Leakage Current in Wooden Structures Used for Power Distribution

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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March 2011
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; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Sachin Pathak

March 2011
Acknowledgements

I would like to express my gratitude to the School of Electrical and Computer Engineering, RMIT University and for providing me with the scholarship and high voltage laboratory facilities to undertake this Ph.D. program.

I wish to acknowledge my former senior supervisor Professor Majid Al-Dabbagh, who gave me enormous support and provided valuable guidance during my first two years of research.

I am very grateful to my current supervisors, Dr. Alan Wong and Professor Xinghuo Yu, for their valuable advice, guidance and encouragement during the latter part of my research work. Without their patience and support, the research contained in the dissertation would have never been possible. It has been both a pleasure and an honour to work with you and learn from you. Without your encouragement throughout the final stages of this research, I would have never made it this far. Most importantly, I thank them for posing challenging questions which led to the attainment of better results. Your comments on the thesis structure were very insightful.
I would also like to thank the local power utilities – Powercor/Citipower and Jemena for providing wood and insulator specimens for conducting the laboratory investigations.

I am grateful to my work supervisor, Bruce Forsyth from ENERGEX, Queensland for his understanding and invaluable support during the final stages of my research. Without your support, finalisation of my thesis work would not have been possible.

I thank Mr Ivan Kiss and Mr Sinisa Gavrilovic for helping me with setting up the experiments in the HV laboratory, PhD student colleagues at RMIT University for their encouragement and Dr. Campbell Aitken of Express Editing Writing and Research for proofreading and making suggestions to improve the quality of this thesis.

I am indebted to my parents who were patient and supportive during my studies and provided unconditional love and encouragement during difficult situations, and my sisters for their support and encouragement.

Last but not least, I thank my wife, Dr. Neha for her understanding and support while I wrote the thesis, especially the times she would sit with me at night comforting me with her presence.
Abstract

In Australia and many other parts of the world, electricity is distributed to industries and households via overhead distribution lines, and most lines are mechanically supported by wooden structures consisting of poles and crossarms. Seventy per cent of the 8.5 million wooden structures in service as part of electricity distribution infrastructure in Australia are over 35 years old. Leakage current flow in these ageing wooden structures imposes continuous stress and has caused numerous pole fires, not only in Australia but in many other countries. Despite the development of wooden pole-crossarm fire mitigation techniques, ageing wooden structures continue to experience pole top fires caused by leakage currents; hence it is important to fully understand the electrical behaviour of these wooden structures from a leakage current perspective under varying environmental conditions.

In this thesis, the electrical characteristics of aged wooden structures are examined and used to further our understanding of leakage current performance; this is the first study of this phenomenon to have been conducted worldwide. The study proved conclusively that leakage current performance of wooden structures deteriorates with age. Next, scanning electron microscopy was conducted and allowed inferences about structural differences in ageing wood specimens. It was found that structural changes
occur during the service lives of wooden structures and play an important role in predicting the leakage current behaviour. The study’s outcomes will assist the assessment of the electrical performance of wooden structures in greater depth, with far greater understanding of the role of ageing in wooden structures, and in developing cost effective asset maintenance and replacement programs which will help in reducing wooden pole fires.

Investigation to study the influence of coastal salt deposition on the surface of ageing wooden structures on leakage current was conducted. It was concluded that in coastal areas seawater distributed by wind and other means allows salt to enter the structure of wood through cracks and fill internal pores. In addition, the accumulation of salts on the surface of wood, particularly when it is wet, significantly reduces electrical resistance and deteriorates the leakage current performance of the wood.

The influence of CCA treatment on the leakage current performance of spotted gum poles was also investigated in detail. It is concluded that CCA-treated spotted gum poles have reduced electrical resistance so are vulnerable to smouldering leading to pole fires. Although CCA treatment of spotted gum poles against fungal and termite attack offers several advantages and is a practice widely used by power utilities, the compromise made with reduced electrical resistance of CCA-treated wood can often lead to excessive leakage current thereby increasing the chances of pole fires. This research points to the need to make effective and balanced decisions on CCA treatment of poles taking into consideration the site weather conditions and location, hence minimising life-cycle costs of inspection and refurbishment of CCA treated wood poles.
Finally, a novel mathematical model based on dimensional analysis was developed to establish relationships between key physical variables and leakage current in wooden structures. Validation of the complete mathematical model was undertaken by comparing the experimental results and model results and they were found to be in good agreement.
List of Publications

The following is a list of publications during the course of this doctoral program

Peer-reviewed Journal Articles


Peer-reviewed Conference Articles


Contents

Declaration ii
Acknowledgements iii
Abstract v
List of Publications viii
Contents xi
List of Figures xvii
List of Tables xx
Glossary xxii
Bibliography 118

1. INTRODUCTION

1.1 Power Distribution in Australia 4

1.1.1 Overhead Distribution System 4

1.1.2 Wooden Poles 6

1.1.3 Concrete Poles and Composite Poles 7
1.4 Project Objectives and Research Questions 14
1.5 Organisation of the Thesis 15

2. LITERATURE REVIEW

2.1 Introduction 17
2.2 Experimental Work on Leakage Current in Wooden Poles 18
2.3 Ageing in Wooden Poles 23
2.4 Existing Mathematical Models 24
2.5 Preservative Treatment of Wooden Poles 26
2.6 Existing Techniques to Measure Leakage Current in Wooden Poles 29
2.7 Key Issues Identified 29
2.8 Summary 30

3. EFFECT OF AGEING ON LEAKAGE CURRENT IN WOODEN STRUCTURES

3.1 Introduction 31
3.2 Experimental Objectives

3.3 Experimental Setup

3.3.1 Fog Chamber

3.3.2 High Voltage Power Supply

3.3.3 Contaminant Conductivity Meter

3.3.4 Wood Moisture Detector

3.4 Materials

3.4.1 Selection of Wooden Specimens used for this study

3.4.2 Insulator Samples

3.5 Experimental Procedures

3.5.1 Clean Fog Measurements

3.5.2 Salt Fog Measurements

3.5.3 Relative Humidity Measurements

3.5.4 Resistance Measurement

3.6 Experimental Results

3.6.1 Leakage current under dry conditions

3.6.2 Effect of Moisture Content

3.6.3 Effect of Relative Humidity

3.6.4 Resistance Measurements

3.6.5 Density Measurements

3.7 SEM Study of Ageing Wood Specimens

3.7.1 Overview

3.7.2 SEM Study Test Setup and Procedure

3.7.3 Visual Observations of SEM Images

3.8 Smouldering Observations in Ageing Wooden Structures
3.9 Discussion of Results

3.9.1 Influence of Ageing on Wood Pole Structures

3.9.2 Porosity in Ageing Wood Specimens

3.9.3 Moisture Content and Relative Humidity

3.9.4 Smouldering in Ageing Wood Structures

3.10 Summary

4. STUDY ON FACTORS OTHER THAN AGEING THAT INFLUENCE LEAKAGE CURRENT IN WOOD

4.1 Introduction

4.2 Study of the Influence of CCA Treatment of Spotted Gum Species on Leakage Current

4.2.1 Use of Preservatives

4.2.2 Experimental study

4.2.3 Experimental Setup

4.2.4 Selection of Wood Specimens

4.2.5 Thermographic Infrared Camera (IR)

4.2.6 Test Procedure and Results

4.2.7 Thermographic IR Camera Images

4.2.8 Pole Resistance Measurement Test

4.2.9 Comparison with Other Researchers’ Results

4.2.10 Discussion of Results

4.3 Study of the Effect of Coastal Salt Deposition on Leakage Current in Wood

4.3.1 Coastal Environmental conditions

4.3.2 Experimental study
5. NOVEL LEAKAGE CURRENT MODEL BASED ON DIMENSIONAL ANALYSIS

5.1 Introduction
5.2 Mathematical Modelling
   5.2.1 The Leakage Current Phenomenon
   5.2.2 Dimensional Analysis
   5.2.3 Past Use of Dimensional Analysis Technique
5.3 Leakage Current Mechanism and Modelling Methodology
5.4 A Leakage Current Model for the Insulator
5.5 A Leakage Current Model for Wood
5.6 A Complete Leakage Current Model for Insulator and Wood
5.7 Validation of Mathematical Model
   5.7.1 Validation Methodology
   5.7.2 Leakage Current and Relative Humidity
   5.7.3 Leakage Current and Coastal Salt Deposit Conductivity
5.8 Summary
6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

6.1.1 Effect of Wood Ageing on Leakage Current

6.1.2 Influence of Coastal Salt Deposition on Leakage Current

6.1.3 Effect of CCA Treatment on Leakage Current

6.1.4 Mathematical Modelling

6.2 Suggestions for Future Research
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>View of wooden pole top fire</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Pole fire experience in Victoria, Australia</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Map of Power Distribution by Utilities in Australia</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>Power Distribution Line Design Commonly used in Australia</td>
<td>5</td>
</tr>
<tr>
<td>3.1</td>
<td>Experimental Setup</td>
<td>33</td>
</tr>
<tr>
<td>3.2</td>
<td>Installation of metal pin into the heartwood</td>
<td>34</td>
</tr>
<tr>
<td>3.3</td>
<td>Leakage current measurement arrangement</td>
<td>35</td>
</tr>
<tr>
<td>3.4</td>
<td>Fog Chamber used for testing</td>
<td>36</td>
</tr>
<tr>
<td>3.5</td>
<td>Wooden crossarms used for testing in HV laboratory</td>
<td>39</td>
</tr>
<tr>
<td>3.6</td>
<td>Wood Specimens used for experiments</td>
<td>40</td>
</tr>
<tr>
<td>3.7</td>
<td>Polluted Pin-Type Insulator Samples with varying pollution</td>
<td>42</td>
</tr>
<tr>
<td>3.8</td>
<td>Three wood specimens in the fog chamber</td>
<td>43</td>
</tr>
<tr>
<td>3.9</td>
<td>Measurement of wood resistivity</td>
<td>47</td>
</tr>
</tbody>
</table>
Figure 3.10 Leakage current in three specimens \((A, B, C)\) over time under dry conditions

Figure 3.11 Effect of varying moisture content on leakage current of specimens

Figure 3.12 Effect of varying relative humidity on leakage current of specimens

Figure 3.13 Comparison of resistance of specimens A, B and C

Figure 3.14 SEM study in the laboratory

Figure 3.15 SEM view of Specimen \(C\) (left) and specimen \(B\) (right) at x40 magnification

Figure 3.16 SEM view of specimen \(A\) at x40 magnification

Figure 3.17 Microscopic View of Sample \(C\) (~>20 years old)

Figure 3.18 Microscopic view of specimen \(B\) (~20 years old)

Figure 3.19 Microscopic view of specimen \(A\) (~10 years old)

Figure 4.1 Test Set for CCA treatment study

Figure 4.2 Pole Specimens 1 (left) and 2 (right) in the HV Laboratory

Figure 4.3 Leakage current of the wood specimens under dry conditions

Figure 4.4 Specimen 1(left) and specimen 2 under wet conditions

Figure 4.5 Leakage current under wet conditions of the Specimen 1 and 2

Figure 4.6 Infrared image of bolt removed immediately after smouldering began

Figure 4.7 Infrared image of the hole following bolt removal
Figure 4.8 Setup used for Resistance Measurements
Figure 4.9 Specimen 1 Resistance for Various Applied Voltage Levels
Figure 4.10 Specimen 2 Resistance for Various Applied Voltage Levels
Figure 4.11 Leakage current and Surface Conductivity
Figure 5.1 Leakage current mechanism on insulator and wooden pole
Figure 5.2 Best fit curve derived from experimental data plot to determine value of $D_1$
Figure 5.3 Comparison of model and experimental results for wood specimen A
Figure 5.4 Comparison of model and experimental results for wood specimen B
Figure 5.5 Comparison of model and experimental results for wood specimen C
Figure 5.6 Comparison of model and experimental results for wood specimen A
Figure 5.7 Comparison of model and experimental results for wood specimen B
Figure 5.8 Comparison of model and experimental results for wood specimen C
List of Tables

Table 1.1 Estimated quantities of poles in service throughout Australia in 2004 7

Table 3.1 Specifications of Test Transformer 37

Table 3.2 Estimated In-Service Period of Various Specimens 40

Table 3.3 Specifications of Insulator Samples 41

Table 3.4 Experimental conditions for Moisture Content Test 44

Table 3.5 Salt quantity and conductivity values 45

Table 3.6 Experimental conditions for Relative humanity test 46

Table 3.7 Average leakage current for each specimen under dry condition 48

Table 3.8 Average leakage current flow in wet conditions 49

Table 3.9 Resistance and Leakage Current Measurement of wood specimens 51

Table 3.10 Density of wood specimens 52

Table 3.11 Voltage and Resolution Range 54

Table 3.12 Smouldering study results in ageing wood specimens 59

Table 4.1 Smouldering study results in CCA treated specimens 79

Table 4.2 Salt quantity and conductivity values 82

XX
Table 4.3 Experimental Conditions 83

Table 5.1 Empirical relationship for leakage current flow mechanism 91

Table 5.2 Dimensions of each parameter 93

Table 5.3 Dimensions of each parameter 98

Table 6.1 Empirical relationship for leakage current flow mechanism 115
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA</td>
<td>Copper Chrome Arsenic</td>
</tr>
<tr>
<td>ACA</td>
<td>Ammoniacal Copper Arsenate</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standard</td>
</tr>
<tr>
<td>AUD</td>
<td>Australian Dollar</td>
</tr>
<tr>
<td>BIL</td>
<td>Basic Insulation Level</td>
</tr>
<tr>
<td>EHV</td>
<td>Extra High Voltage</td>
</tr>
<tr>
<td>LIL</td>
<td>Lightening Impulse Withstand Level</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electro-technical Commission</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>LC</td>
<td>Leakage Current</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SE</td>
<td>Secondary Electron</td>
</tr>
<tr>
<td>BSE</td>
<td>Back-scattered Electron</td>
</tr>
<tr>
<td>PCP</td>
<td>Pentachlorophenol</td>
</tr>
<tr>
<td>FPA</td>
<td>Focal Panel Array</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture Content</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The need for a continuous and reliable source of electricity has increased with Australia’s technological advancement; simultaneously, the ageing infrastructure of Australian electricity networks poses challenges to electricity network utilities and regulators. In particular, leakage current flow in wooden structures consisting of poles and crossarms has caused numerous failures on the network which have resulted in loss of power supply [1, 2, 3, 4].

Figure 1.1 View of wooden pole top fire [1].
Power interruptions caused by leakage current driven pole top fires in wooden structures, as depicted in Figures 1.1 & 1.2, can cause damage in the millions of dollars and the loss of human lives and property.

In Australia and many other parts of the world electricity is distributed to industries and households via overhead distribution lines, and most are mechanical supported by wooden structures [4, 5, 6]. Despite the recent trend towards use of alternative pole-crossarm technologies, wooden structures will continue to be used as they offer advantages such as high insulation properties, low cost and ease of use [6, 7]. Throughout their service life, wooden structures consisting of crossarms and poles are subjected to electrical, environmental and mechanical stresses. Depending on the location and design of the insulator, the nature and magnitude of the stresses to which the wooden structures are subjected can be very different.

Figure 1.2 Pole fire experience in Victoria, Australia [2].
From the electrical engineering perspective, pollution-driven leakage current imposes a continuous stress on wooden structures which can lead to catastrophic events such as excessive arcing, flashover and damaging bushfires [8]. Typical contamination or pollution deposition includes salt, dust, soil and industry pollution such as coal dust or chemicals. Leakage current in ageing wooden structures caused by these environmental stresses has caused numerous pole top fires, not only in Australia but in many other countries [1, 2, 4, 9, 10].

Despite the development of wooden pole-crossarm fire mitigation techniques [10, 11] ageing wooden structures continue to experience pole top fires caused by leakage currents; hence it is important to fully understand the electrical behaviour of these wooden structures from a leakage current perspective under varying environmental conditions. This thesis strengthens the current body of knowledge by studying the leakage current performance of wooden structures under varying environmental conditions and evaluating the influence of key factors on leakage current in wood.

This chapter is organised as follows. First, an introduction is given to the problem of leakage current in wooden structures is introduced. Section 1.1 describes Australian power networks including the use of wooden poles in Australia for power distribution. Section 1.2 describes ageing in wooden structures. Section 1.3 describes the motivation and scope of the research presented in this thesis. This is followed in Section 1.4 by the project’s objectives and research questions. Finally, section 1.5 outlines of the organisation of the thesis.
1.1 Power Distribution in Australia

1.1.1 Overhead Distribution System

There are currently 14 electricity distributors in Australia covering most populated areas (as shown in Figure 1.3). Distributors own and maintain the poles, crossarms and wires, which are the means of transporting electricity to consumers, as well as the electricity meters that measure usage. Electricity is delivered across Australia through approximately 48,000 kilometres of transmission power lines and 80,000 kilometres of distribution power lines [12].

Since the beginning of electrification over a century ago, wooden structures consisting of crossarms and poles have been an essential part of the provision of electrical service to the people of Australia. Transmission and distribution lines deliver power to large
cities, small towns, and remote outposts. Advancements in wood preserving and engineering technology combined with wood’s natural benefits and economics have allowed the wooden structures to remain the foundation of Australian power distribution in the 21st century. About 80% of the poles in Australian energy networks are made of wood [6]. The types of wooden pole-top constructions widely used for power distribution (voltages of 11kV and up to 66kV) in Australia are Flat Shackles, Vertical Delta, Vertical Delta Shackles and Vertical Offset, as shown in Figure 1.4.

Figure 1.4 Power Distribution Line Design Commonly used in Australia.
1.1.2 Wooden Poles

There are approximately 8.5 million wooden poles currently used in Australia [6]; approximately 6 million poles are used for power distribution and transmission and 80,000 new poles are installed per annum. Anecdotal evidence suggests that up to 70% of the timber poles currently in service were installed over the 20 years following the end of World War Two [6]. The type of timber used for poles varies and is usually influenced by local factors. Hardwood poles are preferred in Australia because of their natural strength [13]. Copper Chrome Arsenic (CCA) treated spotted gum and blackbutt, creosote-treated messmate, and untreated naturally durable wood such as ironbark are the most common pole types in Australia are [13]. While traditionally many naturally durable poles were sourced from old growth forests in NSW and Queensland, often local regional forests in individual states are the main sources of wooden poles. Australian Standard AS 2209 - 1994 Timber - Poles for Overhead Lines [14] is used to specify the requirements for wooden power poles. This standard applies to hardwood poles with and without full-length preservatives and softwood poles with full-length preservatives. The estimated breakdown of different types of poles used for power distribution in Australia is shown in Table1.1.
Table 1.1 Estimated quantities of poles in service throughout Australia in 2004 [6].

<table>
<thead>
<tr>
<th>State / Territory</th>
<th>Timber</th>
<th>Concrete</th>
<th>Metal</th>
<th>Other</th>
<th>State Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales (NSW)</td>
<td>2,055,651</td>
<td>93,398</td>
<td>40,229</td>
<td>400</td>
<td>2,189,678</td>
</tr>
<tr>
<td>Queensland (Qld.)</td>
<td>1,260,042</td>
<td>35,951</td>
<td>27,764</td>
<td>0</td>
<td>1,323,757</td>
</tr>
<tr>
<td>Victoria (Vic.)</td>
<td>823,934</td>
<td>265,282</td>
<td>21,949</td>
<td>5,370</td>
<td>1,116,535</td>
</tr>
<tr>
<td>South Australia (SA)</td>
<td>0</td>
<td>78</td>
<td>211</td>
<td>655,763</td>
<td>656,052</td>
</tr>
<tr>
<td>Tasmania (Tas.)</td>
<td>194,451</td>
<td>46</td>
<td>7,108</td>
<td>6,868</td>
<td>208,473</td>
</tr>
<tr>
<td>Western Australia (WA)</td>
<td>681,536</td>
<td>12,334</td>
<td>20,808</td>
<td>0</td>
<td>714,678</td>
</tr>
<tr>
<td>Northern Territory (NT)</td>
<td>0</td>
<td>95</td>
<td>38,125</td>
<td>0</td>
<td>38,220</td>
</tr>
<tr>
<td>Australian Capital Territory (ACT)</td>
<td>50,098</td>
<td>7,031</td>
<td>2,758</td>
<td>375</td>
<td>60,262</td>
</tr>
<tr>
<td>Total</td>
<td>5,065,712</td>
<td>414,215</td>
<td>158,952</td>
<td>668,776</td>
<td>6,307,655</td>
</tr>
</tbody>
</table>

1.1.3 Concrete and Composite Poles

In Australia, concrete poles are used in areas such as swampy and persistently wet areas where the soils could greatly shorten the life expectancy of wooden poles. Moreover, in such cases, the rate of decay may be erratic and uncertain, permitting unsafe condition to arise that may not be discovered before permanent failure results. Concrete poles are also specified in areas of chemical contamination and pollution that may cause rapid deterioration, and in special situations where poles of unusually high strength are required and where guying may be difficult or unobtainable. The principal disadvantages of concrete pole are their higher cost, greater weight and fragility which greatly increase transport, handling and erection costs, and their lack of flexibility in the use of individual structures.

Over the past five to eight years, electricity utilities in Australia have started trialling composite power poles and cross-arms [15, 16]. Composites have the advantages such
as low density (about $\frac{1}{4}$ that of steel), high surface resistance ($>10^{12}\Omega$) and volume resistance ($>10^{15}\Omega\cdot\text{m}$), small leakage current value after being damped ($\mu\text{A}$ level) and high mechanical strength. It is premature to comment on the performance of composite poles as no full life cycle assessment of composite technology has been completed.

1.1.4 Why are Wooden Poles Used in Australia?

Wooden poles offer several advantages for their use in power distribution, including lower cost, excellent basic insulation level and flexibility.

A) Cost

The cost of lower durability native forest-grown hardwood poles is less than or equal to the cost of higher-durability native forest-grown hardwood poles. A medium-sized wooden pole currently costs approximately AUD$500, considerably less than non-timber alternatives [6]. Concrete poles are relatively expensive and their use is limited to special situations such as termite infested areas.

B) Basic Insulation Level (BIL)

The BIL defines the ability of a structure to withstand a lightning impulse. A basic impulse insulation level of less than 300 kV can produce lightning flashovers when lightning strikes near the electric distribution line. A BIL equal to or greater than 300
kV (dry flashover) can be achieved on wooden poles using standard pole-top assemblies rated for the operating voltage. The wood provides the additional insulation needed to achieve the required BIL. On metal or concrete poles, fiberglass links or extra insulators must be added to the standard pole-top assembly hardware to achieve the same BIL as wooden poles.

C) Flexibility

A wooden pole is very flexible and can survive many adverse natural events. When trees fall on conductors and guy wires, a wooden pole will deflect significantly before breaking. Many times, fallen trees can be cut off the line or lines and the pole will spring back into position. Wooden poles are forgiving to changes in conductor tension between spans. On very rigid poles, such as concrete, the change in conductor tension brought about by expansion and contraction due to temperature change can bend cross-arm pins; in contrast a wooden pole will flex with the change in conductor tension and not damage the hardware. Wooden poles are also preferred where lines are required to be relocated in the short to medium term or where lines follow road reserves where span lengths are short and there are frequent changes of direction [17].
1.2 Ageing in Wood Structures

There is a substantial peak in the ages of the wooden poles currently in service. In Victoria alone, there were 37,000 wood poles 50 years and older in 2004; however this was projected to increase to approximately 62,000 by 2010 even with average replacement of 1,500 wood poles per year [8]. As noted earlier, the performance of a wooden pole during its serviceable life is impacted by environmental, mechanical and electrical stresses; pole top fires caused by these stresses have been observed on ageing wooden pole structures in power distribution networks around the world [1, 2, 9]. A detail of these stresses is given in the sections below:

1.2.1 Electrical Ageing

Electrical ageing of wooden poles is caused by electrical stress. Leakage current, lightning strikes and insulator flashover are the three major electrical stresses impacting the performance of wooden structures. Extensive research has been conducted on the lightning strike and insulator flashover performance of insulator and wooden poles [18]; however, the leakage current performance of wooden poles of varying age is yet to be fully established.

1.2.2 Mechanical Ageing

The ability of wooden poles to resist loads depends on several factors, including the type, direction, and duration of loading, and ambient conditions of moisture content and
The strength and mechanical properties of wooden poles are affected by the environmental conditions under which the poles have been used as well as the humidity of the environment and type of loading to which the system is subjected.

### 1.2.3 Wood Decay

Wood decay is most commonly caused by the activity of fungi, which produce enzymes to break down the constituents of wood cell walls into more readily assimilated substances that are required for their growth and metabolism. Decay fungi are usually classified into three groups: brown rots, white rots and soft rots [6, 20]. One of the major problems in attempting to preserve poles from decay is the identification of the microorganism that is present in a particular type of pole; this may be dependent upon the local soil fungi and wind borne spores.

Termites are the greatest destroyers of wooden poles in Australia and are a significant factor in the degradation of trees growing in forest areas [21]. Durability against termite attack is measured differently to durability against decay. Timber species are characterised as either susceptible or non-susceptible to termite attack [6, 21]. Most termites that damage timber in service in Australia are subterranean. Dampwood termites generally live in damp rotting logs or in dead or living trees; they may be found in decaying wood in-service. Drywood termites obtain water from the wood in which they feed and have no contact with the soil or with any other source of moisture. These
termites are of economic concern, but are mostly confined to the coastal and adjacent tableland areas of tropical and sub-tropical Australia [21].

1.2.4 Weathering of Wood

Exposure to sunlight (UV and visible light), moisture (rain, fog, dew) and temperature change causes weathering of wood over a long period of time. Natural weathering of wooden poles results in checking and cracking and causes chemical deterioration which contributes to overall ageing.

1.3 Motivation and Scope of Research

Despite considerable technological advancement in the field of insulation failure, electrical failures including pole top fires in ageing wooden structures remain one of the most challenging problems faced by power utilities. Over the past ten years, Australian power utilities have been penalised millions of dollars due to the unreliability of power supply caused by insulation failures in wooden structures including pole top fires [1, 2]. Utilities spend significant amounts of money on preventive maintenance strategies to mitigate pole top fires, which include treatment of wooden structures, insulator washing and silicon coating of insulators. These maintenance operations are scheduled according to the subjective judgement of line engineers based on historical experience. The rate of wooden pole failures in some parts of Australia is well above industry norms, with the Western Australian network experiencing between 1.88 and 4.34 failures per 10,000 poles per year, in comparison with the industry target of 1 per 10,000 per year [22].
In 2009, Victoria experienced catastrophic bushfires that resulted in 173 fatalities. Five of the 11 major fires that occurred on 7th February 2009 were found to be caused by failure of ageing electricity assets [8]. The Victorian Bushfires Royal Commission noted that Powercor, a local power distribution utility, managed 11,374 route kilometers of distribution line structures aged between 55 and 64 years, and 10,318 kilometers aged between 65 and 74 years. In 2010, the Victorian Bushfires Royal Commission suggested major upgrades to the ageing assets which will cost utilities over $7.5 billion; this could result in consumers paying 20 percent more on their power bills every year for 20 years [8].

Power losses which result from leakage current associated with fires and other insulation failures in ageing wooden poles have posed significant challenges to power utilities in terms of the overall performance of Australian power networks. Significant losses are contributed by the leakage current flow on overhead power structures, on top of the actual corona losses and conductor $I^2R$ losses in the system. Any power loss caused by ageing power poles (infrastructure) triggers more power generation to substitute losses on the network and hence results in higher carbon emissions. With carbon emissions being a growing global concern, it is crucial that power utilities address this issue.

At present, very little information is available to power utilities to help them understand the leakage current performance of their wooden poles. In the past, researchers [23, 24, 25] have studied the leakage current performance of various types of insulators under various environmental conditions, but the subject of leakage current in ageing wooden structures and the associated fire risk has received little research attention. It is
imperative that the factors influencing leakage current flow in wooden structures be understood.

The outcomes of this research will be significant new knowledge about leakage current flow in wooden structures, and information enabling power utilities to develop effective asset maintenance and replacement policies and guidelines.

This thesis describes the investigation of the effect of ageing on the leakage current performance of wooden structures. The significance of this work is that it substantially strengthens the understanding of leakage current behaviour of wooden structures under varying environmental conditions. In addition, influences of CCA treatment and coastal salt deposition in wood on leakage current performance are studied in detail.

1.4 Project Objectives and Research Questions

The four main objectives of the thesis are listed below:

1. To investigate the influence of ageing in wooden structures on leakage current performance
2. To understand the structural changes in wood specimens of different ages from a leakage current performance perspective
3. To investigate the influence of CCA treatment and coastal salt deposition in wood on leakage current performance
4. To establish a relationship between leakage current in wooden structures and various influential factors by developing a unique mathematical model.

The research questions guiding the evaluation of leakage current performance of wooden structures under varying environmental conditions were:

1. How do different age profiles of wooden structures behave when leakage current flows through them under varying environmental conditions?

2. How do various ages of wooden samples differ structurally from a leakage current flow prospective?

3. How do salt conductivity deposits on the wood surface and CCA treatment of wood affect its leakage current behaviour and performance?

4. How leakage current relates to various influencing factors from a modelling perspective?

1.5 Organisation of the Thesis

Chapter 1 introduces the power distribution system and use of wooden poles in Australia. A brief summary of ageing in wooden structures, pole fire problem and its economic impact is presented followed by the project’s objectives and research questions.
Chapter 2 summarises the previous research carried out in the area of leakage current in wooden structures. A comprehensive literature review is carried out in this chapter.

In Chapter 3, an experimental study of the influence of ageing in wooden structures on leakage current performance is described. Details on selection of wood specimens, test setup, test procedure and results are presented in this chapter. The work is extended to structurally study three different age wood samples with the help of a scanning electron microscope. Smouldering observations are briefly presented followed by discussion of results obtained from experimental study.

In Chapter 4, an experimental study on influence of CCA treatment and salt contamination deposits of wood on leakage current performance is presented. Details on selection of wood specimens, test setup, test procedure and discussion on results are provided.

In Chapter 5, a novel mathematical model based on dimensional analysis is developed. This chapter first provides background on dimensional analysis and its application. A novel leakage current mechanism for the insulator-wood combination is introduced, followed by development of the complete mathematical model. The chapter concludes by describing the validation of the complete model.

Chapter 6 is dedicated to the main conclusions that are drawn from the work. Suggestions for further studies are presented.
Chapter 2

Literature Review

2.1 Introduction

Wooden structures consisting of crossarms and poles are widely used for overhead electricity distribution in Australia and constitute an important component of utilities’ assets. In dry climates combined with salt spray or other deposits, line insulators may become very dirty, and the onset of foggy or humid conditions may give rise to prolonged and excessive leakage leading to fire. Excessive leakage current in wooden structures depends on many factors and is a complex problem. Different types of stresses such as environmental, mechanical, and electrical stress can impact the overall life and performance of wooden structures. Coastal environmental conditions in Australia pose major challenges to the operation and maintenance of a healthy power network.

This chapter contains a comprehensive review of the research in the area of leakage current performance of overhead wooden structures used for power distribution.

The layout of this chapter is as follows. In Section 2.2, experimental work conducted by previous researchers on leakage current in wooden structures is reviewed. Section 2.3
presents and discusses previous work on ageing in wooden structures. Section 2.4 outlines the existing mathematical models on leakage current in wooden structures. A review of preservative treatment of wooden poles is given in Section 2.5, which is followed by a survey of existing techniques used to measure leakage current in wooden structures presented in section 2.6. Based on the literature, some key issues are identified and presented in section 2.7. Finally, a brief summary of the chapter is presented.

2.2 Experimental Work on Leakage Current in Wooden Poles

The characteristics of wooden structures regarded as insulators are very challenging to summarise. Under sustained application of power voltage, the insulating properties of wooden poles and cross-arms are non-linear and are largely unpredictable. This is due to the properties of the wood changing due to exposure to outdoor environmental conditions.

In 1947 in Ohio, PM Ross [26] carried out research on the burning of wooden structures by leakage current flow. He went on to explain the ideal field operating conditions for the occurrence of wooden structure fires: a long dry period followed by fog and misty rain. He conducted laboratory tests on wooden crossarm and pole samples by simulating natural dry and wet environmental conditions (including wind) on pole burning. Wood specimens experienced pocket burning at a current of ~10mA. The study concluded that the main cause of pole burning was due to the formation of dry band zone in the vicinity of metallic contacts as a result of voltage concentration which causes electrical breakdown in wood. Although Ross studied the cause of burning in wooden structures,
he did not investigate the leakage current performance of wooden structures of different age profiles leading to smouldering and fire.

In 1948, Wickham et al. [27] (Chicago) conducted experiments to identify the factors which might contribute to fires in wooden structures. They noted that deep pocket burning which is often started by smouldering without open flame. In some of Wickham et al.’s tests, leakage currents with magnitudes as low as 5mA initiated fire. The authors confirmed that it is not the magnitude of leakage current but the concentration of current in dry band region which give rise to serious burning in wood; their results are in agreement with Ross’s findings [26]. Caulking the gain lines with a plastic compound was proposed as a means of mitigating pole burning. Wickham et al. also proposed another method of bonding which is essentially wrapping both the pole and crossarm with wire on all sides of the gain.

In 1954, Clayton et al. [28] investigated the impulse characteristics of wooden structure and insulator combination. This combination essentially consists of insulator mounted on wooden crossarm. They compared the impulse performance of wood-insulator combination by changing the length of the wood and showed that impulse strength of high voltage circuit is dependent on the length of the wood added the circuit. The authors did not study the leakage current performance of wooden structures under varying environmental conditions.

In Illinois, from 1960 to 1962, Schroeder et al. [29] conducted experiments for evaluating leakage current performance on a 345kV Wood-Pole Test Line. Leakage current measurements were recorded on 345kV overhead structures to examine the performance of H-type frame structures with metal cross arm spacers. It was found that
leakage current flow was relatively same for both voltage levels of the order of 100uA to 300uA. The concentration of leakage current in an H-type frame is reduced due to size and contact area of the spacer fittings which suspends the insulator strings (H-type frame wooden structures for line designs are no longer used in Australia for power distribution)

In 1967, Darveniza et al. [7] (Australia) studied impulse strength and arc quenching of wood from a lightning performance perspective with a particular emphasis on shielded and unshielded lines. The authors discussed the significance of moisture content on the electrical properties of wood. Darveniza et al. confirmed Ross’s [26] characterisation of the ideal condition for occurrence of pole fire but added to Ross’s list the phenomenon of spark discharge at loose wood-metallic contact where adequate supply of air exists. Darveniza et al’s research revealed important factors affecting outage rates on unshielded lines including the arc quenching properties of wood. The results show that a relatively high arc voltage gradient is required to maintain an arc which involves wood, either when confined internally or located near the surface.

The authors also conducted a power frequency leakage current study [30] to evaluate the various factors that could influence fire in wooden poles. Precipitations such as fog or rain produce uneven wetting on the wood and together with wind were found to cause ignition of the wood. Natural shrinkage and cracking of the wood loosening the metal and wood connection may allow spark discharge inside the bolt hole with sufficient leakage current magnitude and adequate air in sparking zone. Authors concluded that one of the important prerequisite of pole fire is loosening of wood
metallic contact however recent research [31] shows that pole fires can even occur on poles with very tight wood metallic contacts.

In 1976, Lusk et al. [32] (Minnesota) conducted experimental tests on Extra High Voltage (EHV) wood pole configuration (H type frame) and investigated a new type of pole fire problem. The authors found that surface leakage current did not contribute to fires in the vertical pole membrane of wooden high voltage transmission line towers. Lusk et al. asserted that electrical and charging currents resulting from the capacitive coupling existing between the poles and the phase wires and the high electric field intensities were major cause of fires. The authors added a new dimension to the knowledge of pole fires by noting their occurrence due to coupling effect rather than leakage current.

In 1990, Grzybowski et al. [33] conducted a study of flashover voltage characteristics under steep-front, short duration pulse application to single distribution class insulators, wood crossarms and certain combinations of insulators plus wood crossarms under dry and wet conditions with both positive and negative polarities. The results showed that under wet conditions, a wood crossarm adds 80kV/ft to the electrical strength of an insulator when used as the second component of an insulation system.

From 1995 to 1997, Loxton et al. [4, 9, 10, 34,] conducted number of investigations on 22kV lines aiming to study pole top fires in KwaZulu (Natal, South Africa). They concluded that factors such as humidity, marine pollution and marine fog influence the leakage current activity on insulator leading to pole top fires. Although, the authors conducted some good field tests evaluating leakage current activity on insulator, the influence of the identified factors solely on leakage current in wood was not
investigated. The authors also studied the influence of insulator creepage distance on leakage current activity and burning mechanism in wood. The investigations highlighted the need for higher insulator specific leakage levels for coastal and heavily polluted areas to mitigate pole fires however this does not completely eliminate the burning in wood as concluded by Persadh [35].

In 2007, Aruna et al. [36] (Manchester, UK) studied wooden pole structure performance in reducing electric field under EHV transmission lines. Experiments were conducted on wood samples to evaluate variation of electrical resistivity with moisture content and relative humidity. Based on their field results, the authors concluded that resistivity is inversely proportional to the moisture content of the wood based on the field results. Simulation results and electric field measurements implied that wooden framework reduces the average internal electric field which highlighting the benefits of using wooden poles.

In 2007, Persadh [35] studied the burning in wood due to leakage currents and evaluated the practical implications of bonding used as one of the pole fire mitigation techniques. He summarised the mechanism of burning in wood. He concluded that internal burning in wooden crossarms is caused due to high electric fields between spindle thread and wood whereas external burning is caused due to high electric fields between spindle washer edge and wood surface. Persadh also modelled the phenomenon of neutral shift in bonded crossarms from a pole top fire mitigation prospective and concluded that in high pollution areas, neutral shift is more prominent which increases the chances of pole top burning.
It must be pointed out that the majority of the experimental studies of leakage current performance of wooden structures were conducted in the 1940s to 1960s. Over the past 40 years, very little research has been undertaken on leakage current in wooden structures. It is now clear that previous researchers experimentally studied in detail the leakage current driven pole top fire issue without giving any consideration to the age of the wooden structures. In addition, influence of salt deposition on the surface of wood pole has never been studied.

2.3 Ageing in Wooden Poles

Sandoz et al. [37] conducted a study of ageing in wooden structures using non destructive testing tools based on environmental conditions in Europe. The authors defined the ageing process in wood poles in two forms: first, the pole weakens under the effect of applied load and at the same time it develops cracks due to environmental changes, especially wetting and drying cycles. Second, ageing occurs due to biodegradation of wood as a result of fungal and termite attacks. For the non destructive laboratory testing of wood poles, the authors selected two parameters, i.e., pole residual strength and internal hygroscopic state which are related to the mechanical ageing and biodegradation (rotting) of wood respectively. Although these authors conducted impressive experiments, they did not evaluate parameters related to the electrical ageing of wooden structures.

Goodman et al. [38] conducted a case study of management of wooden poles using non destructive testing technique. The authors investigated the structural integrity of
Douglas fir, southern pine and western red cedar species. The test data showed degradation of strength with the age of timber was caused primarily due to mechanical stresses in wood poles.

Gravito et al. [39] developed criteria for the evaluation and maintenance of wooden poles. The authors conducted internal and external inspections of the wooden poles in Brazil, and provided useful information for decision-making about pole maintenance and replacement. Their proposed criteria for evaluation of wooden pole do not take age into account.

From the above discussion, it can be concluded that past research on the ageing of wooden structures has been based largely on mechanical and biodegradation aspects. Knowledge and understanding of leakage current performance of the ageing wooden structures at present is very limited.

2.4 Existing Mathematical Models

Numerous models [40, 41, 42, 43] for leakage current flow on insulator have been developed in the past. Nevertheless, very few authors have produced leakage current models for wooden structures.

In 1979, Darveniza et.al [18] developed a model for a wood and insulator combination (i.e., an insulator mounted on a wooden structure) to study the impulse strength of an overhead distribution network. This model calculates breakdown strength of wood porcelain combination with known impedances. It also predicts the average breakdown
strength with an accuracy of at least 10% for a wide range of wood-porcelain combinations.

Lusk et al. [32] developed an electrical pole fire model based on the coupling effect wherein the pole’s wet wood surface acts as a field coupling electrode to the transmission line phase conductors. The resultant charging current of the air coupling capacitance between the pole and the phase conductors uses the electrical conductance of the wet pole wood as a path to ground. The fasteners holding the wire to the pole along with any additional direct contact points that exists between the wire and wet wood become collecting points for the charging current. Lusk et al. also discussed the impact of insufficient quantity of metal fasteners resulting in excessive heating of fasteners and the formation of a dry zone. If the current density and heat transfer condition in the fastener area are right, then electrical breakdown of dry zone in wood will result and the dry zone will char. With adequate oxygen available, the internal charring will eventually result in fire.

In 1990, Filter [44] developed a 60Hz ladder network to describe wooden pole electrical behaviour. The model included the influence of moisture content gradients, treatment type and penetration, species, dimensions, and rain. The wooden pole was modelled by three resistances namely sapwood, heartwood and radial resistance. The resistances in the ladder network were determined by the wood species, preservative treatment and moisture content of the pole portion represented by that particular resistor. Body current values were calculated based on several contact scenarios in varying environmental conditions. Filter concluded that during foul weather conditions and if wood fire inception currents are flowing (as a result of polluted insulators), body currents as high
as 4-6 mA are possible with poles treated with water-borne preservative treatments. These body current levels are non-hazardous, but may result in a painful electric shock.

A mathematical model was proposed as a tool for assessing body currents resulting from pole contact for any species or treatment. Although the hazard model provides good insight into the safety aspects of wooden poles based on body currents, the authors did not account for the effect of salt contamination on the surface conductivity of pole.

In 2010, Wong et al. [45] extended the ladder network tool used previously by Filter [44] to study current distribution in wooden pole. The results show that the bulk of the leakage current flows through the internal section under wet weather conditions and the metal insertion along the radial section of the wood increase the magnitude of the leakage current.

The studies reviewed above show that although several mathematical models that have been developed to explain the leakage current mechanism in wood, a mathematical model which can relate all the significant variables influencing leakage current in wooden structures is lacking.

2.5 Preservative Treatment of Wooden Poles

Water-born and oil borne preservative treatment of wooden poles has been used to prolong the life of wood by protecting them against fungal and termite attack. Whilst it is understandable that power utilities use these preservatives to extend the lives of their wooden poles, the electrical performance of the treated poles is compromised.
In 1947, Wickham et al. [27] studied the influence of leakage current on treated and untreated wooden pole samples. The results showed that untreated wooden poles absorb surface moisture readily and a plentiful supply of moisture was necessary to produce low resistance and the leakage current necessary for burning. However, after wooden poles treated with creosote were exposed to the weather, the creosote was leached from the outer surface which resulted in high leakage current. This was later confirmed by the field observations.

Filter [46] conducted detailed laboratory testing of the electrical performance of two water-borne wooden pole preservatives: Ammoniacal Copper Arsenate (ACA) and Chromated Copper Arsenate (CCA) in comparison with pentachlorophenol preservatives. Water-borne and oil-borne treated wooden stubs 1.5m in length were subjected to electrical current. Filter’s objectives were to compare the relative performance of treated woods under one set of controlled conditions, rather than to study actual in-service configurations accurately. Laboratory test indicated that for poles treated with water-borne preservative, fire inception currents were two to three times greater than for comparable pentachlorophenol treated poles; the difference was attributed to different leakage current flow mechanism. Average glow currents ranging from 2mA to 13mA were measured for pine and cedar wood specimens. Filter’s work has very limited relevance to the Australian context as most wooden poles currently used in Australia are made from spotted gum or ironbark.

The electrical and mechanical performance of *Eucalyptus citriodo* crossarms impregnated with polymer was studied by Altafim et al. [47]. Partial discharge tests, impulse tests and mechanical tension tests were conducted on resin-impregnated wood
samples. The insulation performance of these samples under electric stress particularly under partial discharge during critical operating conditions was also investigated. Altafim et al. found that the level of partial discharge on wooden samples impregnated with polyurethane resin was reduced particularly at holes in the crossarm which are the critical points in situations of electrical insulation failure, thus improving its operation in the electric power distribution system. The electric impulse tests revealed a 34% increase in the LIL (Lightning Impulse Withstand Level) for the crossarms impregnated with resin (without filler) and of 57% for the ones impregnated with resin (with filler).

In 1963, Katz et al. [48] studied the effects of CCA and ACA preservatives on electrical resistance of red pine. The authors found that CCA-treated red pine offers better electrical resistance than ACA-treated wood under electrical stresses caused on overhead lines.

Goodman et al. [49] studied the effectiveness of oil-borne and water-borne preservative treatment of wooden poles in 1990. Their case study concluded that the process of impregnating wood with either oil-borne (pentachlorophenol) or water-borne preservatives (ACA and CCA) eliminates biological attack by fungi, insect, termite and woodpeckers and also increase the mechanical and insulation strength.

In summary, most of the research on treatment of wood with preservatives was aimed at the mechanical properties and biodegradation of wood rather than evaluating electrical properties.
2.6 Existing Techniques to Measure Leakage Current in Wooden Structures

An accurate technique to measure leakage current in wood is very critical due to the complex structure of wood. It has been found that the heartwood section of a wooden structure has the lowest resistance level due to higher percentage of moisture content level which resides in the heartwood section [50]. The sapwood moisture content of wooden structures changes relatively more frequently with changing weather conditions as compared to the heartwood section and offers varying level of resistance. Due to the relative difference in moisture content of sapwood and heartwood, the electrical resistance of wood pole structure varies from sapwood to heartwood sections within the pole which leads to complexity in accurately measuring leakage current.

In the past, most of the researchers [26, 27] used current sensors by connecting them between a high voltage source and wood specimens to measure leakage current flow in wood. The main disadvantage with this method is that it does not accurately measure leakage current flow in sapwood and heartwood section of wooden structure and can cause arcing between the foil and wood surface.

2.7 Key Issues Identified

From the comprehensive literature survey conducted in the previous sections of this chapter, the following key issues were identified:
1. Previous researchers experimentally studied the leakage current driven pole fire issue without given any consideration to the age of the wood pole. Knowledge of leakage current performance in ageing wood pole structures is very limited.

2. A mathematical model which can relate all the significant parameters influencing leakage current in wood poles is lacking.

3. The influence of coastal salt level deposits of wood surface on leakage current has never been researched. In addition, the influence of preservative treatment in spotted gum species has not been fully evaluated.

2.8 Summary

A comprehensive review of leakage current in wood is presented in this chapter. Experimental studies conducted on leakage current in wood and existing mathematical models based on leakage current in wood were reviewed and a few key issues highlighted. Research on preservative treatment of wooden structures from electrical performance prospective was discussed. Finally, key issues arising out of literature research were highlighted.

In general, it can be concluded that leakage current in wooden structures has not yet been comprehensively studied and there is a lack of understanding about this topic.
Chapter 3

Effect of Ageing on Leakage Current in Wooden Structures

3.1 Introduction

Seventy per cent of the 8.5 million wooden poles in service as part of electricity distribution infrastructure in Australia are over 35 years old [6]. Ageing in wooden poles is a focus of Australian power utilities, which are obviously keen to ensure that their wooden structures replacement and refurbishment programs are as cost-effective as possible. To maintain wooden poles in the most efficient manner, it is important to understand the influence of ageing in wood on leakage current performance.

In this thesis, the electrical characteristics of aged wooden structures are examined and used to further our understanding of leakage current performance. Results of experiments involving leakage current flow on wooden structures with different age profiles are presented.

This chapter is organised as follows. Section 3.2 briefly outlines the experimental objectives of this research. Section 3.3 describes the experimental test setup required to carry out the detailed investigation. Details of test materials used for the ageing study are presented in section 3.4, and descriptions of tests conducted in the high voltage laboratory in section 3.5. In section 3.6, experimental results are presented in the form
of graphs and tables. Section 3.7 presents the Scanning Electron Microscope (SEM) study conducted on each of the ageing wood specimens. In section 3.8, Observations of smouldering in ageing wood specimens is presented. Section 3.9 contains discussion of the results, and is followed by a summary of the chapter in section 3.10.

3.2 Experimental Objectives

One of the main objectives of this research was to understand and evaluate the performance of varying age profiles of wood when leakage current flows through the heartwood section and hence evaluate how these wooden structures behave under varying environmental conditions. Another objective was to study the smouldering phenomenon leading to fire in wood specimens of different age. To achieve these objectives, wood specimens of varying age were electrically tested in the laboratory under both wet and dry conditions. Moisture content and relative humidity were varied to understand the leakage current behavior of wood. Details of the experimental work are presented in the following sections.

3.3 Experimental Setup

A Tektronix 350 MHz TDS5034B digital phosphorous oscilloscope was used to measure leakage current on wooden samples. The TDS5000B has the capability to deliver up to 1GHz bandwidth, 5 GS/S real-time sample rate and 16 M record length. It
has the capability to register the time variation of the leakage current, the supply voltage and the phase shift between them. The leakage current was measured through a shunt connected in series with the test samples. Different shunts could be selected (100 ohm, tolerance ±3-5%, 100W, 1000V) depending on the level of the leakage current. The selected shunts were characterised by low inductance and were capable of withstanding high power impulses. The voltage drop across the shunt passed through the protective system and was observed in the digital oscilloscope. In parallel, the supply AC voltage was also measured in the oscilloscope through a resistive voltage divider, as shown in Figure 3.1. High voltage was applied to test specimens with the help of a single phase variac and corresponding leakage current was measured for different environmental conditions.

Figure 3.1 Experimental Setup.
No standard technique exists for measuring leakage current in wood at various locations on a wooden pole and crossarm. Ross wrapped a metallic strip around the wood surface to measure current in wood [26], similar to the technique applied here. For the purposes of this research, it was important to design and test an accurate technique for measuring leakage current.

In order to detect the current in the wood, a new test method named ‘Pin Insertion’ was proposed. In this test method, a metal pin with a diameter of 8.9mm was inserted into the wooden structure as shown in Figure 3.2 and the current measured via a shunt resistor connected in series with the pin.

![Figure 3.2 Installation of metal pin into the heartwood.](image-url)
A switching arrangement consisting of four switches (S1, S2, S3 and S4) was implemented as shown in Figure 3.3. Leakage current at each location was measured individually and an average value was calculated over a 30-minute interval.

![Figure 3.3 Leakage current measurement arrangement.](image)

Pin insertion method resulted in more accurate measurement than the copper foil wrapping technique based on the comparison of preliminary leakage current measurements obtained from coil wrapping and pin insertion methods. Pin insertion method closely simulates the standard pole design which includes bolts for mechanically supporting insulators, transformers, stay wires etc. The area near the bolts has been identified as the prime location of fire. The new technique allows accurate measurement of leakage current at these prime locations.
3.3.1 Fog Chamber

A cylindrical fog chamber 1950 mm tall and 1690 mm in diameter was used to investigate leakage current through wooden samples under different simulated environmental conditions. The chamber was built on a steel chassis, and the walls and the roof were joined by fibreglass rods. Polycarbonate sheets were used to construct the chamber as they possess excellent mechanical strength, transparency and flexibility as shown in Figure 3.4. Inside the fog chamber, fog was produced by a combination of ten nozzles that atomised water with a stream of compressed air flowing at right angles to each nozzle. The distribution of fog around and over the whole length of insulator and wood was achieved using pressurised water supplied by a water pump. Air pressure was adjusted to between 80-90 psi.

Figure 3.4 Fog Chamber used for testing.
3.3.2 High Voltage Power Supply

A 415V/100kV, 50kVA single phase transformer was used as a high voltage source. The output voltage was controlled by means of a three-phase variac protected by a miniature circuit breaker of 32A. The output of the transformer was connected to the insulator sample using an Aluminium Conductor - Steel Reinforced conductor. The current and voltage rating of the transformer is shown in Table 3.1.

<table>
<thead>
<tr>
<th></th>
<th>PRIMARY</th>
<th>SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>500V – 1000V</td>
<td>50kV – 100kV</td>
</tr>
<tr>
<td>Current</td>
<td>100A – 50A</td>
<td>1A – 0.5A</td>
</tr>
</tbody>
</table>

Table 3.1 Specifications of Test Transformer.

3.3.3 Contaminant Conductivity Meter

An Ex-Stik EC 400 conductivity meter was used to measure salinity and conductivity values in mg/L and µS/cm. The amount of salt deposition on the surface of the wood was measured with the help of this meter. The conductivity readings of the salinity of slurry used for artificial contamination of the insulators were also recorded.
3.3.4 Wood Moisture Detector

To measure moisture content in wood, a Protimeter Timbermaster moisture meter was used. The meter was calibrated before each reading for the type of wood species used during experiments. The Timbermaster meter has the ability to detect moisture content to a depth of 360mm in wood. A large liquid crystal display shows moisture content and temperature. The moisture range of this device is from 6% to well beyond fibre saturation (99.9%).

3.4 Materials

Selection of type of material for experimental testing was critical to the outcome of this research. Materials consisted of specimens of wood and insulators. Wood and insulator specimens described in the following sections were selected after intense consultation and preliminary tests. Technical consultants at two Australian power utilities were consulted regarding the appropriate specimens of wood for laboratory testing purposes.

3.4.1 Selection of Wooden Specimens used for this Study

The vast majority of the wood poles and crossarms used for power distribution and subtransmission in Australia belong to hardwood species, commonly blackbutt and spotted gum [6, 51, 52]. Moreover, the review of the literature presented in chapter 2 suggests that most previous experimental studies [18, 46] of leakage current in wood structures were conducted on softwood species such as Douglas fir, southern pine, red pine, and
cedar. Therefore, to represent the Australian situation, the Blackbutt wood species was selected for the experimental study. The two electricity distribution utilities operating in Victoria (Powercor and Jemena) kindly provided a dozen blackbutt crossarm specimens (see Figure 3.5).

![Figure 3.5 Wooden crossarms used for testing in HV laboratory.](image)

Of the dozen crossarms shown in Figure 3.5, three specimens of varying age were selected for the study (see Figure 3.6). As detailed in Table 3.2, specimen A is a timber crossarm from a new pole that had been in service less than 10 years, specimen B was taken out of the network after 10 to 20 years of service, and specimen C had been in service for more than 20 years. The dimensions of the pole are 470x92x98mm and of the crossarm 940x90x90mm.
Note that due to the limitations of the HV laboratory, particularly the size of the fog chamber, smaller size wood crossarm and pole specimens were used and single phase HV supply was feasible. The selection of mix of varying age wood specimens allowed evaluating the leakage current performance of each wood specimen.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Estimated In-Service Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>0-10 years</td>
</tr>
<tr>
<td>$B$</td>
<td>10-20 years</td>
</tr>
<tr>
<td>$C$</td>
<td>Above 20 years</td>
</tr>
</tbody>
</table>

Table 3.2 Estimated In-Service Period of Various Specimens.

Apart from their varying in-service life (age), the other distinction between the three specimens is the compactness of their wood fibre. Wood fibre is composed of layers of
crystalline cellulose wrapped in a cylindrical shape with an open centre. As the wood structure deteriorates over time, the compactness of the wood fibre decreases. The internal (heartwood) moisture content of the specimens was 8.4% which suggest that all three specimens were dry.

### 3.4.2 Insulator Samples

A pin-type insulator was used to investigate leakage current. This type of insulator is rigidly mounted on a separable pin. In the past, most pole top fires occurred on wooden crossarms with a pin type insulator mounting [2, 3]. The specifications of the insulators used for testing are shown in Table 3.3 below.

<table>
<thead>
<tr>
<th>Voltage Class (kV)</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard lightning impulse withstand voltage (kV)</td>
<td>125</td>
</tr>
<tr>
<td>Standard short duration power frequency wet withstand voltage (kV)</td>
<td>50</td>
</tr>
<tr>
<td>Standard power frequency puncture performance (kV)</td>
<td>210</td>
</tr>
<tr>
<td>Creepage distance (mm)</td>
<td>180</td>
</tr>
</tbody>
</table>

Table 3.3 Specifications of Insulator Samples.

From the literature review it was clear that the majority of the documented pole fires occurred as a result of excessive leakage current flow primarily due to salty
contamination pollution found in coastal areas. To simulate typical coastal weather conditions, the 11kV insulator sample was contaminated with slurry consisting of 40g/l kaolin plus five grams of NaCl according to the IEC 60507 [53] to simulate an intermediate degree of contamination, as depicted in Figure 3.7.

![Figure 3.7 Polluted Pin-Type Insulator Samples with varying pollution.](image)

3.5 Experimental Procedures

3.5.1 Clean Fog measurements

Moisture content is the greatest single cause of variation in resistivity: for example, a change from 50 percent for unseasoned wood to 15 percent for seasoned wood changes the resistivity by at least two orders of magnitude [54, 55]. To identify the effect of varying surface moisture content on the leakage current behaviour of three wooden specimens of different ages, four sets of tests were conducted under the experimental conditions shown in Table 3.4. Firstly, wood specimen A was kept in the fog chamber
for 30 minutes and its surface moisture content recorded directly afterwards. Next, insulator-wood specimen \( A \) was subjected to a high voltage supply as per the test setup shown in Figure 3.1 and leakage current measured. This process was repeated for wood specimens \( B \) and \( C \). Figure 3.8 below shows the specimens \( A, B \) and \( C \) in the fog chamber. Tests were conducted stable temperature of 27\(^{\circ}\)C and Humidity of 63%.

![Figure 3.8 Three wood specimens in the fog chamber.](image)

It must be pointed out here that only the wood specimens were exposed to fog during these 30-minute periods; the insulators were kept out of the fog chamber. This was done to evaluate the effect of surface moisture content on the leakage current of each wood
specimen in isolation from its corresponding insulator. The experiments were performed using a water flow of 0.8 litres per minute in the fog chamber.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Insulator and Wood Specimens</th>
<th>Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Artificially polluted Insulator and wood specimens</td>
<td>Surface moisture content 20%</td>
</tr>
<tr>
<td>2</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>Surface moisture content 25%</td>
</tr>
<tr>
<td>3</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>Surface moisture content 30%</td>
</tr>
<tr>
<td>4</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>Surface moisture content 35%</td>
</tr>
</tbody>
</table>

Table 3.4 Experimental conditions for Moisture Content Test.

3.5.2 Salt fog measurements

Previous research revealed sea spray causes higher leakage current flow on the surface of insulators located in coastal environmental conditions [56]. Therefore, to evaluate the effect of varying salt level on leakage current of each wood specimen, a series of tests was conducted at a saline water conductivity level of 0.5mS/cm to 5mS/cm. These conductivity levels were achieved by adding varying levels of NaCl in a gallon of water as per Table 3.5.
<table>
<thead>
<tr>
<th>NaCl Salt level (Grams/gallon of water)</th>
<th>Conductivity (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.08</td>
<td>0.5</td>
</tr>
<tr>
<td>2.16</td>
<td>1</td>
</tr>
<tr>
<td>3.24</td>
<td>1.5</td>
</tr>
<tr>
<td>4.32</td>
<td>2</td>
</tr>
<tr>
<td>5.4</td>
<td>2.5</td>
</tr>
<tr>
<td>6.48</td>
<td>3</td>
</tr>
<tr>
<td>7.56</td>
<td>3.5</td>
</tr>
<tr>
<td>8.64</td>
<td>4</td>
</tr>
<tr>
<td>9.72</td>
<td>4.5</td>
</tr>
<tr>
<td>10.8</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.5 Salt quantity and conductivity values.

First, the insulator wood configuration for specimen A (as per the test setup shown earlier in Figure 3.1) was kept in the fog chamber for 30 minutes at a salinity level of 1mS/cm. After this, the specimen was subjected to high voltage supply (at 11kV) in order to measure leakage current. The process was repeated for specimens B and C.

### 3.5.3 Relative Humidity Measurements

Previous researchers [36, 57] found that the relative humidity of air controls the equilibrium moisture content of air and soil which indirectly affects the moisture content within exposed wood and hence the electrical resistance of the wood. The electrical resistance of wood varies greatly with its moisture content, especially below the fibre saturation point. To study the effect of relative humidity on leakage current flow in each wood specimen, another six experiments were conducted based on the experimental conditions tabulated in Table 3.6.
Humidity inside the fog chamber was measured by a humidity meter. Leakage current measurements were recorded for each wood specimen for different levels of relative humidity inside the fog chamber. Experiments were conducted at fog conductivity of 1.5mS/cm and stable temperature of 27°C.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Insulator and Wood Specimens</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>40%</td>
</tr>
<tr>
<td>2</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>60%</td>
</tr>
<tr>
<td>4</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>70%</td>
</tr>
<tr>
<td>5</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>80%</td>
</tr>
<tr>
<td>6</td>
<td>Artificially polluted Insulator polluted and wood specimens</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 3.6 Experimental conditions for Relative humanity test.

### 3.5.4 Resistance Measurement

To measure the resistance of the three wood specimens considered in this study, each was tested in the laboratory based on testing setup shown in Figure 3.9. A high voltage conductor was directly connected to the wood via a bolt drilled into the wood surface. A high voltage ammeter was connected in series to measure current. The applied voltage was increased in steps of 5kV to a maximum of 40kV to monitor any variability in the
current flow through wood and the corresponding primary current values were recorded. By applying Ohm’s law, the electric current values were calculated.

![Measurement of wood resistance](image)

Figure 3.9 Measurement of wood resistance.

**3.6 Experimental Results**

**3.6.1 Leakage Current Under Dry Conditions**

Under dry conditions, the leakage current in wood was measured at $S_2$, $S_3$ & $S_4$ and the average value of leakage current was calculated. The entire testing procedure for specimen $A$ was repeated for specimens $B$ and $C$. An average leakage current of $431 \mu A$ was recorded from specimen $B$. The leakage current waveforms of specimens $A$, $B$ and $C$ are shown in Figure 3.10 and the average results are tabulated in Table 3.7.
Figure 3.10 Leakage current in three specimens (A, B, C) over time under dry conditions.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average leakage current in the specimen (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>147</td>
</tr>
<tr>
<td>B</td>
<td>431</td>
</tr>
<tr>
<td>C</td>
<td>992</td>
</tr>
</tbody>
</table>

Table 3.7 Average leakage current for each specimen under dry condition.

3.6.2 Effect of Moisture Content

To understand the effect of the moisture content of wood on leakage current, wood specimens were tested in wet conditions. The moisture level of each specimen was varied between 20% and 35%.
The leakage current values were measured and recorded as shown in Figure 3.11; averages are tabulated in Table 3.8. It is to be noted that the relative humidity varied from 75% to 85% during the length of testing of each specimen.

![Figure 3.11 Effect of varying moisture content on leakage current of specimens.](image-url)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average leakage current in the specimen (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>202</td>
</tr>
<tr>
<td>B</td>
<td>612</td>
</tr>
<tr>
<td>C</td>
<td>1185</td>
</tr>
</tbody>
</table>

Table 3.8 Average leakage current flow in wet conditions.
3.6.3 Effect of Relative Humidity

As per the test procedure discussed in section 3.5.3, leakage current values were recorded for each of the wood specimens and are shown in Figure 3.12 below.

![Graph showing leakage current vs relative humidity for specimens A, B, and C.](image)

Figure 3.12 Effect of varying relative humidity on leakage current of specimens.

The graph above shows that leakage current values increased with the level of relative humidity for each of the wood specimens. Specimen C (the oldest specimen) experienced higher leakage current than specimens B and C across the entire humidity range.
3.6.4 Resistance Measurements

As wood structure deteriorates over time, the compactness of the wood fibre decreases. Since wood’s resistance changes with the structure of the wood fibre, the resistance of the specimens was examined. The measurement of the wood resistance of specimens was carried out under dry conditions using the standard experimental set up with high voltage power supply and micro-ammeter as previously shown in section 3.9. It was found that the resistances of specimens A, B, C were 3.14 MΩ, 2.99 MΩ and 2.84MΩ respectively. The experimental results are tabulated in Figure 3.13 and Table 3.9.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Resistance (MΩ)</th>
<th>Average leakage current in the heartwood (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.14</td>
<td>147</td>
</tr>
<tr>
<td>B</td>
<td>2.99</td>
<td>431</td>
</tr>
<tr>
<td>C</td>
<td>2.84</td>
<td>992</td>
</tr>
</tbody>
</table>

Table 3.9 Resistance and Leakage Current measurements of wood specimens.

Figure 3.13 Comparison of resistance of specimens A, B and C.
Figure 3.13 shows that wood’s resistance decreases over its service life. Lower resistance, in part caused by less compact wood fibre, contributes to the fact that leakage current is higher in specimen C.

### 3.6.5 Density Measurements

Checks and small ruptures along the grain in wood are caused by environmental conditions. The amount of wrapping and checking that occurs as wood changes its dimensions with age are also directly related to wood density. To understand the effect of wood density on leakage current performance, the density of each specimen was calculated from measurements of its weight and volume. The masses of specimens A, B and C were measured at 9.1 kg, 7.58kg and 6.45kg respectively. The measured density of each specimen is tabulated in Table 3.10

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>758</td>
</tr>
<tr>
<td>B</td>
<td>631</td>
</tr>
<tr>
<td>C</td>
<td>537</td>
</tr>
</tbody>
</table>

Table 3.10 Density of wood specimens.
3.7 SEM Study of Ageing Wood Specimens

3.7.1 Overview

Structural variations affect the density and thermal conductivity of wood. To understand the structural variation in wooden specimens of different ages as a result of varying in-service environmental conditions, a microscopic study was undertaken with the help of a Scanning Electron Microscope (SEM). Specimens used previously to study leakage current were examined again, as they had experienced continuous mechanical, electrical, thermal and environmental stresses for up to 30 years.

3.7.2 SEM Study Test Setup and Procedure

The structural changes in wood were studied using a FEI Quanta™ scanning electron microscope as shown in Figure 3.14. The Quanta 200 SEM is a versatile high performance, low-vacuum scanning electron microscope with a tungsten electron source, with two imaging modes (high vacuum and low vacuum) to accommodate the widest range of samples of any SEM system.
Its four quadrant image display simultaneously provides surface information and phase distribution through the live imaging of secondary electron and back-scattered electron images. The operating voltage range of the SEM system is 500V to 30kV as shown in Table 3.11 below.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 kV</td>
<td>2.0 nm</td>
</tr>
<tr>
<td>15 kV</td>
<td>2.1 nm</td>
</tr>
<tr>
<td>8 kV</td>
<td>2.5 nm</td>
</tr>
<tr>
<td>3 kV</td>
<td>3.5 nm</td>
</tr>
<tr>
<td>1 kV</td>
<td>5 nm</td>
</tr>
<tr>
<td>500 V</td>
<td>7 nm</td>
</tr>
</tbody>
</table>

Table 3.11 Voltage and Resolution Range.
Rectangular cuboids shaped wood specimens of dimensions 15×15×20 mm were cut carefully from each wood specimen. Cuboids were cut with care and precaution as a clear, smooth cutting surface on the samples is important to the microscopic observations.

### 3.7.3 Visual Observations of SEM Images

The anatomic structure of the each of the three specimens revealed by electronic microscopy shows differences in their structures as can depicted in images shown in Figures 3.15 and 3.16. These images were scanned at x40 magnification and 20kV voltage.

Figure 3.15 SEM view of Specimen C (left) and specimen B (right) at x40 magnification.
1) Specimen C

SEM analysis of sample C shows cohesive failure of the middle lamella believed to be caused by loss of adhesion between the middle lamella and the outer cell wall layers (as shown in Figure 3.17); this has resulted in fibrils becoming loosened and wavy. The surface degradation, with many of the pit structures coalescing and creating deep crevasses in the wood, is due to exposure to natural environmental conditions.

Figure 3.16 SEM view of specimen A at x40 magnification.

Figure 3.17 Microscopic View of Sample C (~>20 years old).
The images in Figure 3.17 also reveal micropores, cracks and large voids in the structure of specimen C. The voids in the structure of this specimen offer pathways for water absorption due to rain and accumulation of coastal salt. The size of voids shows enlargement and thus weakening of the whole fibre structure. It also appears that the pit borders are left largely intact but some structural damage due to water can be observed. Checks are visible across or through the annual rings.

2) Specimen B

In comparison with specimen C, SEM study of specimen B showed a lower level of wood degradation caused by harsh environmental conditions (in particular rain, coastal salt and UV light). The number and size of voids is much smaller, indicating less shrinkage and checking than in specimen C as shown in Figure 3.18. Although the images reveal cohesive failure of the outer cell wall and middle lamella, this didn’t lead to significant loosening of structure.

Figure 3.18 Microscopic view of specimen B (~20 years old).
3) Specimen A

SEM images of the approximately 10 year old specimen A, shown in Figure 3.19, reveal no failure of the middle lamella or outer cell wall. The occurrence of voids and crack is rare compared to specimen C and B.

Figure 3.19 Microscopic view of specimen A (~10 years old).

3.8 Smouldering Observations in Ageing Wooden Structures

The ageing study presented in the precious section was extended to study the smouldering phenomenon leading to fire in ageing wood structures. The aim of this exercise was to study and compare the smouldering phenomenon in three wood specimens of varying age. Past investigations [26, 46] on the smouldering phenomenon leading to pole fire were based on finding factors influencing smouldering with no reference to the age of the wood. All three wood specimens (A, B and C) used
previously for leakage current testing, with dimensions 940 x 90 x 90mm were subjected to applied voltage for 30 minutes.

The test setup used resistance measurements presented previously in Figure 3.9 was used. A thin metallic nail was tightly inserted 8.9mm deep in the middle of crossarm to trigger smouldering in the wood by the heating effect of metallic contact. The temperature of the metallic pin was monitored throughout the testing period of each of the wood specimens. The wood specimens were wetted by a light mist applied with a spray gun on either side of the inserted metallic nail. It is to be noted that all three specimens were conditioned in the laboratory for three months under a fixed temperature of 26°C.

The time taken to smouldering for each sample was measured and results are tabulated in Table 3.12. Specimen C experienced smouldering after 16 minutes of initial applied voltage.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temperature of inserted Pin (degree C)</th>
<th>Time to Smouldering(minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>56</td>
<td>23</td>
</tr>
<tr>
<td>B</td>
<td>57.2</td>
<td>21</td>
</tr>
<tr>
<td>C</td>
<td>55.8</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3.12 Smouldering study results in ageing wood specimens.
It is evident that a relationship exists between the time it takes for smouldering to occur and age of wood. It was also found that that temperature range from $-55^0\text{C}$ to $58^0\text{C}$ was sufficient to start smouldering in wood specimens.

### 3.9 Discussion of Results

#### 3.9.1 Influence of Ageing on Wood Pole Structures

Specimen $C$ (>20 years old) offered lower electrical resistance and experienced higher leakage current than specimens $B$ and $C$. Table 3.8 shows the resistance of wood specimens $A$, $B$ and $C$ as $3.14 \ \text{Mohm}$, $2.99 \ \text{M}\Omega$ and $2.84 \ \text{M}\Omega$ respectively. The relatively high magnitude of leakage current flow in specimen $C$ as compared to specimen $B$ and $A$ is attributed to the fact that specimen $C$ had much longer exposure to varying environmental stresses during its service life. Those environmental stresses caused structural changes (observable via SEM) in the form of shrinkage, increased pore size and checks in wood specimens as a result of exposure to longer periods of wet and dry weather.

SEM images of specimens $A$, $B$ and $C$ presented in section 3.7.3 reveal clear differences in fibre porosity, size and wall thickness. For instance, specimen $A$ is made up of fibres with very thick cell walls and hence has a low porosity or lumen/wood tissue ratio, compared with specimen $C$ whose fibres have large lumens, thin cell walls and high porosity.
3.9.2 Porosity in Ageing Wood Specimens

It is well known that the available space for air and moisture in wood depends on the density and porosity of wood. Porosity is the volume fraction of void space in a solid, and void volume is the amount of empty/air spaces comprised by cell cavities and intercellular spaces in a given volume of wood.

The percentage of air and/or vapour in the cell lumen can be calculated based on Siah’s [58] wood porosity ($V_a$) definition:

$$V_a = 1 - G \left( \frac{1}{G_0^w} + 0.01MC \right)$$  \hspace{1cm} (3.1)

Where, $G$ ---- specific gravity;
$G_0$ ---- ovendry cell wall specific gravity, =1.53; $MC$ ---- moisture content (%);

$V_a$ is calculated based on total volume $V$ of wood. In order to base the porosity on the volume of cell lumen, it needs to be multiplied by $V/V_lumen$, which is the inverse of $V_a$ at $MC = 0$. Therefore,

$$V_1 = \frac{1 - G \left( \frac{1}{G_0^w} + 0.01MC \right)}{1 - G \frac{1}{G_0^w}}$$  \hspace{1cm} (3.2)

This $V_1$ is the percentage of porosity (contains air and vapour) in the cell lumen at certain $MC$ above FSP.
It is evident from equation (3.2) that porosity plays an important role in moisture content distribution in wood structure. Moisture distribution varies in wood of different ages. Moisture is found in wooden poles in two states, that which is in the cell cavities and that which fills voids of the cell wall. Large size voids and void spaces interconnected by openings in ageing wood allow moist air to enter the wood and affect electrical resistance.

Moreover, due to the opening of cavities and pores in ageing wood, high surface moisture (such as from rain or dew) forms a surface layer of low electrical resistance and high dielectric constant. These physical facts agree with the experimental results presented above that specimen \( C \), which spent over 20 years in an outdoor environment, offers less electrical resistance to leakage current than wood specimens \( B \) and \( A \). In addition, it appears that high porosity in specimen \( C \) resulted in increased mobility of charge carriers produced by leakage currents. During the experiments, it was observed that the temperature of wood-metallic contacts in specimen \( C \) rose slightly due to leakage current flow, promoting increased mobility of charge carriers due to thermal effects and high ionic conduction. A further increase in the temperature of the wood-metallic contact (in the experimental case, centred on king bolts) resulted in higher leakage current flows due to the thermal effect.

The results obtained from density measurements for specimens \( A \), \( B \) and \( C \) shows that wood specimen \( C \) has lower density than specimens \( B \) and \( A \). SEM images of specimens suggest that the lower density of specimen \( C \) can be attributed to the reduced thickness of the cell wall relative to the void space in and between the cells. Due to wider fissures in less dense specimen \( C \), faster heat penetration is expected during a pole fire event.
More time is required to heat the greater amount of cell wall substance for highly denser wood due to higher heat capacity.

3.9.3 Moisture Content and Relative humidity

It is a well-established fact that the moisture content of wood will increase as relative humidity increases and it will decrease as relative humidity decreases [55]. The experimental results presented here show that increased relative humidity increased the leakage current flow in all three wood specimens at constant temperature, but specimen $C$ showed relatively large variation in leakage current in comparison with specimens $A$ and $B$ when subjected to increased levels of relative humidity. The large leakage current variation in specimen $C$ is attributed to the fact that this less dense wood specimen has the ability to absorb more water vapours due to high porosity which results in increased moisture content.

3.9.4 Smouldering in Ageing Wooden Structures

From the results shown in Table 3.12, it is clear that specimen $C$, which had more than 20 years in service, smouldering occurred much faster than in specimens $B$ and $C$. This was mainly attributed to the porous structure of specimen $C$ which allowed greater inflow of oxygen which acted as a catalyst in smouldering. In specimen $A$, which has a compact structure and possesses very low porosity, lower inflow of oxygen delayed the occurrence of smouldering. A sufficient amount of oxygen is required for sustainable smouldering leading to ignition in wood. The smouldering process self-accelerates with increasing temperature of the tight wood metallic contact (in this case a metallic pin).
Early research [26] on the electrical properties of wood suggested that the main contributing factor leading to fire in wooden pole structures is the loose metallic contact at the junction between the pole and the crossarm. Previous research [26] evaluated the heating of the metallic contact caused by arcing through the loose contact; however, the experimental results detailed in this chapter show that even a tight wood-metal contact at the T-junction can lead to a pole fire. This is due to the high concentration of leakage current density around the metallic contact which heats up the wood surrounding the contact.

3.10 Summary

This chapter described the effect of ageing on the leakage current performance of wood under varying environmental conditions, the first time this phenomenon has been studied in detail with direct relevance to Australian environmental conditions. The results show that as the in-service life of wooden poles increases, the leakage current that is flowing through the timber strengthens and hence electrical performance deteriorates with age. SEM study confirmed the hypothesis of structural change in each of the wood specimens. In addition, the effect of moisture content and relative humidity on leakage current was evaluated. Finally, smouldering observations showed age-related differences in the leakage current behaviour leading to smouldering in the three wood specimens.
Chapter 4

Study of Factors Other than Ageing that Influence Leakage Current in Wood

4.1 Introduction

From the literature review (chapter 2) it is clear that leakage current in wooden structures depends on multiple factors. Ageing in wooden structures was one of the major factors studied in great detail in the previous chapter. To further enhance our knowledge leakage current flow in wooden structures, it important to study the other influential factors. This chapter presents the results of two separate experimental studies, one involving CCA treatment, and the other involving coastal salt deposition.

This chapter is organised as follows. Section 4.2 presents a detailed study of the effect of CCA treatment in spotted gum species on leakage current performance. This section describes the test setup procedures and wood specimens, presents the results of the tests and finishes with discussion. Section 4.3 presents the study of effect of coastal salt depositions on the leakage current performance of wood specimens of different ages. The test setup and wood specimens are described and the results are discussed. Finally, a brief summary of this chapter is presented in section 4.4.
4.2 Study of Influence of CCA Treatment of Spotted Gum Species on Leakage Current

4.2.1 Use of Preservatives

The vast majority of wooden poles used for power distribution in Australia and other countries are treated with preservatives to prevent or delay damage caused by rotting, fungi, termites and marine organisms. In particular, the attack of wood decaying fungi can be rapid and result in dramatic loss of pole strength [59] and shortening of the service life of the pole. Although preservative treatments and treatment methods generally reduce the mechanical properties and electrical properties of wood, any initial loss in strength due to treatment must be balanced against the progressive loss of strength from decay when untreated wood is used in the field. For many utilities, the investment in treated wooden poles comprises significant portion of a utility’s capital costs. Wood preservation allows about $500 million dollars worth of timber to be used in Australia in areas and applications for which it would otherwise be unsuitable [59]. Most of the wooden poles are treated with one of following three preservatives:

- Creosote (waterborne)
- Pentachlorophenol (oil-borne)
- Chromated copper arsenate - CCA(waterborne)

CCA is most commonly used to treat timber intended for H5 applications in Australia [6]; CCA formulations are water-soluble before the preservatives become fixed in the timber. Softwood poles used in the USA are most commonly treated with CCA,
creosote, or pentachlorophenol, while CCA and creosote are the most common preservatives used to treat poles throughout Europe [60].

4.2.2 Experimental study

The experimental work consisted of experimental setup, selection of wood specimens and testing specimens in dry and wet environmental conditions. Thermographic infrared images were taken for hot spot tracking on the surface of wood during the testing period.

4.2.3 Experimental Setup

The experimental setup consisted of a 50kVA, 415V/100kV, single phase power transformer connected to a single phase variac, two 1000:1 resistive voltage dividers, a wooden sample, galvanised bolts and nails, a 100Ω ground resistor, a Tektronix 350 MHz TDS5034B series digital phosphorous oscilloscope, two temperature sensors and a current transformer ammeter, as shown in Figure 4.1. The variac was used to control the applied voltage.

A 1000:1 resistive voltage divider was connected across the secondary of the transformer to monitor the energised line voltage supplied to the wooden sample via the 1.5MΩ resistor representing a leaking insulator. A 1.5MΩ high voltage resistor was connected in series with the transformer secondary and the wooden sample under test. This high voltage resistor was used to represent a heavily polluted insulator during the
tests. The temperature sensors were used for measuring the temperature of the bolts inserted into the wooden samples and the temperature of the high voltage resistor.

Figure 4.1 Test Set for CCA treatment study.

It is to be noted that for measurement of the resistance of wood specimens 1 and 2, the 1.5MΩ HV resistor was removed from the circuit and the secondary side of the transformer was directly connected to the electrode inserted in the wood specimens.

4.2.4 Selection of Wood Specimens

The electrical performances of waterborne and oil-borne treatments have been previously tested in wood species such as southern yellow pine, red pine, scots pine,
yellow cedar and western cedar [46]. However, the electrical performance of spotted gum wood species, which is widely used for power distribution in Australia [13], is not fully understood. The need to study the influence of CCA treatment on leakage current performance in spotted gum poles was triggered by a fire that occurred in Geelong, Victoria in 2008 [61] on a two year old (service life) CCA treated spotted gum pole located 500m from the coast. Therefore, the present experimental study is based on laboratory testing of CCA treated spotted gum pole specimens. Two CCA treated spotted gum pole specimens were selected for this study, as shown in Figure 4.2.

Figure 4.2 Pole Specimens 1 (left) and 2 (right) in the HV Laboratory.

Specimen 1 was previously installed in a coastal location for two years before it was taken out of the network and specimen 2 was kept in an indoor facility for two years before it was brought to the laboratory. Both samples had been treated with CCA preservative of H5 class as per Australian standards AS1604 and AS2209 [6]. It was recognised that pole and cross-arm geometries as well as ground conditions affect leakage current driven pole fires [26], but the objectives of the studies presented in this
chapter were to evaluate the major factors influencing the electrical performance of different wood species rather than to study in-service configurations accurately. Therefore, the original 12.5m long pole specimens supplied by the utility were cut to 3.5m in length due to the space limitations of the HV testing facility.

4.2.5 Thermographic Infrared Camera (IR)

A Thermo Vision A320 Infrared camera was used for hot spot tracking of the wood surface while the specimens were electrically tested. The spot temperatures of metallic electrodes inserted into the wood specimens were measured. The Thermo Vision A320 camera delivers accurate radiometric imaging and repeatable temperature measurements. It features an advanced, uncooled micro bolometer focal plane array detector that delivers crisp, long wave images in a multitude of palettes. The camera is a lightweight and compact camera system that measures temperatures between -20 °C and 1200°C and detects temperature differences as small as 70mK.

4.2.6 Test Procedure and Results

The following sections provide details of procedure and results for leakage current measurements under dry and wet conditions.

A) Dry Conditions

Two galvanised bolts were inserted at the end and middle of each wooden pole
specimen as per the test setup, shown in Figure 4.1. The end bolt was subjected to high voltage through a 1.5 MΩ resistor bank. A temperature sensor was connected to the bolt in the middle. The base end of the wooden pole sample was earthed through a metal nail. The wooden pole specimens were subjected to a leakage current by varying the voltage applied to the series HV resistor from 0kV to 50kV over a period of 30mins. The measured leakage currents values for the specimens are shown in Figure 4.3.

![Figure 4.3 Leakage current of the wood specimens under dry conditions.](image)

Figure 4.3 clearly shows that leakage current increased as the applied voltage was increased. The temperature of the middle bolt inserted in the wood was the same as the ambient temperature of 29°C for the applied voltage level from 0 to 20kV. As the applied voltage was increased further, the temperature of the metallic contact started to increase. At leakage current value of 4.5mA in both specimens, smouldering began around the middle bolt and the temperature was recorded by the IR camera as 54°C. Note that the average surface moisture for the wood specimens under dry conditions
was 8.5%.

Figure 4.3 shows that slightly higher leakage current values were recorded for specimen 1 than specimen 2. This could be attributed to specimen 1’s longer exposure to harsh coastal environmental conditions. The laboratory tests conducted by Wickham [27] revealed that CCA can leach from the outer surface of treated wood after outdoor exposure resulting in high leakage current. The above results confirm the previous findings.

B) Wet Conditions

Saline water of 1.5mS/cm conductivity was sprayed onto the surface of the wooden pole to simulate a typical 30 minute Victorian coastal rainfall as shown in Figure 4.4. The middle section was kept dry to provide a dry band [46] for heating of galvanized bolt. The average moisture levels of the wet surfaces in the wooden pole specimens were recorded using a Timbermaster Protimeter and were 32% and 30% for the top end and bottom end surfaces respectively.
The Electricity Authority of NSW demonstrated [62, 63] that seldom does a wooden power line pole exposed to natural weather conditions reach a moisture level exceeding much more than 20%. Therefore, the type of drenching employed in the test is a good simulation of rain falling on the surface of the wood pole. The test procedures for the dry condition described above were repeated under wet conditions with similar voltage levels and the calculated leakage currents for the specimens recorded. The results are shown in Figure 5.5.
As can be surmised from Figure 4.5, higher magnitude leakage currents were recorded in wet conditions compared to dry conditions. The surface moisture reduces the electrical resistance of the specimens, thereby producing higher leakage current values. Before the test, the temperature of a metallic electrode inserted in the wood was measured at 29°C, but 3.1mA of leakage current increased the temperatures of the metallic electrodes in both test specimens. IR images presented in the following section confirm the hot spot activity in the wood as a result of leakage current flow.

4.2.7 Thermographic IR Camera Images

Infrared thermographic imaging was performed using an IR camera while testing the specimen-1 and 2 in the high voltage laboratory. Voltage applied to a bolt inserted into a hole in the pole was increased and caused an increasing leakage current flow through the wood, in turn causing the metallic contacts to heat up and eventually start
smouldering in the wood. At this stage the supply was turned off and the bolt was removed from the wood. Infrared images of the bolt and its hole were captured. Figure 4.6 shows the maximum temperature of the metal bolt was 66.7°C and Figure 4.7 shows the maximum temperature of the wood in contact with the bolt was 93.3°C.

Figure 4.6 Infrared image of a bolt removed immediately after smouldering began.

Figure 4.7 Infrared image of the hole following bolt removal.
The IR camera captured the persistent incandescent glow of the bolt caused by the heat produced as result of the leakage current flow in each wood specimen. The threshold value at which the leakage current caused smouldering and glow in wood was measured as 3.2mA in specimen 1 and 4.1mA in specimen 2. These observations validated some of the anecdotal evidence which suggests that the ignition of pole fires usually takes place in the junction between the metallic accessories such as king bolts or insulator base-pins and the timber pole. This junction forms a hotspot in the wooden structure and is prone to smouldering.

### 4.2.8 Pole Resistance Measurement Test

To measure the resistance of the wood specimens, a test setup shown in Figure 4.8 was used.

![Figure 4.8 Setup used for Resistance Measurements.](image-url)
The applied voltage level was increased from 0kV to 40kV to measure the current flow in wood specimens in dry and wet conditions. Metallic electrodes inserted in the wood previously were removed from each specimen. Resistance values were calculated and plotted against the applied voltage as shown in Figures 4.9 and 4.10 below.

Figure 4.9 Specimen 1 Resistance for Various Applied Voltage Levels.

Figure 4.10 Specimen 2 Resistance for Various Applied Voltage Levels.
It is interesting to note that under wet conditions, specimen 1 had very low fixed resistance of approximately 400kΩ for the voltage range of 5kV to 40kV whereas specimen 2 offered high resistance. This is attributed to the fact that natural weathering impacted the electrical properties of specimen 1 during its two year in service in harsh conditions.

4.2.9 Comparison with Other Researchers’ Results

This section compares the results obtained from the present study with those produced by Filter [46]. The average glow current values for CCA treated wood species of jack pine, southern yellow pine and red pine measured by Filter were 5mA, 6mA and 2mA respectively. The present study recorded an average glow current of 3.65mA in spotted gum species, consistent with the results obtained for other species by Filter.

4.2.10 Discussion of Results

As mentioned previously, it was regarded as important to test the leakage current performance of CCA treated spotted gum poles due to recent spate of pole fire issues experienced in Australia. The experiments conducted on two wood pole specimens described above show that CCA treatment greatly reduces the electrical resistance of the pole which offers a low resistance path for leakage current to flow
Leakage current flow in the wood specimens doubled as the surface moisture content increased from 8.5% to 30%. It was found that the effect of salt impregnants is negligible in wood at 8 percent or lower moisture content, but rapidly becomes more important at moisture contents above 10 percent. The CCA salts present in treated wood specimens act as a catalyst to hydrolytic and oxidation reactions within cell walls triggered by ionic charges of leakage current. Salt formulations in CCA generate excessive sodium ions which become available to transport of leakage current, thereby significantly increasing the electrical conductivity.

The Infrared camera images revealed the hotspots in the wood specimens under electric stress. Specimens 1 and 2 started to smoulder within a few minutes of the application of electrical stress. Table 4.1 below shows the time taken for smouldering to start in wood as assessed by visual inspection.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temperature of inserted Pin (C)</th>
<th>Time to Smouldering (minutes)</th>
<th>Environmental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66.7</td>
<td>6</td>
<td>Ambient temperature of 27°C and relative humidity of 67%</td>
</tr>
<tr>
<td>2</td>
<td>67.5</td>
<td>8.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Smouldering study results in CCA treated specimens.
4.3 Study of the Effect of Coastal Salt Deposition on Leakage Current in Wood

4.3.1 Coastal Environmental conditions

As the vast majority of the Australian population lives on or near the coast, coastal pollution plays an important role in the overall performance of overhead transmission and distribution lines supplying electricity. Most wooden poles in service in Australia are contaminated with salt due to the natural evaporation and transport of salt from the ocean; hence the understanding of the influence of salt deposits in wooden pole surface on the electrical performance is important. Strong winds transports sea salt to the wooden pole structures and long periods of dry weather contribute to the accumulation of salty contaminants on the surface of insulator and wooden poles. In addition, during summer in Australia, the sea temperature is higher than the air temperature, and moisture and fog consequently come from the sea [64]; therefore, sea wind in summer contains moisture and heavy salt particles.

In the literature review presented in Chapter 2, it was noted that the effect of salt contamination of insulator surfaces on leakage performance has been studied in detail previously, but the effect of salt contamination on the electrical performance of a wood surface had not. Therefore, the present study makes a novel contribution to its field.
4.3.2 Experimental study

The experiment involved electrical testing of wood specimens artificially coated with sea salt. The experimental work consisted of test setup, artificial salt contamination procedure and the tests themselves; the results are presented in the following sections.

4.3.3 Test Setup and Wood Specimens

A leakage current measurement system as shown in Figure 3.3 and wood specimens $A$, $B$ and $C$ (blackbutt species) used in the ageing study as presented in chapter 3 were used for the study outlined in this section.

4.3.4 Artificial Contamination Procedure of Wood Specimens

There is no current international electro-technical commission standard in place for artificial surface contamination of wood for electrical testing. Therefore, every attempt was made to artificially contaminate the wood samples in a manner as close as possible to natural coastal salt deposits on the surface of wood. Varying amounts of NaCl were added to a gallon water to achieve conductivity levels as shown in Table 4.2. Each specimen was dried for 24 hours each time a contaminant of different salinity level was applied.
<table>
<thead>
<tr>
<th>NaCl Salt level (Grams/gallon of water)</th>
<th>Conductivity (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.08</td>
<td>0.5</td>
</tr>
<tr>
<td>2.16</td>
<td>1</td>
</tr>
<tr>
<td>3.24</td>
<td>1.5</td>
</tr>
<tr>
<td>4.32</td>
<td>2</td>
</tr>
<tr>
<td>5.4</td>
<td>2.5</td>
</tr>
<tr>
<td>6.48</td>
<td>3</td>
</tr>
<tr>
<td>7.56</td>
<td>3.5</td>
</tr>
<tr>
<td>8.64</td>
<td>4</td>
</tr>
<tr>
<td>9.72</td>
<td>4.5</td>
</tr>
<tr>
<td>10.8</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.2 Salt quantity and conductivity values.

4.3.5 Test procedure

As per test # 1 shown in Table 4.3, the first set of experiments consisted of recording leakage current values for each wood specimen before application of artificial contaminants. Then, leakage current values were recorded for each wood specimen after 1mS/cm conductivity level of contamination had been applied to the wood. The above procedure was repeated for test # 3, 4, 5 and 6 as per Table 4.3.
### Table 4.3 Experimental Conditions.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Insulator and Wood Specimens</th>
<th>Environmental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insulator polluted and wood specimens clean</td>
<td>Stable environmental conditions of Temperature at 27C and Humidity at 63% for all tests</td>
</tr>
<tr>
<td>2</td>
<td>Insulator polluted and wood specimens sprayed at 1mS/cm</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Insulator polluted and wood specimens sprayed at 2mS/cm</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Insulator polluted and wood specimens sprayed at 3mS/cm</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Insulator polluted and wood specimens sprayed at 4mS/cm</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Insulator polluted and wood specimens sprayed at 5mS/cm</td>
<td></td>
</tr>
</tbody>
</table>

**4.3.6 Results**

Figure 4.11 shows that the leakage current flow increased with increases in the conductivity level of salt deposits on the surface of the wood specimens. In particular, leakage current in specimen C was significantly higher than in specimens A and B; this is attributed to the accumulation of salt deposits in the pores present in specimen C.
In contrast, wood specimen \( A \) has low porosity and no cracks and salt particles are unable to enter the internal structure of the wood. Prolonged contact with moist salt particles helps the oxidation and conduction of salts in the presence of leakage current charges. Strong sea breezes force moist salt particles into internal pores and external cracks of wood poles which results in an increase in moisture content and the electrical conductivity of the wood.

The measurements reported here of the effect on leakage current of salt deposits on the surfaces of three wood specimens of different ages are the first such data known to have been generated. Although the effect of coastal salt deposit on insulators on leakage current has been studied in great detail, the effect of salt deposits on wood surfaces on leakage current performance has been ignored.
4.4 Summary

It was also confirmed that CCA reduces the electrical resistance of wood and hence induces higher leakage current activity. The effect of surface contamination of wood surfaces due to coastal salt deposition was investigated for the first time; the results suggest that salt deposition on the surface of wooden poles increases the leakage current.
Chapter 5

A Novel Leakage Current Model Based on Dimensional Analysis

5.1 Introduction

Laboratory studies and industrial experience show that numerous physical processes are involved in excessive leakage current (due to contamination on the surface of insulators) leading to fire in wooden structures. It is critical that a novel mathematical model of leakage current on insulators and wooden structures is developed to substantially enhance understanding of the factors contributing to their performance. This chapter presents the development of a model based on dimensional analysis which establishes a relationship between leakage current and relevant influencing factors for both insulators and wooden structures. In this chapter, for the first time, a complete leakage current flow mechanism of insulator and wooden structure is introduced.

This chapter is organised as follows. Section 5.2 briefly outlines the phenomenon of leakage current flow, then gives an introduction to the dimensional analysis technique. Section 5.3 presents the leakage current flow mechanism in insulators and wood and provides details of the methodology used for mathematical modelling. Section 5.4 presents the leakage current model developed for insulators. In section 5.5, a leakage
current model for wood is introduced. A complete mathematical model for leakage current on insulators and wood is presented in section 5.6. Section 5.7 shows how the mathematical model was validated by comparing analytical results and experimental results, and the chapter concludes in section 5.8 with a summary.

5.2 Mathematical Modelling

5.2.1 The Leakage Current Phenomenon

The phenomenon of leakage current flow on insulators and wooden structures is dependent on several important parameters including environmental parameters and the properties of wood, so it is multidimensional in nature. At one point in time, multiple parameters can influence the leakage current flow on an insulator and wood. Several previous mathematical models [40, 41, 42, 43] have been proposed for leakage current flow on insulators due to environmental stresses; however, only a few mathematical models of leakage current flow in wooden structures have been developed. The existing mathematical models [44, 45], based on the ladder network technique, failed to take into account the influences of environmental factors such as temperature, humidity, and coastal salt deposit conductivity on leakage current in wood.
5.2.2 Dimensional Analysis

The first step in modelling any physical phenomenon is the identification of the relevant variables affecting the physical process and then relating these variables via known physical laws. For sufficiently simple phenomena, we can usually construct a quantitative relationship among these variables from first principles. However, for many complex phenomena, such as leakage current flow on insulators and wood leading to a wooden pole fire, which involves multiple influencing variables, theory is often difficult, if not impossible. In these situations modelling methods are indispensable, and one of the most powerful modelling methods is dimensional analysis.

Dimensional analysis is a mathematical modelling tool used primarily for obtaining information about physical systems which are often too complicated for full mathematical solutions to be devised. It enables one to predict the behaviour of large systems from a study of small-scale models. The method is of great generality and mathematical simplicity [65, 66]. This analytical technique can contribute to model formation and has been used successfully on a very wide range of applications in experimentally-based physical sciences and engineering. Dimensional analysis is also used to form hypotheses about complex physical situations that can be tested by experiments.

Dimensional analysis finds the relations among physical quantities by using their dimensions. Most physical quantities can be expressed in terms of combinations of five basic dimensions. These are mass ($M$), length ($L$), time ($T$), electrical current ($A$), and temperature ($K$).
5.2.3 Past Use of Dimensional Analysis Technique

In the field of high voltage insulation failure, dimensional analysis modelling technique has been employed to develop a mathematical relationship between leakage current of wet contaminated insulator and various influencing factors [42]. In addition, this technique was applied [67, 68, 69, 70] for establishing relationship between leakage current and variable contaminant flow rate in insulators under varying environmental conditions.

Dimensional analysis has been applied in aerodynamics, hydraulics, ship design, propulsion, heat and mass transfer, combustion, mechanics of elastic and plastic structures, fluid-structure interactions, electromagnetic theory, radiation, astrophysics, underwater and underground explosions, nuclear blasts, impact dynamics, and chemical reactions and processing [70]. A further application of dimensional analysis is in model design. As noted earlier, often the behaviour of large complex systems can be deduced from studies of small-scale models at a great saving in cost. In the model each parameter is reduced in proportion to its value in the original situation.

5.3 Leakage Current Mechanism and Modelling Methodology

The mechanism of leakage current flows through insulators and wooden structures is a complex one and yet to be fully understood. The complexity is due to the influence of a set of varying parameters that solely impact the leakage current at source level (the insulator) and another set of parameters that solely influence the leakage current at
impact level (wood). It is important to understand the mechanism of leakage current at source and impact level as they are totally different mechanisms driven by different parameters.

![Figure 5.1 Leakage current mechanism on insulator and wooden pole.](image)

The complex leakage current flow phenomenon is shown in Figure 5.1. To simplify the complexity of the overall leakage current mechanism in an insulator-wood pole configuration for modelling purposes, the methodology adopted for developing models for the complex leakage current phenomenon was based on following:

A. Source Level - leakage current model for insulator

B. Impact Level - leakage current model for wood

C. Source and Impact - complete leakage current model for insulator and wood
First, a model was developed for leakage current flow on an insulator based on the dimensional analysis technique. Relevant parameters influencing leakage current flow on insulators were modelled. Second, an empirical relationship was developed for leakage current flow in wood based on dimensional analysis technique. A relationship involving relevant parameters influencing the leakage current flow in wood was developed. Finally, the parameters influencing leakage current in both insulator and wood were combined and a complete empirical relationship was developed.

The outcome of the modelling based on the methodology given above is presented in Table 5.1 below in the form of empirical formulae linking leakage current and parameters influencing the flow of leakage current on insulators and wooden poles.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Empirical Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>( I = D_s \ (H)^{1/2} \ (\alpha)^{1/2} \ (q)^{3/4} \ (V)^{3/4} )</td>
</tr>
<tr>
<td>Impact</td>
<td>( I = D_i \ (k)^{1} \ (C)^{-3/4} \ (t)^{1/4} \ (D)^{-1/2} \ (Z)^{-1/2} )</td>
</tr>
<tr>
<td>Combined (Source and Impact)</td>
<td>( I = D_{si} \ (k)^{1} \ (\alpha) \ (H) \ (V) \ (C)^{-21/4} \ (t)^{3/4} \ (D)^{-9/2} \ (Z)^{-3/2} )</td>
</tr>
</tbody>
</table>

Table 5.1 Empirical relationship for leakage current flow mechanism.

Details on how each of the above empirical relationships was developed are given in the following sections.
5.4 A Leakage Current Model for the Insulator

Most high voltage insulators are used in outdoor applications for power distribution and transmission. Environmental pollution can cause the insulators to become progressively coated with contaminants such as salt, dirt and chemicals in the long term [42, 43, 68]. Under wet atmospheric conditions, the contaminating particles on the insulator surface will dissolve into the water and provide a continuous conducting path between the high-voltage electrode and ground. The surface resistance of the insulator decreases considerably in the presence of wet contaminated conditions. The magnitude of leakage current varies with the contamination level and the volume of contaminants that are accumulated on the insulator surface [71].

Physical parameters such as environmental humidity $H$, contaminant solution conductivity $\alpha$, Contaminant flow rate $q$, Wind Velocity $V$, and the environmental temperature $t$ have been previously found to influence leakage current flow on insulator [42].

According to the dimensional analysis technique, the relationship between leakage current $I$ and the above-mentioned physical parameters can be expressed as:

$$I = f (H, \alpha, q, V, t)$$  \hspace{1cm} (5.1)

The dimensions of these quantities are represented (table 3.2) in $M$ (mass), $L$ (length), $T$ (time), $A$ (electric current) and $K$ (temperature).
According to the Buckingham Pi theorem [72] if \( n \) variables are connected by an unknown dimensionally homogeneous equation, the equation can be expressed in the form of a relation between \( n - r \) dimensionless products \( \pi_s \), where \( n - r \) is the number of products in a complete set. Hence,

\[
f(\pi_1, \pi_2, \pi_3, \ldots, \pi_{n-r}) = 0
\]

The dimensional formula for relation equation (5.1) can be written as:

\[
[M^0 L^0 T^0 A^1 K^0]^01 [M^1 L^{-3} T^0 A^0 K^0]^02 [M^{-1} L^{-3} T^3 A^2 K^0]^03 [M^0 L^3 T^{-1} A^0 K^0]^04 \times
\]
\[
[M^0 L^1 T^{-1} A^0 K^0]^05 [M^0 L^0 T^0 A^0 K^1]^06 = [M^0 L^0 T^0 A^0 K^0]
\]

(5.2)

By equating the powers of the fundamental units on both sides of equation (5.2), a set of simultaneous linear equations are obtained which can later be solved to obtain the
magnitudes of these constants. To utilise the algebraic approach to dimensional analysis, it is convenient to write the dimensions of the variables in matrix form:

\[
\begin{pmatrix}
(a_1) & (a_2) & (a_3) & (a_4) & (a_5) & (a_6) \\
I & H & \alpha & q & V & t
\end{pmatrix}
\]

\[
\begin{pmatrix}
M \\
L \\
T \\
A \\
K
\end{pmatrix}
\begin{pmatrix}
0 & 1 & -1 & 0 & 0 & 0 \\
0 & -3 & -3 & 3 & 1 & 0 \\
0 & 0 & 3 & -1 & -1 & 0 \\
1 & 0 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\]

The rank of the dimensional matrix can be determined by solving the determinant formed from the square matrix of the last five columns, i.e.:

\[
\begin{vmatrix}
1 & -1 & 0 & 0 & 0 \\
-3 & -3 & 3 & 1 & 0 \\
0 & 3 & -1 & -1 & 0 \\
0 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1
\end{vmatrix} = 4
\]
Since this is a fifth order determinant and is not equal to zero, the rank of the dimensional matrix is five. It has been shown [73] that the number of dimensionless products in a complete set is equal to the difference between the total number of variables and the rank of their dimensional matrix. Therefore in the present case, since there are six variables and the matrix is of rank five, there will only be one dimensionless product in the complete set of equations.

**Dimensionless Products**

The homogeneous linear algebraic equations, the coefficients of which are the numbers in the rows of the dimensional matrix, can be written as:

\[
\begin{align*}
  a_2 - a_3 & = 0 & (5.3) \\
  -3a_2 - 3a_3 + 3a_4 + a_5 &= 0 & (5.4) \\
  3a_3 - a_4 - a_5 &= 0 & (5.5) \\
  a_1 + 2a_3 &= 0 & (5.6) \\
  a_6 &= 0 & (5.7) 
\end{align*}
\]

The expressions of \(a_2, a_3, a_4, a_5,\) and \(a_6\) in terms of \(a_1\) can be derived from equations (5.3) to (5.7); they are:
\[ a_2 = -1/2 \ a_1, \ a_3 = -1/2 \ a_1, \ a_4 = -3/4 \ a_1, \ a_5 = -3/4 \ a_1 \quad \text{and} \quad a_6 = 0 \quad (5.8) \]

By assigning the value of \( a_1 = 1 \), the expression for equation (5.8) can be written in matrix form as follows:

\[
\begin{bmatrix}
  a_1 & a_2 & a_3 & a_4 & a_5 & a_6 \\
  I & H & \alpha & q & V & t
\end{bmatrix}
\]

\[ \Pi = I \quad H^{-1/2} \quad \alpha^{-1/2} \quad q^{-3/4} \quad V^{3/4} \quad t^0 \quad (5.9) \]

This can be rewritten as:

\[
I = D_s \ (H)^{1/2} \ (\alpha)^{1/2} \ (q)^{3/4} \ (V)^{3/4} \quad (5.10)
\]

where \( D_s \) is a dimensionless constant.
5.5 A Leakage Current Model for Wood

As per Kirchhoff’s current law, there has to be a closed loop for the current to flow. After flowing through the surface of the insulator, leakage current enters the wood structure and flows through to the ground by closing the loop. The electrical deterioration of the wood, leads to a fire when leakage current flows through it, and is influenced by the various properties of wood such as thermal conductivity, density, specific heat, and electrical resistance. Moisture content has been found to be the most significant parameter influencing the electrical resistance of wood [55]. It is well known that moisture content is dependent on parameters such as atmospheric temperature and density of wood [55], therefore, to account for change in moisture content of wood, these parameters were included in the development of the leakage current model.

A mathematical model was developed to understand the relationship between the leakage current \( I \) flow through wood and parameters such as thermal conductivity \( k \), specific heat \( C \), atmospheric temperature \( t \), density \( D \) and electrical resistance of wood \( Z \).

Applying dimensional analysis, the relationship between leakage current \( I \) and above mentioned parameters can be expressed as:

\[
I = f(k, C, t, D, Z) \quad (5.11)
\]

The dimensions of theses quantities are represented (table 5.3)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage Current</td>
<td>$I$</td>
<td>$M^0 L^0 T^0 A^1 K^0$</td>
</tr>
<tr>
<td>Thermal conductivity of wood</td>
<td>$k$</td>
<td>$M^1 L^1 T^{-3} A^0 K^{-1}$</td>
</tr>
<tr>
<td>Specific heat of wood</td>
<td>$C$</td>
<td>$M^0 L^2 T^{-2} A^0 K^{-1}$</td>
</tr>
<tr>
<td>Environmental Temperature</td>
<td>$t$</td>
<td>$M^0 L^0 T^0 A^0 K^1$</td>
</tr>
<tr>
<td>Density of wood</td>
<td>$D$</td>
<td>$M^1 L^{-3} T^0 A^0 K^0$</td>
</tr>
<tr>
<td>Resistance of wood</td>
<td>$Z$</td>
<td>$M^1 L^2 T^{-3} A^2 K^0$</td>
</tr>
</tbody>
</table>

Table 5.3 Dimensions of each parameter.

As per Buckingham's Pi theorem, the dimensional formula for equation (5.11) can be written as:

$$[M^0 L^0 T^0 A^0 K^0]a_1 [M^1 L^1 T^{-3} A^0 K^{-1}]a_2 [M^0 L^2 T^{-2} A^0 K^{-1}]a_3 [M^0 L^0 T^0 A^0 K^1]a_4 X$$

$$X [M^1 L^{-3} T^0 A^0 K^0]a_5 [M^1 L^2 T^{-3} A^{-2} K^0]a_6 = [M^0 L^0 T^0 A^0 K^0]$$ (5.12)

To utilise the algebraic approach to dimensional analysis, it is convenient to write the dimensions of the variables in matrix form:
The rank of the dimensional matrix was found to be five. Since there are six variables and the matrix is of rank five, there will only be one dimensionless product in the complete set of equations as per the Buckingham Pi theorem.

By equating the powers of the fundamental units on both sides of equation (5.12), a set of simultaneous linear equations can be obtained as shown below:

\[
\begin{align*}
\mathbf{a}_2 + \mathbf{a}_5 + \mathbf{a}_6 &= 0 \\
\mathbf{a}_2 + 2\mathbf{a}_3 - 3\mathbf{a}_5 + 2\mathbf{a}_6 &= 0 \\
-3\mathbf{a}_2 - 2\mathbf{a}_3 - 3\mathbf{a}_6 &= 0 \\
\mathbf{a}_1 - 2\mathbf{a}_6 &= 0 \\
-\mathbf{a}_2 - \mathbf{a}_3 + \mathbf{a}_4 &= 0
\end{align*}
\]

(5.13) \hspace{1cm} (5.14) \hspace{1cm} (5.15) \hspace{1cm} (5.16) \hspace{1cm} (5.17)

The expressions of \(a_2, a_3, a_4, a_5,\) and \(a_6\) in terms of \(a_1\) can be derived from equations.
(5.13) to (5.17); these expressions are:

\[\begin{align*}
    a_2 &= -a_1, \\
    a_3 &= \frac{3a_1}{4}, \\
    a_4 &= -\frac{a_1}{4}, \\
    a_5 &= a_1/2, \quad \text{and} \\
    a_6 &= a_1/2
\end{align*}\]  

(5.18)

By assigning the value of \(a_1 = 1\), the expression for equation (5.18) can be written in matrix as follows:

\[
I = D_i (k)^1 (C)^{3/4} \left(\frac{t}{t_1}\right)^{1/4} \left(D\right)^{-1/2} \left(Z\right)^{-1/2} 
\]  

(5.19)

where \(D_i\) is a dimensional constant.

5.6 A Complete Leakage Current Model for Insulator and Wood

The parameters influencing leakage current in insulators and wood are combined with the aim of developing a complete model to address the leakage current phenomenon taking into account both source and impact (previously shown in Figure 5.1). It is to be noted that the complete model is derived by following the same approach used in developing the models for insulators and wood presented in sections 5.4 and 5.5 respectively.

According to the dimensional analysis technique, the relationship between leakage current \(I\) and environmental humidity \(H\), contaminant solution conductivity \(\alpha\), contaminant flow rate \(q\), wind velocity \(V\), thermal conductivity of wood \(k\), specific heat of wood \(C\), density of wood \(D\), environmental temperature \(t\) and resistance of wood \(Z\), can be expressed as:
\[ I = f (H, \alpha, q, V, k, C, t, D, Z) \]  \hspace{1cm} (5.21)

According to the Buckingham Pi theorem, the dimensional formula for relation equation (5.21) can be written as:

\[
\begin{align*}
[M^0 L^0 T^0 A^1 K^0]^{a_1} [M^1 L^{-3} T^0 A^0 K^0]^{a_2} [M^1 L^{-3} T^3 A^2 K^0]^{a_3} [M^0 L^1 T^{-1} A^0 K^0]^{a_4} \times [M^1 L^1 T^3 A^0 K^1]^{a_5} [M^0 L^2 T^2 A^0 K^{-1}]^{a_6} [M^0 L^0 T^0 A^0 K^1]^{a_7} \times [M^0 L^3 T^0 A^0 K^0]^{a_8} [M^0 L^0 T^0 A^0 K^0]^{a_9} = [M^0 L^0 T^0 A^0 K^0] \end{align*}
\]  \hspace{1cm} (5.22)

By equating the powers of the fundamental units on both sides of equation (5.22), a set of simultaneous linear equations are obtained which can later be solved to obtain the magnitudes of these constants.

\[
\begin{align*}
-3a_2 - 3a_3 + a_5 + a_8 + 2a_9 &= 0 \hspace{1cm} (5.23) \\
3a_3 - a_4 - 3a_5 - 2a_6 - 3a_9 &= 0 \hspace{1cm} (5.24) \\
a_1 - 2a_3 - 2a_9 &= 0 \hspace{1cm} (5.25) \\
a_5 - a_6 + a_7 &= 0 \hspace{1cm} (5.26) \\
\end{align*}
\]

Assigning the values \( a_1 = 1, a_2 = 0, a_3 = 0 \) and \( a_4 = 0 \) in equations (5.23) to (5.27) for the first solution gives:

\[
a_5 = -1, a_6 = 1/4, a_7 = -3/4, a_8 = 1/2, a_9 = 1/2
\]
Similarly assigning the values $a_1 = 0$, $a_2 = 1$, $a_3 = 0$ and $a_4 = 0$ in equations (5.23) to (5.27) for the second solution gives:

$$a_5 = 0, a_6 = 0, a_7 = 0, a_8 = -1, a_9 = 0$$

Similarly assigning the values $a_1 = 0$, $a_2 = 0$, $a_3 = 1$ and $a_4 = 0$ in equations (5.23) to (5.27) for the third solution gives:

$$a_5 = 5, a_6 = -9/2, a_7 = 1/2, a_8 = -3, a_9 = -1$$

Similarly assigning the values $a_1 = 0$, $a_2 = 0$, $a_3 = 0$ and $a_4 = 1$ in equations (5.23) to (5.27) for the fourth solution gives:

$$a_5 = 0, a_6 = -1/2, a_7 = -1/2, a_8 = 0, a_9 = 0$$

<table>
<thead>
<tr>
<th>$\pi$</th>
<th>$I$</th>
<th>$H$</th>
<th>$\alpha$</th>
<th>$V$</th>
<th>$k$</th>
<th>$C$</th>
<th>$t$</th>
<th>$D$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>1/4</td>
<td>-3/4</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>$\pi_2$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\pi_3$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>-9/2</td>
<td>1/2</td>
<td>-3</td>
<td>-1</td>
</tr>
<tr>
<td>$\pi_4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1/2</td>
<td>-1/2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Since the matrix of solutions contains \( n - r \) row where \( n = 9 \) is the number of variables and \( r = 5 \) is the rank of the matrix, it constitutes a fundamental system of solutions.

Each row in the matrix of solutions is a dimensionless product. In the present study, the following complete set of dimensionless products was obtained:

\[
\begin{align*}
\pi_1 &= I \frac{k^1}{k} C^{1/4} t^{3/4} D^{1/2} Z^{1/2} & (5.28) \\
\pi_2 &= H D^{-1} & (5.29) \\
\pi_3 &= \alpha k^5 C^{9/2} t^{1/2} D^3 Z^1 & (5.30) \\
\pi_4 &= V C^{1/2} t^{1/2} & (5.31)
\end{align*}
\]

According to the Buckingham Pi theorem [72], the relation between the dimensionless products of equations (5.28 to 5.31) can be written as:

\[
\begin{align*}
&f(\pi_1, \pi_2, \pi_3, \pi_4) = 0 & (5.32) \\
&\pi_1 = f(\pi_2, \pi_3, \pi_4) & (5.33)
\end{align*}
\]

Equation (5.33) is rearranged in order to show the relationship of leakage current to the other parameters as depicted in equation (5.34):

\[
I = k^1 C^{1/4} t^{3/4} D^{-1/2} Z^{1/2} f(\pi_2^{a_1}, \pi_3^{a_2}, \pi_4^{a_3}) & (5.34)
\]
\(\alpha_1, \alpha_2, \alpha_3,\) and \(\alpha_4\) can be assigned by looking through the relationship between leakage current, environmental parameters, and contamination conductivity. Since it has already been found from experimental study in chapter 3 and 4 that leakage current is directly proportional to humidity, contaminant conductivity, and wind velocity, those factors are assigned as \(\alpha_1 = \alpha_2 = \alpha_3 = 1\)

Finally, the model of leakage current can be written as:

\[
I = D_{si} k^l \alpha H V C^{-21/4} t^{3/4} D^{-9/2} Z^{3/2} \quad (5.35)
\]

where \(D_{si}\) is a dimensional constant.

### 5.7 Validation of Complete Mathematical Model

#### 5.7.1 Validation Methodology

It is important to validate the complete leakage current model previously presented in section 5.6. The validation of this model was performed by comparing the results obtained from experimental study with the analytical results obtained from the model. It must be pointed out here that individual models developed for leakage current insulator and wood in sections 5.4 and 5.4 were not validated as the presented research is focused on understanding the complete leakage current flow mechanism. Therefore, the complete model presented in section 5.6 was validated. The final empirical equation (5.35) derived previously consists of multiple parameters which influence leakage
current flow on insulators and wood. It must be noted that to validate the correlation between all the parameters and leakage current in wood at one time is a cumbersome process. To avoid this, simplified mathematical expressions were developed based on the experiments presented previously in chapters 3 and 4 and presented in the following sections.

5.7.2 Leakage Current and Relative Humidity

Experimental study of the effect of relative humidity on the leakage current performance of each wood specimen shows a linear relationship exists between leakage current and relative humidity.

Equation (5.35) includes variables which influence the leakage current in wood. Some of the variables have negligible effect on leakage current under any given environmental conditions. Therefore, to highlight the relationship between relative humidity and leakage current in wood, variables such as wind velocity V, conductivity flow rate q, thermal conductivity K, contaminant conductivity α, temperature t and specific heat C were considered as constants.

Therefore equation 5.35 can be written as:

\[ I = D_I (H) (D)^{-4.5} (Z)^{-1.5} \]  

(5.36)

where \( D_I \) is a dimensional factor and its value is determined from the experiments.
Experimental data recorded on leakage current values for varying relative humidity values and resistances for each of the three wood specimens $A$, $B$ and $C$ were used to calculate the dimensional constant $D_1$ which are plotted on an XY scatter graph in Figure 5.2. The data show a linear trend. The straight line, which was fitted by the method of least squares, gives a value of 0.990 for the dimensional constant $D_1$.

![Figure 5.2 Best fit curve derived from experimental data plot to determine value of $D_1$.](image)

The analytical results obtained from the model are compared with the experimental results for the three wood specimens $A$, $B$ and $C$ and are shown in Figures 5.3, 5.4 and 5.5.
Figure 5.3 Comparison of model and experimental results for wood specimen $A$. 

Figure 5.4 Comparison of model and experimental results for wood specimen $B$. 
The results presented in Figures 5.3, 5.4 and 5.5 show that the model results are in good agreement with the experimental results.

5.7.3 Leakage Current and Coastal Salt Deposit Conductivity

From the experimental results, it was found that leakage current increases with increased coastal salt deposit conductivity in wood structures under fixed temperature and humidity conditions. To further validate the model, experimental results on the effect of relative humidity on leakage current flow were compared with the results obtained from the model.

To highlight the relationship between salt deposit conductivity on the surface of wood and leakage current, experiments were conducted under stable environmental conditions.
conditions. Therefore, wind velocity \( V \), conductivity flow rate \( q \), thermal conductivity \( K \), temperature \( t \), humidity \( H \) and specific heat \( C \) were considered as constants.

Therefore equation 5.35 can be written as:

\[ I = D^2 \alpha (D)^{4.5} (Z)^{-1.5} \]

(5.37)

where \( D^2 \) is a dimensional factor with value determined from the experiments.

To determine the value of dimensional factor \( D^2 \), the method of least squares was again applied to the experimental data plot obtained from testing each of the three wood specimens under varying contaminant conductivity levels. The value of \( D^2 \) was found to be 0.784.

The analytical results obtained from the model were compared with the experimental results and shown in Figures 5.6, 5.7 and 5.8.

Figure 5.6 Comparison of model and experimental results for wood specimen A.
The above graphs show that the results calculated from the model are in good agreement with the experimental results.
5.8 Summary

A novel mathematical model was developed based on the dimensional analysis technique. This unique model establishes a relationship between leakage current and the factors influencing its flow in wooden pole structures. The modelling approach undertaken simplifies the leakage current flow on insulator and wooden pole structures, thereby establishing an empirical relationship between various parameters affecting the leakage current flow on both insulators and wooden poles.
Chapter 6

Conclusions and Future Work

6.1 Conclusions

The previous chapters described detailed modelling and experimental studies on the influence of ageing, CCA treatment and coastal salt deposits on leakage current flow in wooden poles, crossarms and insulators, all of which are important components of overhead electricity distribution infrastructure. The behaviours of three wood specimens of different ages when subject to electrical stress were described in chapters 3 and 4. Chapter 6 explains the importance of the results obtained in this research and provides potential avenues for further development of the work presented in this thesis.

6.1.1 Effect of Wood Ageing on Leakage Current

This thesis describes an experimental study of the effect of wooden structure ageing on leakage current performance; this is the first study of this phenomenon to have been conducted worldwide. The study proved conclusively (chapter 3) that leakage current performance of wooden structures deteriorates with age. Investigations using SEM
revealed large structural differences between blackbutt wood specimens of different ages, implying that structural changes occur during the service lives of wooden structures and play an important role in predicting the leakage current behaviour.

Given that 70% of the 8.5 million wooden poles in service as part of electricity distribution infrastructure in Australia are over 35 years old [6], the outcome of this study have two major practical benefits for power utilities. The study’s outcomes will assist the assessment of the electrical performance of wooden structures in greater depth, with far greater understanding of the role of ageing in wooden structures, and in developing cost effective asset maintenance and replacement programs [74] which will help in reducing wooden pole fires.

In addition, better pole replacement predictions models [75, 76] can be based on the effect of ageing on electrical performance. The huge cost of the infrastructure and the potential for losses resulting from pole fires means that there is considerable scope for economic gains from improved pole inspection programs.

6.1.2 Influence of Coastal Salt Deposition on Leakage Current

The investigation of the influence of coastal salt deposition on the surface of ageing wooden structures (presented in section 4.3) was another novel aspect of this research. With age, in-service wooden pole structures develop cracks, checks and internal pores. It was concluded that in coastal areas seawater distributed by wind and other means allows salt to enter the structure of wood through cracks and fill internal pores. In addition, the accumulation of salts on the surface of wood, particularly when it is wet,
significantly reduces electrical resistance and deteriorates the leakage current performance of the wood.

From an Australian power utility perspective, wooden structures installed near the coast need to be closely monitored through pole inspection programs for any damage caused leakage currents. The research suggests the need for power utilities to consider shorter inspection cycle programs [77] tailor-made for wooden structures located near the coast.

6.1.3 Effect of CCA Treatment on Leakage Current

The influence of CCA treatment on the leakage current performance of spotted gum poles was investigated in detail. Although CCA treatment of wooden poles protects the wood from termite and fungal damage, electrical performance is compromised and this was reflected in the experimental results presented in section 4.2.6. A glow current of 3.65mA was recorded in CCA-treated spotted gum specimens as shown in section 4.2.7, a result consistent with those produced by other researchers [46].

It is concluded that CCA-treated spotted gum poles have reduced electrical resistance so are vulnerable to smouldering leading to pole fires. Although CCA treatment of spotted gum poles against fungal and termite attack offers several advantages and is a practice widely used by power utilities, the compromise made with reduced electrical resistance of CCA-treated wood can often lead to excessive leakage current thereby increasing the chances of pole fires. This research points to the need to make effective and balanced decisions on CCA treatment of poles taking into consideration the site weather
conditions and location, hence minimising life-cycle costs of inspection and refurbishment of CCA treated wood poles [76].

6.1.4 Mathematical Modelling

A novel mathematical model based on dimensional analysis was developed to establish relationships between key physical variables and leakage current in wooden structures. In section 5.3, three equations were derived based on the mechanism of leakage current flow on insulator and wooden structure as shown in Table 6.1.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Empirical Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>( I = D_s (H)^{1/2} (\alpha)^{1/2} (q)^{3/4} (V)^{3/4} )</td>
</tr>
<tr>
<td>Impact</td>
<td>( I = D_i (k)^I (C)^{-3/4} (t)^{1/4} (D)^{-1/2} (Z)^{-1/2} )</td>
</tr>
<tr>
<td>Combined (Source + Impact)</td>
<td>( I = D_{si} (k)^I (\alpha) (H) (V) (C)^{-21/4} (t)^{3/4} (D)^{9/2} (Z)^{3/2} )</td>
</tr>
</tbody>
</table>

Table 6.1 Empirical relationship for leakage current flow mechanism

Validation of the complete mathematical model was undertaken by comparing the experimental results and model results and they were found to be in good agreement. The equations derived in section 5.6 can be used to calculate the leakage current in wooden structures taking into account the influence of environmental factors.
6.2 Suggestions for Future Research

The leakage current performance of various wood pole specimens has been studied to improve our understanding of the influence of different factors in varying conditions. However, there are many aspects to the problem of wood pole fires caused by leakage current that require further investigation. Therefore, a few suggestions are made here for future research:

1. From the point of view of understanding the effect of wood ageing on leakage current performance, an important question has yet to be answered; whether there is a trend in signature of leakage current waveforms in varying age wood specimens under varying environmental conditions. The present research shows that leakage current performance of wood deteriorates with in-service age. Using the knowledge obtained from the present work, a study based on analysis of signature of leakage current waveforms for different age wood specimens would help in gaining further in-depth understanding of wood poles and assist in development of a leakage current detection system for mitigation against wood pole fires.

2. Another avenue for future research could be to undertake economic analysis of wooden structures replacement and maintenance programs based on electrical ageing of wood.
3. Another possible extension of this work would be to study the thermal degradation mechanism of wood as a result of leakage current of wood and its effect on thermal properties such as thermal conductivity and specific heat. To develop a relationship between thermal and electrical mechanism of wood from a leakage current prospective is challenging.
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