 3 shows the opposite activity. This unpredictable pattern was caused by the erratic variation of the water droplet footprint and contact angles due to the loss of hydrophobicity, carbonization near the electrodes, and extensive damage to the insulator surface. The changes to the shape of water droplets is not uniform, as shown in the photographs in Figure 3.22 for Stages 2 and 4. These non-uniform changes to the water droplets are further demonstrated in Table 3.2, which displays approximate contact angles for the water droplets at each stage up to Stage 4 (after which the insulator material completely loses its hydrophobicity).
Figure 3.22. Shape of the two water droplets (a) 2nd Stage (b) 4th Stage

Table 3.2. Approximate contact angle of water droplets for different stages of condition of the insulator.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Approx. Contact Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energized Droplet</td>
</tr>
<tr>
<td>1st</td>
<td>71</td>
</tr>
<tr>
<td>2nd</td>
<td>21</td>
</tr>
<tr>
<td>3rd</td>
<td>51</td>
</tr>
<tr>
<td>4th</td>
<td>16</td>
</tr>
</tbody>
</table>

The voltage spectral density of dry-band arc discharge radiation in the 800 – 900MHz frequency band peaks at Stage 2, and then quickly decays, as seen in Figure 3.23. At Stages 5 – 7 where the material has entirely lost its hydrophobicity, a relatively constant voltage spectral density was detected from the dry-band arc discharges. The 1.25 – 1.4GHz band shows similar behaviour, albeit at a much lower magnitude. This peak at Stage 2 in 800 – 900MHz band, coupled with the fact that the dry-band arc discharge emissions drop lower than the corresponding corona levels at Stages 3 and 4 (seen in Figure 3.21(a)), could be used to assess the degradation in surface condition of the insulation material if continually monitored.
3.6 Summary

This chapter has discussed the variation in EM radiation due to corona discharge between two water droplets for various distances between water droplets, different volumes of water droplets, and water droplets sitting on different HV insulation surfaces. The discharge path varies due to changes in the electric field enhancement/distribution around the droplets, which is a function of the contact angle, distance and the applied electrical stress. This gives rise to modified EM radiation characteristics from the discharge.

Experimental analysis conducted in this chapter has indicated that for uniform water droplets, the transition from corona discharge to dry-band arc discharge can be identified by using EM sensing in the 800 – 900MHz and 1.25 – 1.4GHz bands. The average detected voltage spectral density was shown to be higher for dry-band arc discharges at 800 – 900MHz, whilst corona discharge exhibited stronger levels in the 1.25 – 1.4GHz band. This finding was observed to be independent of water droplet volume and separation for the experiments conducted.

Damage to the insulator surface caused by discharge activity was shown to cause the deformation of water droplets, primarily due to a reduction in hydrophobicity. For an extensively damaged surface it is difficult to observe the transition from corona discharge to dry-band arc discharge as the water droplets immediately wet the surface, eradicating corona.
However, it is notionally possible to monitor the degradation of the insulation surface by sensing the reduction of the voltage spectral density due to dry-band arc discharges in the 800–900MHz band, and detecting where it drops below the corresponding corona levels. All of these findings may be employed in a remote monitoring system which detects RF radiation to classify discharges and monitor the condition of HV insulators.
Chapter 4

Detection of contamination level of the insulator surface using electromagnetic radiation due to partial discharge

4.1 Introduction

Salt deposit pollution on the surface of high voltage insulators plays a major role in insulator failures in coastal areas [77-79]. Failure in one insulator may incite cascaded failure in adjacent insulators [80], and potentially cause significant damage to the electricity grid costing power companies millions of dollars. Hence simple and reliable detection of the salt deposit level of the pollution layer is vital to stave off insulator failures and increase the reliability of the power grid. Power companies have employed costly manual cleaning regimes to prevent these kinds of insulator failures [81]. A non-contact pollution monitoring technique that can identify insulator location with the potential to breakdown would allow targeted cleaning and/or recovery processes, and hence reduce maintenance costs.

Detection methods evaluating equivalent salt deposit density, non-soluble deposit density and surface resistance have been used to monitor the contamination level of high voltage (HV) insulators [82]. The use of the harmonic characteristics of leakage current and the time domain variation of the leakage current with the change of conductivity to monitor the contamination level of the HV insulator has been discussed [82-85]. A novel detection method which uses combination of VHF, leakage current and ultrasound sensors as well as pattern recognition to monitor the contamination level has also been proposed [86]. These methods require the insulator to be removed and tested inside a laboratory, and therefore are not capable of detecting a potential fault whilst the insulator is in service. Infra-red cameras and corona cameras [87] can detect in-service faults, however these methods require human interaction to operate. Fontana et al. proposed a real-time online contamination monitoring method which measures the leakage current using fiber-optic sensors [88]. In this method the fiber-optic sensors need to be attached to every insulator in the power pole. The relationship between insulator pollution, leakage current and variation in electric field distribution around a polluted insulator has been analysed using Finite Element and Boundary Element Method based simulation software [44, 45]. Habib et al. proposed a detection system which uses a Toroidal coil to monitor this variation in electric field distribution with respect to the leakage current for a polluted insulator [89]. These sensors also need to be attached directly to each insulator for testing. Hence both detection methods proposed by Fontana et al. and Habib et
al. are not practically feasible due to health and safety issues and the cost involved in attaching sensors to each insulator. For this reason, Power companies are reluctant to deploy directly attached sensors into the existing power grid. Therefore electromagnetic sensing can play an important role in high voltage fault detection as it is a non-contact, safe and cost effective sensing method.

VHF antennas have been employed as sensors to detect Partial Discharge (PD) detection. Stewart et al. detected and characterised PD on different HV insulators structures in the 0 – 60 MHz range [90]. Wong discussed physical fault detection inside ceramic insulators using PD activity in the 30 – 300 MHz band [31]. Anis et al. also proposed a detection system using an electromagnetic sensor to monitor the degree of pollution on the insulator [91]. The research used an EM sensor operating from 0.5 – 100 MHz, but mainly focussed on the detection system so did not have an extensive study on the radiated spectrum from PD activity.

The propagation of PD signals in un-insulated overhead power cables has been studied and a PD detection system based on EM sensors has been proposed in chapter 5 of this thesis. The realisation of small EM sensors can avoid implementation complications. Detection frequencies above 300 MHz can produce physically small EM sensor, hence the identification of EM radiation components from PD activity over wide frequency spectrum that exceeds 300 MHz is an important and unexplored step towards this goal. In chapter 3, the high frequency EM sensing has been previously investigated for analysing insulator degradation due to repetitive corona discharge between water droplets, and the detection of transition from water droplet corona discharge to dry-band arc discharge. However, the EM radiation from discharges due to the salt contamination level on a HV insulator surface has not been discussed before.

Insulator contamination can produce a creeping discharge on the surface of the insulator, which results in contamination flashover [92]. Creeping discharges have been studied by Kebbabi and Beroual using fractal analysis at solid/liquid interfaces, and examined the influence of the nature and geometry of solid insulators [93]. The experiments employed a point to plane discharge configuration, and the total length of all the branches of the creeping discharge was used as a metric to express the intensity of the discharge. The total length of the discharge reduced with the increase of the thickness of the insulator sample, and also varies with material properties (such as relative permittivity) and electric field strength. Beroual et al. investigated creeping discharge propagation over epoxy resin and glass insulators in the
presence of different gases and mixtures [94, 95]. The total length of the creeping discharge was shown to be proportional to the difference between the applied voltage and the threshold voltage to initiate the discharge. However a gap in the literature exists in determining variations in creeping discharge with the conductance of the polluted HV insulator surface.

This chapter investigates the relationship between the salt content of pollution on a HV insulator surface and the level of EM radiation from PD activity. This relationship has been linked to variations in creeping discharge length, the conductivity of the polluted surface and the breakdown voltage. The findings may be used as a technique to monitor the salt deposit level on epoxy insulators using the EM radiation level from PD.

4.2 Experimental Method

The electromagnetic radiation from five polluted nano-composite epoxy samples was evaluated using the experimental setup shown in Figure 4.1. The epoxy samples are supplied by EMC Pacific Pty Ltd and contain hydrophobic silica nano-filler, which is used for the commercial manufacture of Epoxy HV insulators. The composition of the hydrophobic silica nano-fillers and loading rate of the epoxy samples are the intellectual property of EMC Pacific [96]. The epoxy samples were polluted by spraying five different liquid contaminants, and then left to dry in the laboratory for two days before being used in the experiments. The five different liquid solutions used to pollute the epoxy samples were prepared according to IEC507 standards. The liquid solutions comprised of 1 L of tap water, 40 g of Kaolin, and salt concentrations from 0 g to 10 g (each with a difference of 2.5 g). The salt deposit level on the polluted surface has been shown to increase with a higher salt concentration in the solution sprayed on each sample [79]. The surface conductance was also measured for all samples.

Each polluted sample was tested for PD activity in seven different locations using two metal electrodes with a constant distance between them. Time domain radiation data was recorded twenty times for each test location using a wide band horn antenna and a Tektronix TDS5104 real time oscilloscope. Each individual set of data was then converted into the frequency domain using a Fast Fourier Transformation and averaged across all measurements on the polluted sample. This data acquisition and processing method was employed due to the stochastic nature of PD activity. The average voltage spectrum variation of the EM radiation for the 0 – 2.5 GHz band observed for different salt contamination levels was examined for frequency bands which show a clear increment in average voltage with salt contamination level, considering the standard error in the measurements.
The discharges on each sample were also photographed by a high speed video camera to observe variations in the creeping discharge with the salt content. This variation has been compared using the total of length of all branches in the observed creeping discharge [93, 95]. The length has been measured using the pixels associated with each branch and calculated in millimetres using image processing software.

4.3 Analysis of the Partial Discharge from polluted insulator samples

The conductance of the polluted surface has been measured to observe the variation in the conductance with the increase in salt level of pollutant mixture sprayed on each sample. As shown in Figure 4.2, the surface conductance increased with the increase of the salt content of the pollutant mixture. This increase in the conductance of the dry polluted surface will increase the capacitive leakage current [97].
Figure 4.2. Surface conductance verses salt concentration (g/L, 40g Kaolin) of the pollution layer

The experimental setup in Figure 4.1 was used to measure the electromagnetic radiation from discharges on the polluted epoxy insulator samples using the method described in section 4.2. A 12.5 kV and 10 kV AC voltage have been used as the excitation voltage for distances between electrodes (D) of 2.5 cm and 2 cm respectively, maintaining a constant field strength of 5kV/cm between the two electrodes. This was performed to determine the effect of electrode distance (D) on the EM radiation spectrum. The creeping discharge on the polluted insulator samples has been observed for both electrode distances (D), and an example of the still images for the electrode distance of 2.5 cm are shown in Figure 4.3.

Figure 4.3. Pictures of creeping discharge on the polluted surface for D of 2.5 cm and salt content of: (a) 0g (b) 5g (c) 10g
A minimal level of creeping discharge is seen in the polluted surface with 0g of salt in Figure 4.3(a). The creeping discharge observed for 5g of salt appears to have longer branches than that for 10g of salt, when comparing Figure 4.3 (b) and (c). However the discharge observed for 10g of salt has many more visible branches than for 5g of salt. Hence according to Figure 4.3, the number of visible branches of the discharge increased with higher salt content of the pollutant. The increase in the number of visible branches of the discharge has also been observed when D = 2 cm. The increase in number of branches results in an increase in the total length of the creeping discharge [93].

The approximate total discharge length at the two electrodes was measured for both electrode distances to observe the relationship between the salt content of the pollutant and the total discharge length. Figure 4.4 shows a logarithmic increase in the total discharge length with the increase in the salt content for both scenarios. It is also observed that for 10g of salt the total discharge lengths at energised and ground electrodes for electrode distance of 2 cm is only about 75% of that at the electrode distance of 2.5 cm. Hence it would be instructive to determine if the supply voltage is close to the breakdown voltage for the examined cases, and build a relationship between the creeping discharge length and the difference between the supplied voltage and the breakdown voltage.

As reported in previous studies the increase in the salt concentration of the pollution layer results in a reduction in the breakdown voltage, due to an increase in the leakage current [88, 98]. An increase in the conductance of the pollutant layer has been demonstrated in Figure 4.2, and the increase in the resultant leakage current should reduce the breakdown voltage [97]. The ratio between the test voltages used in this investigation and the average breakdown voltage has been plotted against the salt concentration in Figure 4.5. This will give a good understanding on how close the respective constant supply voltages are to the breakdown voltage for the different samples.
Figure 4.4. Approximate total length of the branches in the creeping discharge when the distance between electrodes is: (a) 2 cm (b) 2.5 cm
Figure 4.5. Ratio between the test voltage and the average breakdown voltage verses salt concentration (g/L, 40g Kaolin) for discharge lengths of 2 and 2.5 cm.

The ratio between average breakdown voltage and the test voltage increases from 0.81 to 0.89 for a discharge path length of 2 cm, and from 0.88 to 0.93 for a discharge path length of 2.5 cm for salt concentrations of 0 to 10 g. Overall, the supply voltage for the distance path length of 2.5 cm is much closer to the breakdown voltage. For both cases the constant supply voltage becomes closer to the breakdown voltage, due to the breakdown voltage reducing with increasing surface conductance. Hence increased PD activity is expected for a D of 2.5cm than for 2 cm.
Figure 4.6. Total length of the creeping discharge versus difference between breakdown voltage and supply voltage when ‘D’ is (a) 2 cm at supply voltage of 10 kV (b) 2.5 cm at supply voltage of 12.5 kV.
To understand the relationship between the observed creeping discharge and the breakdown voltage further, the total length of the creeping discharge versus the difference between breakdown voltage and the supply voltage has been plotted in Figure 4.6. The total length of the discharge ($L$) exponentially decays with an increased difference between breakdown ($V_B$) and supply voltages ($V_s$). The relationship can be demonstrated by equation (4-1), where ‘$A$’ and ‘$k$’ are constants which depend on the polarity of the electrodes and the distance between electrodes, as shown in Table 4.1.

$$L = Ae^{-k(V_B - V_s)}$$

(4-1)

**Table 4.1. Value of the constants used in equation (4-1)**

<table>
<thead>
<tr>
<th>Distance between electrodes (D)</th>
<th>Polarity of the Electrode</th>
<th>$A$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2cm</td>
<td>Energised</td>
<td>259.4</td>
<td>1.769</td>
</tr>
<tr>
<td></td>
<td>Grounded</td>
<td>180</td>
<td>1.725</td>
</tr>
<tr>
<td>2.5cm</td>
<td>Energised</td>
<td>276.76</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>Grounded</td>
<td>378.87</td>
<td>2.603</td>
</tr>
</tbody>
</table>

Furthermore, Figure 4.6 reiterates that the discharge length increases when the breakdown voltage gets closer to the supply voltage (12.5kV when D is 2.5cm and 10kV when D is 2cm) with the increase of the surface conductance. Flashover will initiate when the supply voltage is equal to the breakdown voltage (i.e. when $(V_B - V_s)$ is zero). Previous work has stated that strong PD activity can be observed when the supply voltage gets closer to the breakdown voltage [99, 100]. Thus it can be concluded that the strength of the PD activity, length of the creeping discharge and proximity of the breakdown voltage are related to each other. Stronger PD activity will cause an increase in the intensity of the EM radiation. Thus, the EM radiation due to PD activity on a polluted insulator surface is investigated as a means for evaluating the level of pollution.

**4.4 Partial Discharge radiation from polluted insulator samples**

Figure 4.7(a) depicts the average frequency spectra from 0 to 2.5 GHz for each of the five pollution cases. Whilst significant radiation levels were recorded at lower frequencies (particularly in the 0 – 200 MHz band), this investigation will focus on signal components
above 500MHz. At these higher frequencies, the physical size of the electromagnetic sensor required to detect the PD radiation is significantly smaller, which will reduce complications that may arise when deploying the sensor into existing power networks.

The 520 – 600MHz, 700 – 740MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz bands show clear increments of the average magnitude of the received radiation level across the range of salt concentrations of the pollutant. In Figure 4.7(b), the results between 520 – 600MHz are the focus and error bars depicting the standard error have been added. Reasonable separation between the extents of the error bars is observed for 0 g, 2.5 g, and 10 g of salt resulting in a high level of confidence in evaluating these concentration levels across this band. While the average voltage magnitude for the mid-level salt concentrations of 5 g and 7.5 g generally remain between the average magnitude for salt level of 2.5g and 10g, the error bars do show some overlap. Similar results were observed for the 1.53 – 1.57GHz band in Figure 4.7(c), with the error bars for the mid-level salt concentrations showing some overlap. Even though these overlaps occur, a reasonable gauge of the salt concentration can be determined particularly when higher levels are reached (i.e. closer to breakdown). Once again, the average voltage magnitude of the majority of the 1.53 – 1.57GHz spectrums for salt concentrations of 2.5 g, 5 g and 7.5 g lie between the average magnitude for 0g and 10g. It has been observed that the 700 – 740MHz, 860 – 890MHz and 1.09 – 1.11GHz bands show a similar magnitude of variation to the 1.53 – 1.57GHz band. It is also worth noting that while these broad frequency bands have been identified, the practical detection of EM radiation can be measured over a very narrow range where the increment level due to salt concentration is clear (e.g. 1.54 – 1.55GHz).

To clarify the relationship between salt concentration and EM radiation due to PD activity, the average voltage spectral density is shown in Figure 4.8 for the 520 – 600MHz, 700 – 740MHz, 860 – 890MHz, 1.09 – 1.1 GHz frequency and 1.53 – 1.57GHz bands. The average voltage spectral density displays an increasing trend with higher salt concentrations of the pollution layer. This trend can be used to monitor the level of pollution electromagnetically within the entirety (or sections of) the defined frequency bands to determine if the insulation is at risk of damage or failure.
Figure 4.7. Frequency spectrum variation with a change in the salt concentration of the pollution layer when the discharge path length is 2.5 cm.
(a) 0 – 2.5 GHz  (b) 520 – 600MHz  (c) 1.53 – 1.57 GHz
Figure 4.8. Average Voltage Spectral Density for the 520 – 600 MHz, 700 – 740 MHz, 860 – 890 MHz, 1.09 – 1.11 GHz and 1.53 – 1.57 GHz bands when the discharge path length is 2.5 cm.

As the radiation trends in Figure 4.8 have been analysed in specific frequency bands, it is important to determine whether the discharge path length (D) in the experimental setup defines the observed phenomena. Hence the experimental procedure was repeated with a discharge path length of 2 cm. A 10 kV AC supply was used as the excitation source to ensure the electric field strength between electrodes was 5 kV/cm, similar to the previous experiment.
Figure 4.9. Frequency spectrum variation with a change in the salt concentration of the pollution layer for a 2 cm discharge path length

The frequency spectrum from 0 to 2.5GHz given in Figure 4.9 for a 2 cm discharge path length exhibits minimal observable differences to Figure 4.7(a), particularly in the 500 – 1600 MHz band. The variation of average voltage spectral density for 520 – 600MHz, 700 – 740 MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz bands shown in Figure 4.10 when discharge path is 2 cm also shows approximately the same increasing trend that was seen in Figure 4.8. Hence it is apparent that these bands could be used to monitor the contamination level of the insulator surface independently of the discharge path length. The reason the EM radiation variation appears in the 520 – 600MHz, 700 – 740MHz, 860 – 890 MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz bands is yet be established, with extensive further research required to determine this due to the stochastic nature of the discharges. It is hypothesised that the defined bands could be related to the form of the creeping discharges on the polluted insulator surface.
The experiments in this chapter have shown the variations in salt concentration of the pollution layer on nano-composite epoxy insulator samples can be electromagnetically monitored using radiation measure in part or all of the 520 – 600MHz, 700 – 740MHz, 860 – 890 MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz frequency bands. A link between the pollutant salt concentration, breakdown voltage, surface conductance and the magnitude of the electromagnetic radiation has been identified. Further research is needed to establish why the variations in EM radiation occur only for specific frequency bands for the discharge paths and creeping discharges observed. It is conceivable that an electromagnetic sensor designed to detect radiation within the highlighted frequency bands could be used to monitor the salt contamination level of the pollution layer on the surface of high voltage insulators and provide an early warning of impending breakdown.

**4.5 Summary**

The experiments in this chapter have shown the variations in salt concentration of the pollution layer on nano-composite epoxy insulator samples can be electromagnetically monitored using radiation measure in part or all of the 520 – 600MHz, 700 – 740MHz, 860 – 890 MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz frequency bands. A link between the pollutant salt concentration, breakdown voltage, surface conductance and the magnitude of the electromagnetic radiation has been identified. Further research is needed to establish why the variations in EM radiation occur only for specific frequency bands for the discharge paths and creeping discharges observed. It is conceivable that an electromagnetic sensor designed to detect radiation within the highlighted frequency bands could be used to monitor the salt contamination level of the pollution layer on the surface of high voltage insulators and provide an early warning of impending breakdown.
Chapter 5

Partial Discharge transmission, detection and localisation on uninsulated power distribution lines

5.1 Introduction

The electrical industry has implemented preventative measures to avoid damage due to electrical discharges by using new epoxy insulator materials that can handle the stress from partial discharge, and by quality controlling insulator manufacturing. However, existing infrastructure using outdated insulator technology still presents a problem. A real time PD detection mechanism which can detect and locate discharges in their early stages is essential in the prevention of catastrophic failure in power networks.

As discussed in previous chapters, the Electromagnetic (EM) radiation due to PD activity is present in UHF region. The UHF spectral components generated by PD activity is currently used to detect and locate faults in HV transformers and Gas Insulated Substations [14, 101, 102]. While UHF couplers have been widely used in these scenarios, Electromagnetic (EM) sensors have rarely been used in the detection and location of faulty HV distribution line insulators.

The Rogowski Coil is a commonly used sensor for various detection techniques. It has been widely used in detecting faults from XLPE cables [25, 27, 103, 104], and it has also been used in PD localization systems [25]. However it is impractical and hazardous to use a Rogowski Coil to detect PD pulses from bare Aluminium un-insulated cables since direct attachment of the sensors is required. The Rogowski coil is also incapable of detecting frequency components in the UHF band. Therefore it is important to look at the possibility of using EM sensors for PD detection and localization in bare cable distribution systems, and examine how the PD pulses traverse around the network.

This chapter begins with a theoretical examination of PD pulse propagation along Aluminium overhead power line conductors. Numerical simulation is used to obtain the attenuation of these lines at high frequencies. An investigation into the EM radiation from the power line due to PD pulse propagation is then undertaken using Single Wire Earth Return and three phase overhead power lines configurations. The emission frequency findings presented in the
previous four chapters for different discharge types are incorporated into the discussion of radiation properties. Finally, the ultimate target of this research, an EM based PD detection and localisation system for overhead power lines, is presented as a proof of concept demonstrator.

5.2 PD pulse propagation on uninsulated power distribution cables

The critical performance criteria for HV cable sensing systems are: PD pulse propagation, attenuation of particular frequency components, and radiation from the cable into the far field. XLPE cables are covered conductors that are widely used in the HV industry, and have been extensively evaluated in terms of PD pulse propagation. It has been shown that the XLPE cable displays significant attenuation at high frequencies due to its insulation layer [48, 49], and that its core has less contribution towards the attenuation than the insulation layer [49]. However, PD pulse propagation along un-insulated Aluminium cables used in overhead power distribution lines has not been investigated before. This section investigates PD pulse propagation along un-insulated Aluminium cables (AS 1531 Conductors) [105], which are primarily used in 11 kV power distribution systems. The propagation is assessed in terms of the ability of the cable to be used as part of a detached EM radiation detection and localization system for faulty HV insulators in distribution networks. Due to practical limitations, a simulation model has been used to investigate the PD pulse propagation.

5.2.1 Simulation Technique

The propagation and radiation from a single wire earth return (SWER) cable at 100 kHz has previously been investigated using a theoretical model created in MATLAB [106]. ATP and EMTP simulations employing a quasi-static approximation using Carson and Polaczeck theory has shown PD pulse propagation along an XLPE cable [27, 107, 108]. This theory assumes that the height of the cable is significantly small compared to the wavelength at the frequency used for simulation [20]. Fundamental antenna theory and Maxwell’s equations can be used to reduce inaccuracies associated with high frequency simulations [20]. 3D simulations based on the Finite Element Method (FEM) and the Finite Integral Technique (FIT) (which applies Maxwell equations) can be used in these situations, since they enable the simulation of the real physical cable or system.

The Finite Integral Technique uses the integral form of Maxwell’s equation rather than their discrete forms. This can be used for the numerical simulation of various electromagnetic
problems ranging from static field calculations to high frequency scenarios in either time or frequency domain [109]. CST Microwave studio is a commercial software package that uses FIT in combination with the Perfect Boundary Approximation (PBA) to yield a high accuracy. Unlike FEM based software it is capable of simulating electrically large structures in the time domain, which is more computationally efficient than using the frequency domain [110]. However, significant computer resources are still required to accurately evaluate large (in terms of a wavelength) problems.

5.2.2 Simulation Setup

A typical PD emission can be approximated numerically by a Gaussian pulse [111]. A Gaussian pulse with centre frequency of 1.25GHz, bandwidth of 2.5GHz and amplitude of 1 V has been used as the excitation source for the following simulations. The cable structure simulated in CST is shown in Figure 5.1. A 5 m long un-shielded Aluminium overhead distribution cable resides 10 m above a ground plane made of dry soil. To minimise the effect of reflection, perfectly matched layer (PML) boundaries were employed at the edges of the simulation cell. Voltage monitors are located at every meter along the length of the cable, including one at the source. A discrete port has been used to excite the cable, connected via a 50 Ω resistor to minimize impedance mismatch.

Figure 5.1. Overhead distribution cable structure for the pulse propagation simulation
5.2.3 Investigation on PD pulse propagation

Figure 5.2 shows the signal recorded at each of the voltage monitors along the length of the 5 m cable. The voltage monitor at 0 m shows the input pulse after transition though the discrete port. This is assumed to be the reference level at the input to the cable. As the pulse traverses along the cable, the amplitude drops slightly, and the tail of the pulse exhibits minor distortion due to the frequency dependant characteristics of the cable.

A Discrete Fourier Transformation (DFT) was performed in MATLAB to analyse the Power Spectral Density (PSD) of the signal observed at each voltage monitor. This was used to determine the attenuation verses frequency, the results of which are shown in Figure 5.3. It has been shown that XLPE cables have considerable attenuation at high frequencies due to the surrounding dielectric layer [48, 49], a typical value being 2 dB/m at 1GHz. The simulation results in Figure 5.3 for bare Aluminium cables show a significantly lower level of attenuation. At 2.5GHz, a very low attenuation of 0.14 dB/m is observed.

![Figure 5.2. Pulse propagation along an un-insulated cable from 0 m to 5 m](image)

Figure 5.2. Pulse propagation along an un-insulated cable from 0 m to 5 m
It can be deduced using antenna theory [112] that the radiation loss from the power line is very low, and is only a minor contributor to the total power loss [106, 113]. Hence we can assume that the power loss (attenuation) occurring in this Aluminium cable is mainly due to ohmic loss.

\[
R_{\text{loss}} = \frac{\sqrt{\pi \mu_0}}{\sigma} \frac{l}{2 \pi (a - \delta/2)} \tag{5-1}
\]

where \(\delta = \frac{1}{\sqrt{\pi \mu_0 \sigma}}\) \tag{5-2}

Equation (1) shows the loss resistance due to conductor loss. In (5-1) and (5-2), \(\delta\) is the skin depth, ‘a’ is the cable radius, \(\sigma\) is the conductivity, ‘\(l\)’ is the length of the cable under test, ‘\(f\)’ is frequency in Hz and \(\mu_0\) is the permeability of free space. \(R_{\text{loss}}\) is plotted in Figure 5.4 as a function of frequency. The loss resistance at 2.5GHz reaches approximately 0.15 \(\Omega/m\). Therefore, the power dissipation due to ohmic loss is very low, and the attenuation values obtained from the simulations are justified.
The wave propagation along a power line has been discussed previously [20, 114], along with UHF and VHF radiation from insulators [14, 31, 101, 102]. However there has been minimal discussion on the electromagnetic radiation pattern exhibited by a PD signal travelling along a HV cable. It has been demonstrated in earlier chapters that there is a significant level of radiated energy due to PD, which can be detected in the VHF and UHF regions. Earlier simulation works show that the radiation from an insulator generating PD displays an omni-directional radiation pattern [56, 115], and that the energy from the PD activity is enough to excite the power cable.

The simulated power cable structure excited by a PD pulse shown in Figure 5.1 exhibits distinctive travelling wave radiation patterns at different frequencies. Figure 5.5 displays these patterns at various frequencies. The radiation patterns in Figure 5.5(b)-(f) all display a travelling wave shape [112] since the cable’s electrical length of 5 m is equal or longer than one wavelength at that particular frequency. Figure 5.5(a) does not show the travelling wave radiation pattern since the cable’s electrical length is 0.33 wavelengths at 20MHz. This is an artefact of the limited simulation size, as a travelling wave radiation pattern would result if the
simulated cable length was extended to 15m (or greater), which is a full wavelength at 20MHz.

A long wire antenna is a straight wire or cable with the length of one or more wavelengths [112]. It is an elementary antenna which has been used in short wave transmissions for a very long time. Long wire antennas exhibit a travelling wave radiation pattern. Hence, uninsulated Single Wire Earth Return (SWER) distribution cables can be classified as long wire antennas when the cable length is in excess of a wavelength at a particular frequency.

Directivity is a measure of how well an antenna emits or receives radiation in a particular spatial direction. The directivity of the un-insulated power cable in the direction of the main radiation lobe rises as frequency increases, as shown in Table 5.1. Therefore higher frequency components of the propagating PD signal will show more significant radiation in a particular direction than lower frequency components. The angle between the cable direction and the maximum of the radiation pattern main lobe reduces with the incrementing frequency component. Hence it can be concluded that a judiciously placed EM sensor can be used to efficiently detect radiated high frequency components universal to PD.

Table 5.1. Directivity and main lobe direction for various frequencies (dBi = Directivity in dB relative to isotropic radiator)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Electrical length of the 5m long cable</th>
<th>Directivity (dBi)</th>
<th>Direction of the Main lobe from the main cable (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.33λ</td>
<td>-9.9</td>
<td>72</td>
</tr>
<tr>
<td>60</td>
<td>1λ</td>
<td>-2.6</td>
<td>47</td>
</tr>
<tr>
<td>100</td>
<td>1.67λ</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>400</td>
<td>6.67λ</td>
<td>6.1</td>
<td>19</td>
</tr>
<tr>
<td>900</td>
<td>15λ</td>
<td>9.1</td>
<td>12</td>
</tr>
<tr>
<td>1100</td>
<td>18.33λ</td>
<td>9.9</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 5.5. Radiation patterns in the x-z plane from a single un-insulated power cable at various frequencies (relative cable lengths) (a) 20MHz (0.33 wavelengths) (b) 60MHz (1 wavelength) (c) 100MHz (1.67 Wavelengths) (d) 400MHz (6.67 Wavelengths) (e) 900MHz (15 Wavelengths) (f) 1.1GHz (18.33 Wavelengths)
5.4 Electromagnetic Radiation from typical electrical discharges

In Chapter 2 the PD activity due to cavity discharge shows dominant radiation in the 840 – 1120MHz band for Perspex samples and 760 – 1120MHz for Epoxy nano-composite samples. Chapter 3 concludes that the 800 – 900MHz and 1.25 – 1.4GHz bands can be used to detect the transition from corona to dry-band arc discharge. In Chapter 4, analysis of the EM radiation due to partial discharge in 520 – 600MHz, 700 – 740MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz bands can be effectively used as an indicator of the contamination level on the insulator surface. Therefore the four different types of PD discharges discussed in this thesis show EM radiation activity in different bands inside 760 – 1570MHz frequency range. Referring to Table 5.1, the antenna directivity in these bands is above 8dBi for a signal travelling along an un-insulated power cable, hence assisting detection. Therefore these bands have high capability of detecting PD activity using EM sensing.

5.5 EM Radiation from an 11 kV three phase cable system

Section 5.3 primarily discusses the radiation activity of a single un-insulated power cable due to PD pulse propagation. Distribution networks are predominantly three phase systems, and hence the investigation of signal propagation and coupling in a three cable architecture is important. Power distribution system cables are spaced apart from each other in order to minimize the interference from the electric fields of a propagating 50Hz AC signal.

![Figure 5.6](image)

*Figure 5.6. Simulation configuration of a three cable system with the middle cable excited.*
Figure 5.7. Measured pulses at the end of each of the three HV cables (a) Pulse measured at the end of the middle cable (Cable connected to the PD source) (b) Pulse measured at the end of the left cable (c) Pulse measured at the end of the right cable
The coupling between adjacent cables at higher frequencies resulting from propagating discharges is examined using the CST simulation setup shown in Figure 5.6. Three 5 m long Aluminium cables are separated by a distance of 60 cm, which is a standard spacing for 11 kV overhead power distribution. The central cable has been excited by a Gaussian pulse, emulating an insulator fault on the middle cable. Voltage monitors are used to measure the propagating signal in each cable.

The voltage signals detected at the end of each of the three cables are given in Figure 5.7. The induced pulses measured on the left and right cables are around 20 times smaller than the pulse measured from the middle cable, which had the directly connected input pulse. The speed of PD pulse propagation along a bare conductor is equal to the speed of light. Therefore the PD pulse takes approximately 17ns to travel 5m along the middle cable as shown in Figure 5.7(a). Pulses monitored at the end of neighbouring cables have shown approximately 1-2ns of extra delay compared to the pulse observed at the end of the middle cable. This is most likely due to the time require for the pulse to couple to and excite the neighbouring cables. The pulse shape has changed considerably, indicating that the coupling is frequency dependant. For a PD detection system employing RF sensors, the effect these adjacent cables have on the radiation pattern of a propagating pulse is of primary concern.

Table 5.2. Directivity and main lobe angle comparison for single and three cable configurations (dBi = Directivity in dB relative to isotropic radiator)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Directivity (dBi)</th>
<th>Direction of the main lobe From Cable (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single cable system</td>
<td>Three cable system</td>
</tr>
<tr>
<td>550</td>
<td>7.25</td>
<td>7.67</td>
</tr>
<tr>
<td>800</td>
<td>8.56</td>
<td>9.69</td>
</tr>
<tr>
<td>900</td>
<td>9.1</td>
<td>10.37</td>
</tr>
<tr>
<td>1100</td>
<td>9.8</td>
<td>11.13</td>
</tr>
</tbody>
</table>
The radiation patterns displayed in Figures 5.8 – 5.11 compare the single and three cable systems at 550MHz, 800MHz, 900MHz and 1.1GHz in all three primary planes. As discussed in Section 5.4, 550MHz, 800MHz, 900MHz and 1.1GHz are in the detectable radiation bands for the different types of partial discharges explored in previous chapters. The radiation patterns for the three phase cable system still display the basic travelling wave shape. Distortion of the three cable system pattern is seen in the y-z plane due to the presence of the adjacent cables. A slight variation in the directivity on the main radiation lobe is also evident.

This slight directivity variation is quantified in Table 5.2. The directivity of the three cable system is about 0.42dB – 1.33 dB higher than single cable system. This could be due to the induced pulse on the outer cables causing each cable to act as an individual element of a non-uniform array [119] resulting in increased directivity, or simply by the pattern shaping caused by the cables in the y-z plane. Table 5.2 also shows that the direction of the main lobe has been increased by about 1 degree for the 3 cable system. Overall, the direction of the main lobe is relatively unaffected by the adjacent cables. Therefore, the antenna orientation for an EM sensing system can remain at a set inclination for both single cable and three cable systems.
Figure 5.8. Radiation pattern comparison for single line cable configuration and three cable configuration at 550MHz
Figure 5.9. Radiation pattern comparison for single line cable configuration and three cable configuration at 800MHz
Figure 5.10. Radiation pattern comparison for single line cable configuration and three cable configuration at 900MHz.
Figure 5.11. Radiation pattern comparison for single line cable configuration and three cable configuration at 1.1GHz.
5.6 Detection and localisation of Partial Discharge activity

The simulations in the preceding sections indicate the possibility of partial discharge detection by sensing the radiation from the HV cable. This section will discuss an initial practical methodology of partial discharge detection and localisation that has been implemented on live power distribution lines.

A representation of the PD detection system using RF sensing is shown in Figure 5.12. A PD pulse from a faulty insulator propagates along a bare Aluminium cable, radiating energy in a specific pattern at each frequency. With an understanding of the propagation and radiation behaviour of these cables, sensing antennas can be used to receive and monitor radiation at given angles for a particular frequency. If a PD signature is detected by more than one of these monitoring stations, a localization algorithm can determine the exact position of the faulty insulator.

![Figure 5.12. The EM sensing architecture](image)

5.6.1 Partial discharge detection and localization system

The PD monitoring station shown in Figure 5.13 consists of an EM sensor, a GPS unit, a Data Acquisition Unit and a computer. The EM sensor is placed 1m below the power line. The signal received by the EM sensor will be collected by the Data Acquisition unit. The background noise of the location has been measured before the installation of the unit. A
threshold level is set higher than the background noise level so the data acquisition unit can avoid false readings. The GPS Unit has been connected to the DAQ unit to time stamp the data collected when there is PD activity. A personal computer stores the entire set of data collected by the DAQ and GPS units.

![Block diagram of partial discharge monitoring station](image)

**Figure 5.13. Block diagram of partial discharge monitoring station**

Multiple monitoring stations are spaced an equal distance apart from each other along a stretch of power distribution line. The time stamped data from each monitoring station is analysed, and a Time of Arrival (TOA) [25] technique is applied to estimate the location of the fault. The estimated location using TOA has shown an error of 0.67% during the field trials (Section 5.6.2). The ideal distance between each monitoring station is dependent on the configuration of the line section to be analysed, and further trials are required to determine this.

### 5.6.2 Field trials with SP AusNet and results.

Several trial sites were selected by the Asset Innovation and Research Division at SP AusNet to study and verify the performance and capability of the PD detection system. These sites include a 300 m long 11 kV overhead Aerial Bundle Conductor (ABC) line at Kallista, Australia, and a 21.3 km long 22 kV overhead line between Venus Bay/Inverloch, Australia.

An initial trial was carried out in Kallista, Australia. The aim of this trial was to isolate the fault location within the 300 m long ABC line provided by SP AusNet, and verify the functionality of the system. This 300 m long section is known to SP Ausnet as an area with
possible high risk of fault due to PD activity. Two monitoring stations and sensor setups were used as seen in Figure 5.14. In order to determine the influence of weather on PD activity, two weather stations were also installed at both monitoring station locations to monitor weather patterns during the trial period. Faults recorded using the EM sensors over the trial period were downloaded from the PC in the monitoring station to a laptop via a wireless link. This data was manually post-processed to calculate the fault location using TOA. Post-processing includes GPS time stamp matching and data filtering/sorting. This trial was carried out between 20th September 2010 and 5th October 2010.

Figure 5.14. Pictures of the field trial at Kallista trial site (a) PD monitoring system under test for Aerial Bundled Cable (ABC) system (b) Sensor configuration

One hundred faults were identified during the trial period, and each fault location with reference Monitoring Station 1 is plotted in Figure 5.15. The majority of the faults were detected within the area located 100 m – 150 m distance away from the Monitoring Station 1. It was observed that this area has a significant level of fungus built up on the lines and insulators due to the wet environment. An average of 0.3mm/min of rain intensity was also recorded on most of the days during the trial period. Hence it is likely that the PD activity observed was due to the partial arc generated on the cable caused by a combination of wet weather and fungus. This theory is consolidated by the absence of PD activity in the 0 – 90 m region of the line where there was no visible fungus build up on the cable.
Figure 5.15. Fault location calculated for the Kallista Trial

A subsequent trial was conducted at the Venus Bay-Inverloch site (Figure 5.16). The pole-mounted monitoring stations were installed in two locations 21.3 km apart as depicted in Figure 5.17. The same data storing and analysis method used in Kallista trial has been used in this trial, in order to locate the fault. This trial was carried out from 28th October 2010 to 20th November 2010.

Figure 5.16. Venus Bay – Inverloch Trial site
The fault location map in Figure 5.18 shows that 18 faults were recorded on the right hand side cable, while 1 and 2 faults were recorded from middle and left hand side cables respectively. The number of faults recorded in this trial was significantly lower than the previous trial at Kallista. A relatively dry climate and no fungus build up were observed along the Venus Bay – Inverloch trial line. The rain intensity at Venus Bay – Inverloch trial site was also recorded, and was typically between 0 and 0.1mm/min, compared to an average of 0.3mm/min at Kallista. As shown in Table 5.3, the faults recorded during this trial mainly occurred between 1 am and 8 am. This could be caused by partial arcing across insulators generated due to the combination of the morning sea breeze or dew, excessive moisture on insulators, and high salt content (due to the coastal location). The right hand side cable has shown significant level of PD activity when compared to the other two cables, potentially due to a higher level of salt content or moisture on these insulators. The minimal number of faults and scattered fault locations suggest that these arcing activities are highly random, and therefore no particular high risk fault location could be identified. Further trials are currently underway in Kallista, on a 1.6 km long section of ABC distribution line.
Figure 5.18. Fault location calculated for Venus Bay – Inverloch Trial

Table 5.3. Fault locations with date and time of occurrence and rain intensity

<table>
<thead>
<tr>
<th>Sensor position</th>
<th>Fault Location (km)</th>
<th>Date</th>
<th>Time</th>
<th>Rain Intensity (mm/min)</th>
<th>Possible Reason for the Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor for the left hand side cable</td>
<td>1.69</td>
<td>30/10/2010</td>
<td>09:20:21</td>
<td>0.5</td>
<td>Rain just before the fault</td>
</tr>
<tr>
<td></td>
<td>6.75</td>
<td>30/10/2010</td>
<td>09:25:31</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.92</td>
<td>02/11/2010</td>
<td>09:07:30</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td>Sensor for the middle cable</td>
<td>15.99</td>
<td>31/10/2010</td>
<td>06:52:56</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.59</td>
<td>30/10/2010</td>
<td>08:39:19</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.48</td>
<td>30/10/2010</td>
<td>08:40:11</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.95</td>
<td>30/10/2010</td>
<td>09:02:39</td>
<td>0.1</td>
<td>Due to rain intensity of 0.1 recorded at 08:56:01</td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>30/10/2010</td>
<td>01:34:31</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>8.82</td>
<td>30/10/2010</td>
<td>04:40:16</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>17.43</td>
<td>30/10/2010</td>
<td>04:40:17</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>6.13</td>
<td>30/10/2010</td>
<td>05:03:16</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>14.08</td>
<td>30/10/2010</td>
<td>10:48:54</td>
<td>0.2</td>
<td>Due to rain intensity of 0.2 recorded at 09:25:25</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>31/10/2010</td>
<td>01:54:24</td>
<td>0.1</td>
<td>Due to rain intensity of 0.1 recorded at 01:01:38</td>
</tr>
<tr>
<td></td>
<td>9.46</td>
<td>31/10/2010</td>
<td>02:30:06</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>5.96</td>
<td>31/10/2010</td>
<td>03:45:09</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>6.48</td>
<td>31/10/2010</td>
<td>04:40:59</td>
<td>0.1</td>
<td>Due to rain intensity of 0.1 recorded at 04:00:05</td>
</tr>
<tr>
<td></td>
<td>4.03</td>
<td>31/10/2010</td>
<td>08:55:00</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>17.35</td>
<td>31/10/2010</td>
<td>08:55:06</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>07/11/2010</td>
<td>04:41:48</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>10.69</td>
<td>07/11/2010</td>
<td>06:28:32</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>12.32</td>
<td>11/11/2010</td>
<td>01:06:31</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>14.25</td>
<td>13/11/2010</td>
<td>12:38:49</td>
<td>0.1</td>
<td>Likely due to morning dew</td>
</tr>
<tr>
<td></td>
<td>4.97</td>
<td>13/11/2010</td>
<td>01:13:34</td>
<td>0.1</td>
<td>Due to rain intensity of 0.1 recorded at 00:54:27</td>
</tr>
</tbody>
</table>
5.7 Summary

A simulation and discussion of the propagation and radiation behaviour of PD on un-insulated overhead distribution lines has been presented in this chapter. Bare Aluminium overhead cables show very low attenuation levels, even at GHz frequencies. Hence high frequency components of a PD signal will travel for a significant distance along a cable, allowing for remote detection.

The radiation patterns for the high frequency components of PD propagating on single wire and three phase systems have also been investigated. Travelling wave radiation patterns analogous to a long wire antenna were observed. High directivity values were recorded at 550MHz, 700MHz, 800MHz, 900MHz and 1.1GHz, which are in the high radiation bands for different PD types. Knowledge of the changing directivity and direction of main lobe radiation with frequency can be used to efficiently configure the orientation of an EM sensor in a PD detection and localisation system.

This chapter has also described the collected results and findings from field trials conducted with a pilot PD detection and localisation system. These trials have demonstrated the success of the PD monitoring system in identifying faults at heavily contaminated areas of line, as well as random events. System improvements such as the miniaturisation of the monitoring station, tailoring of the EM sensor, automation of localisation and communication of data/events are currently being developed to commercialise the PD detection and localisation system.
Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis has discussed EM radiation from four types of common partial discharge activities which can be observed on overhead power line infrastructure, PD pulse propagation and radiation along overhead power lines, and detection and localisation of PD activity by sensing power line radiation due to PD activity. The understanding gained from this research on EM radiation due to PD activity can be used to design an EM sensor for a cost effective PD detection and localisation system for overhead power lines.

Chapter 2 analysed the EM radiation from cavity discharges using Perspex and Epoxy nano-composite samples. Cavity discharges in Perspex exhibited EM radiation significantly above the noise level in the 10 – 170MHz and 760 – 1120MHz bands. For Epoxy nano-composite insulators the voltage spectra from 30 – 140MHz and 840 – 1120MHz displayed heightened levels during cavity discharge. The average voltage spectral density in these band exhibited escalation as more cavities were introduced in the tested samples. A PD detector was used to measure the charge level of the cavity discharges, which showed a logarithmic increasing trend. The average voltage spectral density measured from the resulting EM radiation for both insulator types also showed a logarithmic increasing trend. These results indicate that the increase in the level of cavity discharge activity in Epoxy and Perspex insulators can potentially be monitored by a non-contact EM sensor working in the UHF band. For the specific samples analysed, the monitored bands of 840 – 1120MHz for Epoxy nano-composite insulators and 760 – 1120MHz for Perspex can be used (in part or in full).

Chapter 3 examined the EM radiation generated by corona and dry-band arc discharges. This chapter discussed variation in EM radiation due to corona discharge with the change of contact angle and distance between two water droplets, and also with different high voltage insulator materials. The experimental analysis conducted in this chapter indicated that for uniform water droplets, the transition from corona discharge to dry-band arc discharge can be identified using RF sensing in the 800 – 900MHz and 1.25 – 1.4GHz bands. The average detected voltage spectral density was shown to be higher for dry-band arc discharges at 800 – 900MHz, whilst corona discharge exhibited stronger levels in the 1.25 – 1.4GHz band. This
finding was observed to be independent of water droplet volume and separation for the experiments conducted.

It was also shown in Chapter 3 that damage to the insulator surface caused by discharge activity caused the deformation of water droplets, primarily due to a reduction in hydrophobicity. For an extensively damaged surface it is difficult to observe the transition from corona discharge to dry-band arc discharge as the water droplets immediately wet the surface, eradicating corona. However, the results showed it is possible to monitor the degradation of the insulation surface by sensing the reduction of the voltage spectral density due to dry-band arc discharges in the 800 – 900MHz band, and identifying where it drops below the corresponding corona levels.

Chapter 4 discussed the variation in EM radiation due to partial discharge activity with the increase in the conductivity of polluted high voltage insulators. This chapter identified frequency bands which can be used to detect the pollution level of insulators efficiently. Hence, a new method of detection of insulator pollution level using EM radiation from partial discharge activity was proposed. The experiments in this chapter demonstrated that variations in the salt concentration of the pollution layer on nano-composite epoxy insulator samples can be electromagnetically monitored using EM radiation measured in part or all of the 520 – 600MHz, 700 – 740MHz, 860 – 890MHz, 1.09 – 1.11GHz and 1.53 – 1.57GHz frequency bands. A link was established between the pollutant salt concentration, breakdown voltage, surface conductance and the magnitude of the electromagnetic radiation.

Chapter 5 presented partial discharge transmission, detection and localisation on uninsulated overhead power distribution lines. A simulation and discussion of the propagation and radiation behaviour of PD on un-insulated overhead distribution lines had shown that the bare Aluminium overhead cables show very low attenuation levels, even at GHz frequencies. Hence high frequency components of a PD signal will travel for a significant distance along a cable, allowing for remote detection.

The radiation patterns for the high frequency components of PD propagating on single wire and three phase systems was also investigated. Travelling wave radiation patterns analogous to a long wire antenna were observed. High directivity values were recorded at 550MHz, 700MHz, 800MHz, 900MHz and 1.1GHz, which were in the high radiation bands identified in the previous chapters for the various different PD types. Knowledge of the changing
directivity and direction of main lobe radiation with frequency can be used to efficiently configure the orientation of an EM sensor in a PD detection and localisation system.

This chapter has also described the results and findings from field trials conducted with a pilot PD detection and localisation system. These trials have demonstrated the success of the PD monitoring system in identifying faults on heavily contaminated areas of line, as well as random events.

6.2 Future work

This thesis discussed the EM frequency spectrum for four common types of partial discharge. However the EM spectrum observed for different types of discharges often displayed different EM signatures. The root cause of this variation in EM signature requires further investigation, and a few topics for future research are explained below.

- Cavity discharge is often hard to observe since it occurs inside insulators. Discharges cause electron movement inside the cavity [116, 117]. This electron movement may have an influence on the frequency spectrum of the EM radiation resulting from cavity discharges. The relationship between electron movement inside the cavity and frequency spectrum of the EM radiation is a potential area of future research.

- The relationship between EM radiation from corona discharges and the shape of the water droplet was discussed in Chapter 3. Traceable variations in the voltage spectral density of the EM radiation were observed in specific frequency bands. However, the discharge path in the experiments varied with the contact angle of the water droplets. The relationship between discharge path and EM spectrum variation observed in the defined frequency bands has not been fully established. Further exploration into this relationship would provide a deeper understanding of the generation of EM radiation due to corona discharge and to improve early detection mechanisms for insulator failures.

- The radiated frequency spectrum observed from creeping discharge on polluted insulator surfaces was presented in Chapter 4. Variation in the salt content of the polluted surface can be observed by monitoring the voltage spectral density in specific frequency bands. The nature of the EM spectra could be related to the branching observed in the photographs of creeping discharge. The creation mechanisms for
creeping discharge have been discussed by various researchers in the field of plasma physics. However, the relationship between the creeping discharge mechanisms and branch lengths and the resulting EM radiation need to be established in future work.

- The investigation discussed in Chapter 4 has been conducted only for a single composition of Epoxy nano-composite samples, which contains a silicon nano-filler with the same loading rate used in commercial products by EMC Pacific Pty Ltd. The investigation could be extended to incorporate different nano-composite insulation samples which contain different types of nano-fillers, as well as different loading rates. The relationship between the type of nano-filler and its loading rate can then be correlated to the EM radiation signatures of creeping discharge to broaden the impact of this study.

A key aim of this research was to design a successful PD detection and localisation system for overhead powerlines which can be used commercially. The PD detection and localisation system presented in this thesis is a prototype and currently in the testing phase. The following improvements can be made to the PD detection and localisation system to make it more commercially feasible.

- Designing and implement a more efficient EM sensor – The knowledge gained from this thesis on the radiated frequency spectrum for different types of PD and power line transmission/radiation due to PD activity can be used to set specifications for this EM sensor. However further development and testing is needed in order to optimise the sensor design.

- Sensitivity of the early warning system – False triggering is one of the reasons for failures in real time PD detection systems and reduce the sensitivity of the system. Hence it is important to investigate methods to eliminate possible causes of false triggering in the system. A better understanding on the relationship between PD inception mechanisms and the resulting EM radiation could be used to improve the sensitivity of the system. As explained before, this relationship needs to be investigated in future research.
● Automation of localisation – The results shown in Chapter 5 are obtained using time consuming manual data analysis. Automation of the data analysis process is required in order to make the system financially viable.

● Effective method of communicating collected data/events – The current PD detection and localisation system employs a wireless 3G internet connection for data collection and remote control of the system. However, consistent downtime in the wireless 3G network meant it was impossible to remotely control the system in areas where the wireless 3G coverage is weak. Hence further work is needed to provide a reliable communication method.

● Miniaturisation of the monitoring station – The current prototype consists of oscilloscope and a desktop computer enclosed in a commercial HV pole mounted enclosure. This system weighs over 20kg. The weight of the system can be reduced through the miniaturisation of the system and will ease the deployment of the system. Therefore possible methods of miniaturisation are required.
Bibliography


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