Study of Pole-top Fire Development in Power Distribution Networks

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

Doctor of Philosophy

Rasara Hewa Lunuwilage
BSc Eng, University of Moratuwa, Sri Lanka

School of Electrical and Computer Engineering
College of Science, Engineering and Health
RMIT University

October 2013
Copyright © 2013 Rasara Hewa Lunuwilage

All rights reserved. No part of the publication may be reproduced in any form by print, photo print, microfilm or any other means without written permission from the author.
Declaration

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

Rasara Hewa Lunuwilage

October 2013
Acknowledgements

First and foremost, I would like to thank my supervisors Assoc. Prof. Alan Wong and Dr. Peter Graszkiewicz for their guidance and support. I thank them for sharing their expertise, and specially for making time in their busy schedules to help me with my research. I would like to specially thank Assoc. Prof. Wong for continuously providing me support throughout my PhD candidature. This thesis would not have been possible without your support, and working under your supervision was a privilege.

I would like to thank my university, RMIT University, Melbourne for providing me financial support, great facilities, and a good work environment to conduct my research. My gratitude also goes to the Australian Government for their contribution to my tuition fees. I would like to also thank The University of Moratuwa, Sri Lanka, the institution at which I did my undergraduate degree, for providing me a sound technical foundation to carry out post-graduate studies and research.

In addition to my supervisors, it is a pleasure to also thank the following staff of School of Electrical and Computer Engineering for their advice and support - Dr. Selva Moorthy, Dr. Brendan McGrath and Prof. Grahame Holmes. Special thanks go to the technical staff, Ivan Kiss and Sinisa Gavrilovic for their constant support with all the experimental work. I would also like to thank Laurie Clinton, Jessica Barnett, Karen Hewitt, Caitlin Raynor, Jan Cumming Eren Muller, Jelena Jovanovic and Mirjana Stanic Kuraica who have helped me a lot in various administrative activities related to my PhD.
I would also like to thank my fellow PhD students who made my time at the university very enjoyable. The following friends, who are all RMIT University students, have helped me one way or the other, and for that they deserve my gratitude – Kashfia Haque, Sahan Fernando, Ghazwan Haddad, Jiangxia Zhong, Premith Unnikrishnan, Ayaz Shaikh, Andrew Przybylski, Sruthi Sahebjada, Hao Hao, Mirza Wajahat, Iman Behzadian and Chandan Kalra. I must also thank Gamini Ranasinghe, Yashika Wijayawickrama, Danisha Goonasekara, Chamila Kaduruwewa, Samanthi Sashipraba, Kasun Udugamakorala, Lakmina Perera, Kasun Wedage, Dilini Makalanda, Senaka Samarasekara, Dulcepa Jayasundara and Manoj Liyanage for their company, for helping me out when I first moved in to Melbourne from Sri Lanka, and for also making my weekends and holidays very enjoyable.

I would also like to express my sincere gratitude to my parents-in-law, Chandana and Yamuna Samarasinghe and my sister-in-law, Savini for their constant support and encouragement throughout my studies.

Last but not least, I would like to express my deepest gratitude to my loving parents Hewa Lunuwilage Samarapala and Wasantha Senaratna, my sisters Dilmika and Amani, and my husband Tharaka, for their support, love and care. This thesis is dedicated to you.
To my loving parents, and husband, for everything.
# Contents

Abstract ........................................................................................................................................ 1

Introduction ................................................................................................................................. 4

1.1 Background .......................................................................................................................... 4
1.2 Wooden Utility Poles .......................................................................................................... 6
1.3 Pole Failures ....................................................................................................................... 10
1.4 Pole-top Fires ..................................................................................................................... 12
1.5 Objectives of the Thesis .................................................................................................... 14
1.6 Thesis Outline .................................................................................................................... 15
1.7 Summary of Original Contributions .................................................................................. 17
1.8 Publications List ................................................................................................................ 18
    1.8.1 Journal papers ........................................................................................................... 18
    1.8.2 Conference Papers .................................................................................................... 19

Background Study and Literature Review .............................................................................. 21

2.1 Introduction ....................................................................................................................... 21
2.2 Creeping Discharges .......................................................................................................... 22
    2.2.1 Lichtenberg Figures (1777-1900) ............................................................................. 22
    2.2.2 Fundamental Studies on Surface Discharges (1900 – 1980) .................................... 25
    2.2.3 Study of Creeping Discharges in Solid Dielectrics (1980 - Present) ....................... 26
2.3 Wooden Utility Poles ........................................................................................................ 29
    2.3.1 Wooden Pole Models ............................................................................................... 31
2.4 Fundamentals of FEM ....................................................................................................... 33
2.5 Pole-top Fires .................................................................................................................... 37
  2.5.1 Mathematical Models ............................................................................................... 38
  2.5.2 Pole-top Fire Mitigation ........................................................................................... 39

Study of Leakage Current and Voltage Distribution in a Wooden Supporting Structure using a Three Dimensional Ladder Network Model ..............................................................44

3.1 Introduction ....................................................................................................................... 44
3.2 Ladder Network Model of a Wooden Utility Pole ............................................................ 46
  3.2.1 Three Dimensional (3D) resistance model ............................................................... 48
3.3 Results and Discussion ...................................................................................................... 50
  3.3.1 Resistance of the pole ............................................................................................... 50
  3.3.2 Leakage Current flow along the Pole ....................................................................... 52
  3.3.3 Analysis of Radial Current ....................................................................................... 52
  3.3.4 Voltage Distribution along the pole .......................................................................... 59
  3.3.5 Discussion of Results ............................................................................................... 63
3.4 Conclusions ....................................................................................................................... 64

Study of Electric Field and Voltage Distribution in a Wooden Supporting Structure using Finite Element Method .............................................................................................................. 66

4.1 Introduction ....................................................................................................................... 66
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure ................................................................................................................................. 67
  4.2.1 Current Density around the Metal Object ............................................................... 70
  4.2.2 Electric field and Voltage Distribution near the Metal Object ......................... 72
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure ................................................................................................................................. 77
  4.3.1 Wooden Pole Model ................................................................................................. 79
  4.3.2 Results and Discussion ............................................................................................. 82
4.4 Conclusions ....................................................................................................................... 93

Development of Arcing in Cellulose Fibre Due to Creeping Discharge ..................... 94

5.1 Introduction ....................................................................................................................... 94
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC ................................................................. 97
  5.2.1 Experimental Setup .................................................................................. 97
  5.2.2 Results and Discussion ............................................................................. 99
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages ........................................................................................................ 107
  5.3.1 Results and Discussion ............................................................................. 108
  5.3.2 Effect of Applied Voltage and External Moisture .................................... 117
5.4 Conclusions ................................................................................................ 124

Creeping Discharge and Arcing Development in a Wooden Utility Pole due to High Electric Field ........................................................................................................ 125

6.1 Introduction ................................................................................................. 125
6.2 Experimental Setup ................................................................................... 127
  6.2.1 Electric Field of the Laboratory Test Setup .............................................. 127
6.3 Creeping Discharge and Arcing Development in the Structure .................. 131
  6.3.1 Results and Discussion ........................................................................... 133
6.4 Novel Pole Design with a Nonconductive King Bolt ................................. 137
  6.4.1 Electric Field Calculations using Finite Element Analysis ..................... 142
  6.4.2 Experimental Results ............................................................................ 143
6.5 Conclusions ................................................................................................ 145

Conclusions and Future Work ......................................................................... 146

7.1 Conclusions ............................................................................................... 147
7.2 Future Work ............................................................................................... 150

Bibliography .................................................................................................... 151
List of Figures

Figure 1.1: Various types of wooden supporting structures in power distribution and subtransmission systems. ................................................................................................................ 7
Figure 1.2: Stobie Pole used in South Australian power distribution network. ......................... 9
Figure 1.3: a) Pole-top fires and b) their consequences. ................................................................. 13
Figure 3.1: Resistance of wooden pole with king bolt insertion. ..................................................... 48
Figure 3.2: (a) The model of the utility pole consisting of eight sections and (b) four subsections. ................................................................................................................................. 49
Figure 3.3: Three dimensional resistance model of the utility pole. .............................................. 51
Figure 3.4: Radial, Heartwood and Sapwood resistances at Subsection 4 in dry weather condition. ........................................................................................................................................... 53
Figure 3.5: Radial, Heartwood and Sapwood resistances at Subsection 4 in wet weather condition. ........................................................................................................................................... 54
Figure 3.6: Radial, Heartwood and Sapwood current distributions at Subsection 4 in wet weather condition. ........................................................................................................................................... 54
Figure 3.7: Radial current distribution at Subsection 4 with and without the king bolt insertion. ........................................................................................................................................... 55
Figure 3.8: Radial current distribution at Section 4 under wet and dry weather condition.... 55
Figure 3.9: Radial current distributions for different locations of the king bolt. ......................... 57
Figure 3.10: Radial current distributions of the four subsections. ............................................... 58
Figure 3.11: Radial current distributions of the 2D and 3D models. .............................................. 59
Figure 3.12: Voltage distributions at Subsection 4 in wet weather condition. .............................. 62
Figure 3.13: Voltage distributions at Subsection 4 in dry and wet weather conditions with and without the king bolt. ........................................................................................................... 62
Figure 4.20: Electric Field along the length of the pole at dry weather condition for a supporting structure using a wooden cross-arm. ................................................................. 89
Figure 4.21: Electric Field of the air gap at wet weather condition for a supporting structure using a wooden cross-arm. ................................................................. 91
Figure 4.22: Voltage Distribution along the length of the pole at wet weather condition for a supporting structure using a wooden cross-arm. ..................................................... 91
Figure 4.23: Electric Field along the length of the pole at wet weather condition for a supporting structure using a wooden cross-arm. ..................................................... 92
Figure 4.24: Electric Field along the air gap for a supporting structure using a wooden cross-arm. ........................................................................................................ 93
Figure 5.1: Burning patterns (a) on the surface of a cross-arm and (b) at a king bolt. .......... 96
Figure 5.2: Experimental setup...................................................................................... 98
Figure 5.3: Stages of creeping discharge development under 16 kV Positive HVDC. .... 102
Figure 5.4: Stages of creeping discharge development under 16kV Negative HVDC. .... 103
Figure 5.5: Stages of creeping discharge development under 16kV HVAC. ................. 104
Figure 5.6: Ionization under (a) positive and (b) negative energization....................... 105
Figure 5.7: Arcing development when the electrode is energized at (a) Positive HVDC, (b) Negative HVDC and (c) HVAC ................................................................. 105
Figure 5.8: The average time taken for creeping discharges to develop into arcing in the three samples, for each energization. ................................................................. 106
Figure 5.9: Burning of hardwood timber due to (a) HVAC (b) HVDC negative voltage (c) HVDC positive voltage ................................................................. 107
Figure 5.10: The Electric field on the hardwood specimen, at the 5mm cylindrical electrode. 108
Figure 5.11: Stages of creeping discharge development in Yellow Stringybark at 16kV (horizontal grain alignment). ................................................................. 110
Figure 5.12: Stages of creeping discharge development in Yellow Stringybark at 16kV (vertical grain alignment). ................................................................. 111
Figure 5.13: Stages of creeping discharge development in Ironbark at 16kV (vertical grain alignment) ................................................................. 112
Figure 5.14: Stages of creeping discharge development in Grey Gum at 16kV (horizontal grain alignment) ................................................................. 113
Figure 5.15: Creeping discharge pattern including widely spread branches and broad sectors.114

Figure 5.16: Stages of spark development in Stringybark at 16kV (horizontal grain alignment).............................................................................................................................115

Figure 5.17: Stages of spark development in Stringybark at 16kV (vertical grain alignment).116

Figure 5.18: The single spark developed due to high ionization.............................119

Figure 5.19: The average time taken for creeping discharges to develop into arcing for each specimen...............................................................................................................................119

Figure 5.20: The specimens, (a) YSB-horizontal, (b) YSB – vertical, (c) IB – vertical, and (d) GG – horizontal, burnt due to arcing. Dotted circle shows the position of the electrode.120

Figure 5.21: Time taken for creeping discharges to develop into arcing at different voltages on the surface of a wet timber sample ...............................................................................................................................121

Figure 5.22: Final length of the burning pattern at different voltages, on the surface of a wet timber sample .......................................................................................................................................................121

Figure 5.23: Burning pattern at (a) 5 kV, (b) 7.5 kV, (c) 10 kV and (d) 12.5 kV on the surface of a wet timber sample.......................................................................................................................................................122

Figure 5.24: Laboratory test setup for partial discharge measurements (Presco AG PD-4). 123

Figure 6.1: Phase configuration for the experimental setup.................................................128

Figure 6.2: AC Electric Field Meter.....................................................................................129

Figure 6.3: Electric field of the test setup measured using the AC electric field meter. ....130

Figure 6.4: Electric field of the test setup calculated using finite element analysis..........130

Figure 6.5: King Bolt (a) with bolt head, (b) without bolt head.............................................134

Figure 6.6: Creeping Discharge at the king bolt (at wet weather condition).......................137

Figure 6.7: Arcing developed in the air gap (at wet weather condition).............................137

Figure 6.8: Novel Pole-top Structure with the fibreglass king bolt....................................140

Figure 6.9: Installing the new king bolt in the structure.......................................................141

Figure 6.10: Electric field along the air gap for metal and fibreglass bolts (at wet weather condition). .............................................................................................................................143

Figure 6.11: Fibreglass king bolt (diameter of 20mm) which is used for the laboratory experiments. ........................................................................................................................................144
List of Tables

Table 1.1: An estimation of service poles in Australia (in 2004) [4] ........................................ 6
Table 1.2: Electricity related ignitions in Victorian bushfires on the 7th February 2009 .............. 14
Table 2.1: ENA Guidelines for the mitigation of pole-top fires [103] ........................................ 42
Table 3.1: Moisture Gradients Relative to Sapwood and Heartwood along the Wooden Pole. 48
Table 4.1: Conductivity and Permittivity according to Moisture Content of Wood ................. 69
Table 4.2: Current and Voltage values at the king bolt using the ladder network model and the finite element model .......................................................... 74
Table 4.3: Moisture gradient of sapwood and heartwood at different weather conditions ....... 80
Table 5.1: Moisture content of wood at the electrode before and after the experiment .......... 106
Table 5.2: Moisture content of wood at the electrode before and after the experiment .......... 120
Table 5.3: Current flow and partial discharges in the timber sample at different voltages ... 123
Table 6.1: Maximum electric field at the cross-arm and the Effective Creepage Distance (CD) of the HV insulator ................................................................. 131
Table 6.2: Electrode Configuration for the experimental setup and the Effective Creepage Distance (CD) of the HV insulator ......................................................... 135
Table 6.3: Arc inception voltage for a structure using a wooden cross-arm and a galvanized steel king bolt ................................................................. 136
Table 6.4: Arc inception voltage for a structure using a wooden cross-arm and a fibreglass king bolt ........................................................................ 144
Abstract

Wooden utility poles are widely used in power distribution and transmission networks in many countries due to their low initial cost, environmental impacts, high durability and electrical properties. However, the high number of pole failures in the networks due to wood deterioration and pole-top fires has become a major challenge for the network operators in the recent years. Pole-top fires can be ignited by the combination of arcing and leakage current concentration at the cross-arm. These fires can potentially lead to power blackout, forest fires and even loss of life, which has motivated finding a cost effective solution to pole-top fires. This thesis presents an original study of electrical characteristics of a wooden utility pole using finite element analysis and the electrical ladder network model. The influence of high voltage, leakage current and electric field in starting a pole-top fire is studied in order to find a solution to issue.

Firstly, leakage current and voltage distribution of a wooden pole are studied using a three dimensional resistance model based on the electrical ladder network. Leakage current and voltage of the model are simulated for different scenarios that could occur in practice. The analysis shows that a large part of the leakage current passes through the heartwood to the ground, except in the area of the metal bolt. These simulations also show that a high voltage is present at the metal bolt, creating a high voltage electrode connected to the dielectric wooden objects. The current and voltage at the metal bolt increase at high moisture contents making the pole vulnerable to fire. These analyses also show that more accurate results could be obtained when the division pattern of the resistance model is similar to an actual wooden pole.
The current flow, electric field and voltage distribution of a wooden utility pole are further investigated using finite element analysis. These results confirm that the electrical characteristics of the utility pole change significantly with the moisture content of the environment. These analyses also show that high voltage and high electric field are present at the metal king bolt and there is a possibility of arcing development near this metal insertion.

With the understanding of the voltage and electric field near the metal / wood interface, this thesis next studies the development of arcing in cellulose fibre. In particular, it focuses on arcing in microfibrils found in hardwood, caused by the creeping discharges under AC and DC voltages. Voltages up to 16 kV are applied to hardwood timber specimens, using a flat-plane electrode arrangement, until arcing between the electrodes occur. The results show that the burning of cellulose materials is caused by sparks and arcing developed on the fibre surface. Higher moisture levels in the fibres reduce the time taken for the creeping discharges to develop into arcing, and with the help of a continuous air supply, arcing eventually leads to burning of the microfibrils. It is shown that the arcing and burning occurs at the points with the highest electric field, and the burning process accelerates when the moisture content of wood was increased. The results showed that the development of arcing is directly related to creeping discharges.

Having established that the creeping discharges and arcing can lead to burning the cellulose fibre near a high voltage energized electrode, this thesis next studies the creeping discharge and arcing development near wood / metal interfaces in a wooden utility pole. A small scale utility pole is tested in the high voltage laboratory under various configurations to investigate the development of arcing near the king bolt. The results show that arcing eventually develops into burning of the wooden surface near the king bolt, especially at wet condition, when the creepage distance of the insulators is reduced due to surface pollution.
Finally, taking all these factors into consideration, a pole-top fire mitigation method using a nonconductive, high-strength king bolt made of fibreglass composite is proposed to overcome the pole-top fire issue. The feasibility of using fibreglass king bolts is studied using finite element analysis and laboratory experiments. The results show that the electric field at the cross-arm is reduced with the fibreglass king bolt and the proposed king bolt reduces the possibility of creeping discharge and arcing development at the cross-arm. The fibreglass king bolt is considered a low cost solution and can be retrofitted into existing distribution poles. This proposed solution has significant potential to eliminate the risk of pole-top fire by reducing the electric field of the bolt / cross-arm junction.
Chapter 1

Introduction

1.1 Background

Electricity has become a basic necessity in the 21st century with industries as well as households demanding an efficient, faultless and uninterrupted power supply. The distribution and transmission networks are two vital components of a reliable power system. Having proper infrastructure for the transmission and distribution networks has become a vital factor in achieving these requirements. Inability to provide such infrastructure not only affects the reliability of the supply, but also may cause atrocious disasters which would affect the wellbeing of mankind [1]. The reliability and the safety of power are the two main motivational factors behind our work.

One of the main responsibilities of a power utility is to sustain the functionality of the components of a power network to enhance the overall system reliability. In order to achieve this objective, many power utilities have embraced new condition monitoring and assessment strategies, improving the performance and reliability of the network and preventing unexpected interruptions in the system [2].

Utility poles and pylons used to support overhead power lines are an important component of a power distribution or a transmission network [3]. When considering these networks, many
1.1 Background

countries use wood for fabricating utility poles for the power distribution and sub-transmission networks. Other commonly used materials for utility pole fabrication include steel, concrete and fibreglass reinforced composites. In many countries, wood is the most popular fabrication material for utility poles because of its low initial cost, environmental impacts and electrical and mechanical properties, which make wood advantageous over most other materials such as concrete, steel and fibreglass reinforced composites. In Australia, there are more than 5 million wooden utility poles used in energy networks, and in the state of Victoria, the number exceeds 0.8 million, which is 74% of the total number of utility poles used in the state. Table 1.1 shows the total number of wooden poles that are utilised in Australian power networks as of 2004. Even though wooden poles have many advantages over its alternatives in terms of the above discussed qualities; they have a major disadvantage, which is the formation of pole-top fires [4], [5]. These affect the reliability of the system by causing interruptions. The fires may also lead to catastrophes such as bush fires, which have become a main concern in Australia over the past few decades.

Finding a solution to this problem started with research on the physical properties of wood and reliability assessments of the pole [4-10]. These works included studying the effect of humidity levels on fire formation in wood and the use of preservatives to reduce the risk of fire. However, the research focus shifted to a more electrical engineering perspective gradually [11, 12]. From this perspective, the main causes of pole-top fires are believed to be dry band arcing and leakage current of high voltage insulators [13-17]. Many solutions have been proposed over the last few years based on the above findings to eliminate the leakage current effect and dry band arcing. However, these solutions have not been able to eliminate the occurrence of pole-top fires, and the cause of pole-top fires is still a question of interest among researchers and the power industry. When it comes to studies, the effect of voltage distribution and electric field of the
1.2 Wooden Utility Poles

structure has not been studied fully with respect to pole-top fires. Since the utility pole is in a high voltage environment and subjected to high electric fields, it is crucial that the influence of the high voltage and electric field is also investigated in the context of pole-top fires. This thesis contributes to the academia as well as the power industry by extensively studying the effects of high voltage, leakage current and electric field on pole-top fire formation, and proposing novel and promising solutions for its prevention.

Table 1.1: An estimation of service poles in Australia (in 2004) [4].

<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>2,199,687</td>
</tr>
<tr>
<td>Queensland (Qld.)</td>
<td>1,250,042</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>655,763</td>
</tr>
<tr>
<td>Tasmania (Tas.)</td>
<td>194,461</td>
<td>46</td>
<td>7,108</td>
<td>6,868</td>
<td>208,473</td>
</tr>
<tr>
<td>Western Australia (WA)</td>
<td>661,536</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>50,988</td>
<td>7,031</td>
<td>2,758</td>
<td>375</td>
<td>60,262</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5,055,712</td>
<td>414,215</td>
<td>158,952</td>
<td>668,776</td>
<td>6,307,655</td>
</tr>
</tbody>
</table>

1.2 Wooden Utility Poles

Wooden utility poles are mainly used in power distribution and sub-transmission networks [3]. Usually, 12 meter wooden poles are used in 11 kV to 33 kV distribution overhead lines, and wooden poles up to 26 meters are used in 138 kV H frame or single circuit systems in 66 kV sub-transmission lines. Fig. 1.1 shows wooden poles used in these networks. Many mechanical and structural aspects such as conductor sags, tension effects, weather loads, conductor characteristics and geometry, are considered when designing these utility poles [18-20]. The standards accepted by utility companies for wooden poles are different depending on the local circumstances such as environmental and weather conditions. The national timber pole standard,
1.2 Wooden Utility Poles

AS 2209 – 1994, specifies requirements for the poles used in power networks according to the durability class of wood [21]. The standard categorizes wood into durability classes 1, 2, 3 and 4. The majority of wooden poles that are used in Australian power networks are durability class 1 and 2 species. Only these species can be used without full-length preservative treatment due to their high pole strength compared to timbers in durability classes 3 and 4. However, most of the wooden poles used in the power networks are preservative-treated since the treatment increases the durability of wood.

The average serve lifespan of a wooden utility pole is expected to be between 30 and 50 years. In Australia, durability class 2 timber species Blackbutt (*Eucalyptus Pilularis*) and Spotted Gum (*Corymbia sp.*) are the most commonly used timber species for wooden poles. The wooden poles made out of durability class 1 species are generally expected to last for about 50 to 60 years in service and the durability class 2 species are expected to last about 40 - 50 years in service. Durability class 3 and 4 poles are used throughout Tasmania, and some parts of Victoria. The commonly utilized durability class 3 and 4 species are Messmate (*Eucalyptus*...
1.2 Wooden Utility Poles

*obliqua)*, Mountain Ash (*Eucalyptus regnans*) and Alpine Ash (*Eucalyptus delegatensis*). These poles are expected to have a service lifespan of between 35 – 45 years.

Even though wood is a popular fabrication material for utility poles, other materials such as concrete, tubular steel or fibreglass composite are used in many power networks to fabricate the supporting structures as well. Fig. 1.2 presents a pole used in the South Australian distribution networks which was developed by the Electricity Trust of South Australia Utilities (ETSA). This pole is called the “Stobie Pole” and it is made up of two vertical steel posts with a slab of concrete between them. The Stobie pole was introduced to the South Australian distribution network to overcome the limited availability of wood supply [22].

In the Northern Territory of Australia, most of the utility poles are made out of steel. There are no wooden utility poles in this state due to the severe local climate with high temperature, this state has the most destructive hazard level, making wooden poles unsuitable for the region. However, wooden poles are still the most favourable choice for power utility companies around the world because of the reasonable cost, natural durability and excellent insulating characteristic of timber [23].

The cost of installing a wooden pole is much less compared to the utility poles constructed of steel, concrete or fibreglass composite materials. Furthermore, wooden poles are considered to be a renewable resource since they are produced by sustainably managed forests. The environmental impacts of wooden poles are proven to be considerably less compared to the poles constructed using materials such as concrete and fibreglass composites, less energy is required to produce timber poles, and significantly less greenhouse gasses are produced when considering raw material production, treatment, installation, inspection, maintenance and disposal. Carbon stored by trees as they grow in managed forests also contributes to reducing
1.2 Wooden Utility Poles

the carbon dioxide levels in the atmosphere. This carbon continues to be held within the wood that is produced even after it has been converted into the final product.

![Stobie Pole used in South Australian power distribution network.](image)

However, even though wooden poles have many advantages over its alternatives in terms of the above discussed qualities, there are several disadvantages of using wooden poles as well. The increase in pole failure rate, shorter service-life, and frequent maintenance are some of the drawbacks of using wooden utility poles. Therefore, most networks also seek alternative options such as concrete, steel and fibreglass composite poles. However, it is hard to compare the lifespan of some of these poles with the wooden poles since no full life cycle assessments of
these installations have been completed yet. One of these disadvantages will be discussed in detail in the next section.

1.3 Pole Failures

In recent years, the annual wood pole failures in some parts of Australia have gone well above industry standards, with the Western Australian network having between 1.88 to 4.34 failures per year, per 10,000, in comparison with the industry target of 1 per year, per 10,000 [24]. Wooden poles are more prone to failures compared to other poles due to the organic nature of the structure.

Failures in wooden utility poles can be caused by several factors [25-28]. The poles in service are exposed to extreme weather conditions, fungi and termite attacks, and bushfires, and are susceptible to structural failure. The environmental conditions affect the strength and mechanical properties of the pole. Exposure to sunlight (UV and visible light), moisture (rain, fog, dew) and temperature change can decay the wood over a long period of time. Sapwood section of the pole that connects to ground can be subjected to Fungi and termite attacks. These attacks can decay the pole at the base, and lead to structural failure of the pole. To avoid this kind of failure, sapwood is treated with preservatives, which prevents fungi and termite attacks and also reducing the exposure to extreme weather conditions.

Proper monitoring and assessment techniques can prevent or minimize the structural damages caused due to biological and environmental impacts. The monitoring techniques include methods such as hammer tests, drilling, or non-destructive testing methods such as regular visual inspection, sonic vibration and infrared camera. Inability to prevent these failures affects the reliability of the system through service interruptions. The failures may also lead to
1.3 Pole Failures

catastrophes such as bush fires, which have become a major concern in Victoria and other parts of Australia in the past decade [29, 30].

Bushfire is an uncontrolled fire which spreads over an area of combustible vegetation. It is a common occurrence in Australia, especially during the long hot summers usually experienced in the southern regions of the country such as Victoria and South Australia [31]. The bushfires pose a great threat to life and infrastructure due to the hot and dry climate in Australia.

Bushfire can be initiated due to natural causes such as lightning, human activities such as campfires, agricultural burns or arson, or due to power lines. Investigations carried out by the ‘Powerline Bushfire Safety Taskforce’ in 2011 [30] has discovered that a number of catastrophic bushfires have been caused by power lines. The taskforce believes that the power lines were responsible for the following number of bushfires over the past decades.

- 9 out of the 16 major fires on 12th February 1977
- 4 out of the 8 major fires on Ash Wednesday (16th February 1983)
- 5 out of the 15 major fires on Black Saturday (7th February 2009)

A bushfire can be caused by live wires touching the vegetation, molten metal insertions, arcing between the power line, and pole-top fire. As reported in [29, 30], power lines were believed to be the cause of major bushfires in 1977 and 1983. The primary causes of bushfires in 1977 and 1983 were vegetation touching live wires, fuses that produced hot metal particles when they operated, and clashing wires. These three methods can start a bush fire instantly. The Victorian Bushfire Taskforce has proposed a list of solutions to reduce the risk of bushfire ignition due to power lines. The other main causes that can start a bush fire are, arcing between the power line and the pole and pole-top fire. A bushfire may not start due to these incidents if the fires on the
1.4 Pole-top Fires

Pole-top Fires were extinguished before they reach any vegetation. However, they still may have a high probability of starting a bushfire since a pole-top fire leads to pole failure.

More than 30 major bushfires have been recorded in Victoria since 1851, burning millions of hectares of land, killing hundreds of people and millions of livestock, and destroying thousands of buildings. Many people were killed in Kilmore during the Victorian Black Saturday fires in 2009. It is believed that failure of power lines and utility poles were responsible for the tragedy. The final report of the investigation carried out by the 2011 ‘Powerline Bushfire Safety Taskforce’ stated that electricity asset failure caused 5 out of the 15 major fires started on the 7th February 2009 as summarized in Table 1.1.

1.4 Pole-top Fires

Bushfire ignitions could be caused by power line asset failures including pole-top fires. Polluted or damaged insulators allow leakage current flow through wooden utility poles, changing the voltage distribution and electric field of the structure. This can lead to fire ignition at the pole-top, especially at the metal wood insertions such as king bolts and insulator pins. Pole-top fires may cause power lines to fall and trigger a spark amongst dry vegetation on the ground.

There are many pole-top fires recorded in the Victorian and Western Australian power networks. Over the past few years, numerous pole-top fire incidents have been reported by Energy Safety, Western Australia. A bushfire was started as a result of a pole-top fire in Dunsborough near the Cape Natural Lighthouse on the 7th February 2009 [32]. The hot coal fallen from the pole-top ignited the vegetation under the power line and triggered the bushfire. Another reported incident was the Toodyay bushfire, where arcing between the conductors was believed to be the cause [33]. There have been several other pole-top fires reported in the Western Australian Network over the past few years. Fortunately, these pole-top fires did not
1.4 Pole-top Fires

start any bushfires, but the power supply was affected in many occasions. Supply to nearly 2500 residential customers was interrupted on one day due to 40 pole-top fires in Perth metropolitan area. The Western Australian power network has been using pole-top fire mitigation techniques such as line washing, pole bonding and silicone coating of HV insulators since 1993. However, due to recent events, it can be seen that these methods have not been very effective.

Therefore, it is important to ensure the reliability of the wooden utility poles in order to prevent bushfire ignition. Studies carried out in the past have shown that pole-top fires are more prone to occur near the metal and wood interfaces of the structure, especially near the cross-arm [11]. Some work has already been carried out to study the effect of the current flow through the structure in generating heat at these interfaces. However, there are other possible mechanisms that may lead to a pole-top fire such as creeping discharges and arcing on the cellulose fibre surfaces. Studying these mechanisms is among the main objectives of this thesis.

![Figure 1.3: a) Pole-top fires and b) their consequences.](image-url)
1.5 Objectives of the Thesis

Table 1.2: Electricity related ignitions in Victorian bushfires on the 7th February 2009.

<table>
<thead>
<tr>
<th>Location</th>
<th>Failure of operation</th>
<th>Energy release</th>
<th>Fatalities, Injury and Property loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beechworth – Mudgegonga</td>
<td>Alleged that tree fell onto a three wire 22kV power line</td>
<td>Arcing between the power line and pole stay wire</td>
<td>2 fatalities, 12 casualties, 38 houses destroyed and 33577 hectares burnt.</td>
</tr>
<tr>
<td>Coleraine</td>
<td>Tie wire securing a SWER power line broke</td>
<td>Contact between the power line and a tree</td>
<td>0 fatalities, 1 casualty, 1 house destroyed and 713 hectares burnt.</td>
</tr>
<tr>
<td>Horsham</td>
<td>Coach bolts securing SWER pole-top assembly came loose</td>
<td>Arcing between the power line and ground</td>
<td>0 fatalities, 0 casualties, 13 houses destroyed and 2346 hectares burnt.</td>
</tr>
<tr>
<td>Kilmore East</td>
<td>SWER power line broke</td>
<td>Arcing between the power line and pole stay wire</td>
<td>119 fatalities, 232 casualties, 1242 houses destroyed and 125383 hectares burnt.</td>
</tr>
<tr>
<td>Pomborneit – Weerite</td>
<td>Alleged that 22kV and 66kV wires may have clashed</td>
<td>Molten metal particles</td>
<td>0 fatalities, 0 casualties, 0 houses destroyed and 1008 hectares burnt.</td>
</tr>
</tbody>
</table>

1.5 Objectives of the Thesis

This research is focused on investigating the cause of pole-top fires in a wooden utility pole based on experimental and computer simulation study, and finding an effective solution to the pole-top fire problem.

The primary objectives of this research are as follows.

1. To develop a three-dimensional resistance model based on the electrical ladder network, for a wooden utility pole, and to analyse the current and voltage distribution along the structure under normal and polluted conditions.
1.6 Thesis Outline

2. To use Finite Element Method (FEM) to analyse the current flow, electric field and voltage distribution of a wooden utility pole in a high voltage environment.

3. To perform a detailed investigation into the development of burning in cellulose fibre of hardwood timber caused by a voltage-dependent mechanism called creeping discharge. In particular, to analyse the creeping discharge patterns and spark development which lead to arcing and burning on the cellulose fibre surfaces under high voltage direct current (HVDC) and high voltage alternating current (HVAC) voltages, and to study the development of creeping discharge and total time taken for burning to occur on the cellulose fibre surfaces under the influence of moisture and increasing voltage.

4. To investigate the creeping discharge and arcing development due to high electric field near metal insertions in a utility pole, based on experimental and simulation studies.

5. To propose and examine an effective pole-top fire mitigation method to eliminate the occurrence of arcing and creeping discharge on wooden structures. In particular, to lead a detailed investigation into nonconductive and high-strength material as replacement for the metal king bolt and other pole hardware such as insulator pins, and to study and verify the feasibility of implementing the proposed design using computer simulations and laboratory experiments.

1.6 Thesis Outline

Chapter 2

Chapter 2 presents a detailed discussion on creeping discharge development on dielectric surfaces. This chapter includes background study of the work carried out by past researchers on creeping discharges and damages caused by these discharges. This thesis is focused on studying
1.6 Thesis Outline

both the influence of creeping discharges on cellulose fibre surfaces on starting a pole-top fire, and the electric field and voltage distribution of the structure, using finite element analysis. Therefore, factors leading to wooden pole failures, wooden pole models, solutions proposed by past researchers, and fundamentals of finite element analysis are also discussed in this chapter.

Chapter 3

Chapter 3 studies the leakage current and voltage distribution of a wooden pole which contains an inserted king bolt to connect the cross arm at the top of the pole. A three-dimensional resistance model is built up based on the electrical ladder network, and the leakage current and voltage distribution along the pole is simulated for different scenarios that could occur in practice. Current and voltage near the king bolt at dry and wet weather conditions are analysed using the three-dimensional ladder network model, and the change in resistance, current and voltage distribution at different moisture contents of wood are presented in this chapter.

Chapter 4

Chapter 4 studies the current flow, electric field and voltage distribution of a wooden pole using finite element analysis. First, an axisymmetric structure similar to a wooden utility pole is modelled using MATLAB, and the current density, voltage distribution and electric field of the structure are simulated using FEM for dry and wet weather conditions. These results are compared with the results obtained using the ladder network model in order to verify the similarities of the two models. Then a three-dimensional model of a utility pole is introduced and electric field and voltage distribution of the structure are simulated using FEM software ANSOFT Maxwell to further understand the electrical characteristics of a wooden utility pole.
1.7 Summary of Original Contributions

Chapter 5

Chapter 5 presents the results of the laboratory experiment carried out in order to study the development of arcing in cellulose fibre. In particular, it focuses on burning of microfibrils found in hardwood due to the creeping discharges under HVAC and HVDC voltages. The effect of voltage magnitude, moisture content of cellulose fibre and the effect of surface moisture content are discussed in detail.

Chapter 6

Chapter 6 studies the development of creeping discharge and arcing in a wooden supporting structure using laboratory experiments. Electric field of the structure, measured in the laboratory and calculated using Finite Element Analysis are used to understand and rationalize the creeping discharge and arcing development at the wood metal interfaces of the structure. This chapter also presents the novel pole-top design proposed in this thesis to prevent pole-top fires in wooden utility poles. The new design consists of a king bolt made of high strength fibreglass composites. In this chapter, electric field calculations and laboratory experiments are presented in order to verify the feasibility of the proposed pole design.

Chapter 7

Chapter 7 presents the conclusions of this research and highlights the most important discoveries made from the research. It also contains suggestions for future work.

1.7 Summary of Original Contributions

1. This research introduces a three-dimensional version of the electrical ladder network diagram for a wooden utility pole. This extended model allows a more detailed study of the electrical characteristics of the structure.
2. For the first time, the burning of hardwood timber in electrical networks is linked to a second electrical phenomenon called creeping discharge, which is a voltage-dependent discharge developed due to high electric field on a dielectric surface.

3. It is found that the distinctive patterns of creeping discharges initiated by positive HVDC in cellulose fibres in hardwood timber create the highest degree of damage (in the form of burning) to the cellulose fibre.

4. Based on experimental study, this research confirms that creeping discharge can initiate burning on a larger structure such as a wooden utility pole. As the creepage distance of an insulator decreases due to pollution, the increasing electric field at the metallic king bolt produces creeping discharge on the surfaces of the cross-arm and the wooden pole.

5. A method to eliminate the development of creeping discharge at the king bolt is proposed. Experimental and simulation work confirms that the development of creeping discharges is eliminated by reducing the electric field of the cellulose fibre near the king bolt, which eventually prevents the development of fire.

1.8 Publications List

1.8.1 Journal papers


**1.8.2 Conference Papers**


Chapter 2

Background Study and Literature Review

2.1 Introduction

Power outages are a major problem faced by the power utilities and an outage can affect the electricity customers, and also can cost the utility companies a lot in terms of penalties. A damaged pole-top structure in a wooden utility pole is one reason for a power outage. These damages can be either caused by wood decay (termite or fungi attacks) or pole-top fires [29], [32-34]. A structural failure of a pole-top in a power distribution or transmission network can be hazardous and may initiate bushfires by the triggered electrical sparks. Over the past few years, several factors have been identified as the causes of pole-top fire. These fires may be caused by the effect of capacitive coupling or high electric field intensities between pole and high voltage conductors. A fair amount of studies have been reported investigating the pole-top fires [35-38]. Many research works have been carried out to study the effect of leakage current flow through the wooden pole in order to identify the causes of pole-top fires at the metal insertion sections such as king bolt, bolt and insulator pins [13-17]. This thesis provides a comprehensive study of the electrical characteristics of a wooden utility pole using finite element analysis, arcing in wooden utility poles due to creeping discharge development, and a novel solution to overcome the pole-top fire issue.
2.2 Creeping Discharges

This chapter will provide a detailed review of the past studies on creeping discharge, current research on the causes of pole-top fires, and mathematical methods that can be used to model and study the voltage and current distribution of wooden poles and pole-top equipment.

2.2 Creeping Discharges

Creeping discharges occur along the surface of a dielectric material as a result of a localized discharge created by a high alternating or static electric field [39]. The study of creeping discharges on dielectric surfaces has been the subject of many works over the past centuries. The earliest studies of these types of discharges date back to the eighteenth century [40]. The knowledge base has matured over the past centuries, instigated with the ground breaking discovery of Lichtenberg figures [41-47].

2.2.1 Lichtenberg Figures (1777-1900)

Lichtenberg figures are named after the German physicist Georg Christoph Lichtenberg who discovered them in 1777. Lichtenberg found the possibility of studying the shape and polarity of surface discharges by using dust figures. This was an unexpected breakthrough and the discovery was reported at the Royal Society of Science of Gottingen on May 3rd, 1777. In a public meeting on February 21st, 1978, Lichtenberg read a report entitled "De nova methodonaturam ac motumfluidielectriciinvestigandi" (On a new method to investigate the motion of electric fluid). The part below describes the events that lead to finding the Lichtenberg figures in Lichtenberg’s own words [47].

"Lichtenberg made a huge electrophorus of about 2 m in diameter. It was so powerful that a spark of about 40 cm in length could be produced. The occasion of observing this phenomenon (dust figure) was as follows:
2.2 Creeping Discharges

About the beginning of spring 1777, my electrophorus was just finished. In my room all was still covered with very fine rosin powder that had risen during planning and polishing of the cake and the metal disk, and later it lay on walls and books. When air motion occurred, it deposited on the metal disk of the electrophorus, to my great annoyance. However, it was not until I had hung the disk on the ceiling of the room many times, that the powder deposited on the cake; then I could not cover it uniformly as had occurred on the metal disk, but to my great joy it was arranged like small stars at certain points. These were dull in the beginning and difficult to see; when I sprinkled more dust intentionally, however, they became very clear and often resembled embossed work. Sometimes innumerable stars, the Milky Way and bigger suns appeared.

The bows were dull on their concave side, and decorated manifoldly with rays on their convex side. Marvellous small twigs emerged; the twigs produced by frost on window glass resemble them. Small clouds of many various forms and grades of shading and finally different figures of particular shape were seen. However, a very pleasant play occurred to me, when I saw that these figures could scarcely be destroyed. Even if I wiped off the dust carefully with a feather or a hare's paw, I could nevertheless not prevent that the figures, which were destroyed just before, quickly developed again to some extent anew and still wonderfully. Therefore, I painted a piece of black paper with adhesive paste, laid it down on the figures and pressed it on them lightly. So I succeeded in making several copies of the figures. I have presented these six copies to the Royal Society. This new variety of printing was very favourable for me in order to progress further very quickly, because I had neither pleasure nor time to sketch or destroy all the figures.”

Lichtenberg noticed that the dust figures appeared where the sparks were formed on the rosin cake of the electrophorus. Lichtenberg interpreted that these figures show the nature of
2.2 Creeping Discharges

electricity or motion of the electric fluid, and he proclaimed that the positive figures were star-like, and the negative figures were moon-like.

Lichtenberg further investigated the dust figures using various scenarios to better understand the phenomenon. First, he used different dusts and cakes, and found out that fine sulphur or rosin in a linen pouch was best for powdering. He also used amber, cinnabar, lycopodium, sugar, wheat flour, metal filings, etc. Then, he carried out experiments in a vacuum and found out that both positive and negative figures were bigger than those in the air.

Lichtenberg’s studies have been the foundation to important research work in many scientific areas such as physics, engineering and medical sciences. These figures have been invaluable in the studies of creeping discharges as well. The first use of dust figures of creeping discharges was recorded in 1786 by J. A. De Luc [48]. Many works were carried out in the 19th century in order to further investigate the characteristics of Lichtenberg Figures. During this time, these figures were considered to be a beautiful and interesting phenomenon due to the distinct patterns of the positive and negative figures, and the scientists believed that analysis of this phenomenon would give valuable information on the nature of electricity. Most of the preliminary investigations were focused on establishing the best conditions for producing the dust figures. Extensive studies were carried out by past scholars such as Reitlinger and Bezold using different kinds of electrodes, dust and test samples [49, 50].

Surface discharges were recorded using dust figures as well as photographic figures in the 19th century. The first photographic Lichtenberg figures were recorded Becquerel [51], and Silliman and Goode [52] in 1841 and 1842, respectively. Photographic Lichtenberg figures are easier to record compared to the dust figures, and therefore, have been the popular method of recording Lichtenberg figures from early 20th century.
2.2 Creeping Discharges

2.2.2 Fundamental Studies on Surface Discharges (1900 – 1980)

Max Toepler [53] used Lichtenberg figures to measure the creeping discharges quantitatively. His research opened up a new era in the studies on creeping discharges, which lead to important discoveries by Pedersen [54], Merril and Von Hippel [41], E. Nasser [55], and so on. Toepler studied the creeping discharges on a surface of a dielectric placed between a high voltage electrode and a ground electrode. Length of the discharges and the shape depended on the polarity and the magnitude of the voltage, and the effect of these two factors was studied using this arrangement in 1920 onwards.

Pedersen applied Lichtenberg figures to the measurement of short time intervals [56] and he carried out an extensive study on the characteristics of positive and negative figures [57]. Merril and Von Hippel studied the surface discharges in terms of electronic ionization, space charges, plasma formation, and neutralization of charges in 1939. This study provided an in-depth discussion of the development of primary figures, back figures and sparks, the distinct patterns of discharges, and sparks developed under positive and negative voltages using the Lichtenberg figures. The primary figures for positive and negative energizations were discussed in this study using the space charge effect, and the spark development was discussed in detail using ionization patterns of primary figures and back figures for both polarities [41]. These fundamental studies provided a very good foundation for research over the next years.

In 1951, Thomas used powder and heat developed Lichtenberg figures to understand the ionization of dielectric surfaces produced by electrical impulses [58]. He discovered that the heat developed Lichtenberg figures can be produced only on a restricted range of solid dielectrics, e.g., resin, petroleum waxes, moulded polythene, and that they are associated with certain surface characteristics. He also discovered that when using an alternating electric field, the effect of an electric discharge of a given polarity on the surface of a dielectric is not
2.2 Creeping Discharges

neutralized or cancelled by a subsequent discharge of opposite polarity. The studies on Lichtenberg figures also lead to research on lightning phenomenon and electric breakdown of gases [42, 59-61].

In 1963, Nasser studied Impulse Streamer Branching using surface discharges [59]. He also measured streamer development with a photographic film put between point and plane electrodes [62] in 1969, and he used these studies to investigate breakdown of air at different air pressures. In 1971, Nasser used the figures to discuss the spark development from a negative point leading to breakdown of air [61]. These studies were further extended by Brzosko (1975), Gross (1975) and other researchers in order to investigate the creeping discharges and Lichtenberg figures on a surface of a dielectric [63, 64].

2.2.3 Study of Creeping Discharges in Solid Dielectrics (1980 - Present)

The studies on creeping discharges gradually progressed into application based research in the late 20th century. The creeping discharge development of solid and liquid dielectrics used in high voltage applications were the main focus of these studies as they are used as insulating materials in transmission and distribution networks. Solid/gas or solid/liquid insulating structures are present in many high voltage equipment such as power transformers, pole-top structures, circuit breakers, high voltage insulators and bushings. Propagation of surface discharges on these interfaces can lead to electrical breakdown and equipment failure leading to system failures [65]. Therefore, it was important to understand the initiation and characteristics of creeping discharges which can lead up to breakdown and subsequent failure of the equipment. Many studies were carried out over the past few decades in order to study the characteristics of creeping discharges of solid/gas and solid/liquid dielectric interfaces.
2.2 Creeping Discharges

Streamer propagation in liquids and over solid/liquid interfaces was studied by Devins and Rzad in 1982 [66]. They studied velocity and the growth of the streamers in non-uniform field geometries, expanding the knowledge base of pre-breakdown streamer development [67]. In 1984, Ohgaki and Tsundo studied the growth characteristics of positive impulse surface discharges on acrylics immersed in paraffin oil using a point-plane electrode geometry. They proposed a model for the streamer growth using mechanisms for the continuous reduction of the potential gradient in the streamer channel as the tip grows, with findings on light emission in the channel [68]. Atten and Saker studied the Streamer propagation over a liquid/solid interface in 1993, specially focusing on the discharge characteristics such as mean propagation velocity, final extension, and electric current and charge [69]. In 1996, creeping discharge characteristics over solid/liquid interfaces were studied by Hanaoka, et al. with a grounded side electrode. They studied the properties of streamers travelling over the surface of oil-immersed solid dielectrics under lightning impulse conditions. They found that the Streamer polarity and the position of a grounded side electrode significantly affected the relationship between the streamer extension length and the applied voltage. The solid surface charging also had a large effect on the streamer propagation. They showed that the propagation of streamers strongly depends on the potential at the solid-liquid interface, and the velocity of the positive streamers was higher than that of the negative streamers [70].

The studies on creeping discharges on solid/liquid and solid/gas interfaces have been further extended to investigate the effects of contributing factors such as voltage, type of dielectric, liquid or gas pressure. In 2000, Bedoui and Beroual studied creeping discharge on solid/liquid insulating interface under AC and DC voltages [71]. They studied the final length of surface discharges and the associated currents as a function of the shape and the polarity of the voltage. It was shown that the final discharge length increases with the voltage and decreases when a
2.2 Creeping Discharges

Hydrostatic pressure is applied to the setup. It was also shown that the number of creeping discharge branches, the associated current pulses, and emitted light are also reduced when the pressure is increased. In 2002, they studied the influence of hydrostatic pressure on the characteristics of discharges propagating on solid/liquid insulating interfaces under HVAC and HVDC voltages [71]. Kebbabi and Beroual studied the influence of the properties of materials and the hydrostatic pressure on creeping discharge characteristics over solid/liquid interfaces in 2003 [72]. These studies showed that the final length and the number of discharge branches, the associated current, and light emission are reduced when a hydrostatic pressure is applied, and the discharge length tends to increase with the dielectric constant of the solid insulation. In 2005, Kebbabi and Beroual showed that the nature and the thickness of the solid insulating material significantly influence the characteristics of creeping discharge. They used Optical and electrical investigations on creeping discharges over solid/liquid interfaces under impulse voltages [73]. They further studied the creeping discharges using fractal analysis [74] showing that the creeping discharges propagate radially and their shape and length depend on the physical and geometrical properties of the solid insulators. They also showed that the fractal dimensions of the discharge patterns depend upon the thickness of the solid samples and the dielectric constant of insulator material. They studied optical and electrical characterization of creeping discharges over solid/liquid interfaces under lightning impulse voltage in 2006 [43], indicating the important role of the capacitive effect in the propagation mechanism. Further studies were carried out by Kebbai and Beroual to analyse the influence of capacitive effect and hydrostatic pressure under AC and DC impulse voltages [44, 75-77]. In 2010, Beroual et al studied the creeping discharges propagating over epoxy resin insulators in presence of different gases and mixtures. They found out that the discharge length was shorter in SF$_6$ than in CO$_2$ or N$_2$, and that adding a small concentration of SF$_6$ in a given gas mixture improves the dielectric strength of the insulating structure [78].
2.3 Wooden Utility Poles

These studies showed that the length, density and the propagation of creeping discharges are influenced by many factors such as voltage magnitude, polarity, nature of the dielectric, dielectric strength of the structure, and the pressure of liquid or gasses. It can be seen that the degree of damage done by the creeping discharges and subsequent events vary depending on the above discussed factors, and the electrical failure of the structures can take place at different intensities [45, 78-82]. Therefore, it is important to analyse creeping discharge characteristics of different types of dielectrics used in power networks. The study in this thesis is focused on analysing the creeping discharge development on cellulose fibre surfaces, for instance hardwood timber used in power system applications.

2.3 Wooden Utility Poles

Wood is a commonly used dielectric in many power system applications such as power transformer insulations and utility poles [3, 82, 83]. Therefore, understanding the mechanism of creeping discharge on cellulose fibre surfaces is very important to the electrical power industry. To this end, hardwood is considered as an anisotropic dielectric which has both conductive and dielectric characteristics depending on the amount of moisture content in the cell walls and lumens. Dielectric properties of wood attributes to the composition of different wood specimens, namely fibres, rays, vessels, air and water (bound water and free water). Many research works have been carried over the past several years in order to study the dielectric characteristics of wood [84]. These studies showed that the dielectric properties of wood change with weather conditions, and the conductivity and permittivity of wood increases with the increase in moisture content. High electric field is the main contributing factor for ionization and electron avalanches, and creeping discharge development on a dielectric varies with the electric field distribution on the material. Since the electromagnetic field distribution mainly depends on the dielectric constant of the material, it can be assumed that the
2.3 Wooden Utility Poles

characteristics of creeping discharge development of wood or cellulose fibre surfaces depend on the moisture content of wood.

The Lichtenberg figures of creeping discharge patterns on wood were recorded using an HVAC voltage source and a limited current of 30 mA in [85]. This study was carried out as part of studying human injuries due to lightning and the Lichtenberg figures created in the process. The burning pattern on wood was shown here, but no further steps were taken to study the burning of wood due to creeping discharges. Studying the creeping discharges developed on wooden structures used in high voltage systems, and the damage caused by the creeping discharges to wooden structures due to arcing and burning are two main focal points of this thesis.

A main application of hardwood timber in power networks is for the fabrication of utility poles used in power distribution networks as discussed in the previous chapter. It is vital to understand the process of creeping discharge development in this kind of a structure where normal dielectrics, anisotropic dielectrics (wood), conductive components and high voltage conductors are present. The damage caused by recurring or periodic creeping discharges can affect the reliability of the supply, or more hazardously, lead to events such as pole-top fires. Therefore, it is important to analyse the electric field and voltage distribution of a wooden utility pole in order to determine the critical areas, where creeping discharges can cause high degree of damage due to arcing and burning.

Computer simulations can be used to analyse a utility pole by modelling the structure using its structural and electrical properties. Several models of wooden utility poles have been proposed by researchers over the past years in order to study the behaviour of the utility poles. They are briefly discussed in the next subsection.
2.3 Wooden Utility Poles

2.3.1 Wooden Pole Models

Wooden utility poles have been represented using different models in the past which can be mainly categorized as electrical resistance models [12, 15, 84, 86], thermal models [87-89] and finite element models [90-93]. These models are based on structural and electrical properties of wooden poles, obtained using whole pole measurements, laboratory studies such as wood stake studies, or computer simulations. Whole pole evaluation techniques are based on on-site full-length resistance measurements of the wooden pole structure by inserting electrode rods at the top and bottom sections [86] of the pole. However, expressing the resistance of a wooden pole as a whole does not represent an actual utility pole as many factors including the contact resistances, moisture content, treatment type and pole dimensions are neglected. Many studies have been carried out in order to build an appropriate resistance model for each type of treatment and pole species of in-service wooden poles. Wood stake studies have been established by examining the resistivity of different wood species having various moisture levels and different types of treatments, under controlled laboratory conditions [84]. However, even these studies have not taken the effect of real service conditions such as weather conditions into account.

Rathsman et al. Proposed an impedance model for a wood-insulator combination subjected to a lightning impulse [94]. Filter and Mintz proposed a resistance model for a wooden pole by combining whole pole evaluations and wood stake approaches to determine the leakage current flow on the human body in contact with a wooden pole [12]. Combination of the two models allowed them to overcome the limitations of the existing wooden pole models. Their models included the variety of pole species, wood treatment and weather conditions in the calculations, and they developed a computer-based electrical equivalent circuit of a wooden utility pole. This improved resistance model was termed the ‘ladder network model’. Modified ladder network
2.3 Wooden Utility Poles

models were used over the past few years in order to understand the factors leading to pole-top fire events [15-17]. Rahmat used a modified ladder network model integrated with the cross-arm resistances in order to investigate the leakage current flow through the wooden utility pole [95], and this study was further extended to analyse the validity of using the shunting arrangements proposed by Ross [13, 14] to overcome the issue of pole-top fires. All these studies have focused on analysing the leakage current flow through the utility pole.

When it comes to creeping discharge development in a structure, understanding the electric field and voltage distribution patterns are more important than analysing the current flow through the structure. A resistance model of the wooden pole can also be used to calculate the voltage distribution of the utility pole. The ladder network model can be further extended in order to analyse the current and voltage distribution of the structure in a three dimensional setting. Therefore, a three dimensional ladder network model is proposed in this thesis in order to calculate the voltage distribution across the structure. This model will be used to understand the high risk areas where creeping discharge can develop due to high voltage of the conductors. The division pattern of a three dimensional resistance model closely resembles an actual wooden pole, which overcomes the two dimensional limitations of the existing models. Therefore, the current and voltage distribution along the pole calculated using a three dimensional model is more accurate than using a two dimensional resistance model.

The other method that can be used to analyse a complex structure such as a wooden utility pole is the Finite Element Method. It is advantageous to use FEM when calculating the electrical characteristics of a utility pole due to its complex structure, which includes objects of various sizes and different physical properties. In [91-93], a three-dimensional finite element model of a wooden pole was developed for stress distribution prediction purposes. This model was used to measure and calculate the mechanical strength and failure location in full-size wooden poles.
These results showed a close resemblance to the actual scenario. Therefore, this technique is a potential candidate for non-destructive testing carried out to improve visual grading methods for wooden poles.

Finite element Method is a valuable tool which offers many advantages in terms of wooden pole inspections and assessments. In particular, it can be used to calculate the electrical characteristics of wood. Finite element analysis (FEA) coupled with Maxwell equations can be used to calculate the voltage distribution, electric field and current distribution of the structure [96]. Unlike the ladder network model, both conductive and dielectric properties can be used in these analyses, providing a more accurate representation of a wooden utility pole. However, FEM has not been previously used in the context of studying the electrical properties of a wooden utility pole. This thesis uses FEM as a main tool to calculate the electric field and voltage distribution of a wooden utility pole. Given in the next section are some important fundamentals of FEM, which will be used to analyse the behaviour of a wooden utility pole under a high voltage environment.

2.4 Fundamentals of FEM

Finite Element Method is one of the well-known methods of calculating potential distributions of a complex structure. The volume of the structure is divided into a finite number of elements and the electric field and voltage distribution are calculated for each of these elements [97, 98] as discussed below. A wooden utility pole used in power distribution systems has both conductive and dielectric properties. The field equation for a region where materials hold both conductive and dielectric properties is given in [96] as

\[
\text{div} \left[ \sigma \text{grad}(\phi) + \frac{\partial}{\partial t} \{\varepsilon \text{grad}(\phi)\} \right] = 0 \tag{2.1}
\]
2.4 Fundamentals of FEM

where $\sigma$ is the conductivity, $\phi$ is the potential and $\varepsilon$ is the permittivity.

It is also known that solving (2.1) is equivalent to minimizing the instantaneous energy of the field $J$, which can be written as

$$J = \int \frac{\sigma}{2} \{ \nabla(\phi)^2 \} dv + \frac{\partial}{\partial t} \int \frac{\varepsilon}{2} \{ \nabla(\phi)^2 \} dv$$  \hspace{1cm} (2.2)

Since an AC field with angular frequency $\omega$ is discussed in this study, the above equation can be re-written as follows.

$$J = \int \frac{1}{2} \{ \sigma + j\omega\varepsilon \} \{ \nabla(\phi)^2 \} dv$$  \hspace{1cm} (2.3)

where $\phi = \phi e^{j\omega t}$

is the complex voltage, and $\omega = 2\pi f$ (the frequency that is specified in this model is 50Hz). The above equation can be converted to the differential form using Cartesian coordinates, where $x$, $y$ and $z$ are the directional vectors in the three perpendicular planes, respectively. Therefore,

$$J = \int \left[ \frac{1}{2} \{ \sigma + j\omega\varepsilon \} \left( \frac{\partial \phi}{\partial x} \right)^2 + \left( \frac{\partial \phi}{\partial y} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right] dx dy dz$$  \hspace{1cm} (2.4)

The potential $\phi$ for each node is calculated using FEM, and the potential of the $i$th node is represented by $\phi_i$. The minimum energy condition is satisfied when

$$\frac{\partial J}{\partial \phi_i} = 0 \text{ \hspace{1cm} For all } i \in \{1,2,3, \ldots, n\}$$  \hspace{1cm} (2.5)
where $i$ is the node number and $n$ is the number of nodes in the model. The finite element analysis using isoparametric elements is used for the simplicity of calculations [9], and through this, (2.5) can be minimized into the following equation of nodal potentials:

$$[KK][\phi] = 0$$

(2.6)

where $\{\phi\}$ is the complex potential matrix and $[KK]$ is the system matrix of the considered system, and $[KK] = \sum[K_e]$.

$[KK]$ is built assembling the element matrices of the whole system. The element matrix [99] is determined using (2.4). By differentiating (2.4) with respect to the nodal potentials for an element, we obtain

$$\frac{\partial J_e}{\partial \phi_{ei}} = [K_e]\{\phi_e\}$$

(2.7)

where

$$[K_e] = \int \int [B]^T[P][B] \, dx \, dy \, dz$$

(2.8)

$[B]$ is the gradient matrix of the element, and $[P]$ is the complex permittivity matrix. $[B]$ is obtained using the derivative of the complex potential of an element

$$\left\{ \frac{\partial \phi}{\partial x} \right\} = [J]^{-1} \left\{ \begin{array}{c} \frac{\partial N_{x1}}{\partial \xi} \\ \frac{\partial N_{x1}}{\partial \eta} \\ \frac{\partial N_{x2}}{\partial \xi} \\ \frac{\partial N_{x2}}{\partial \eta} \\ \frac{\partial N_{en}}{\partial \xi} \\ \frac{\partial N_{en}}{\partial \eta} \end{array} \right\}$$

(2.9)
2.5 Pole-top Fires

\[ = [B]^T \{ \phi_{el} \} \]

where \([J]\) is the Jacobian matrix. \(N_{el}\) to \(N_{en}\) are the shape functions of the element and are functions of the local coordinates \((\xi, \eta, \zeta)\)[23].

The complex permittivity matrix is given by

\[
[P] = 2\pi \left[ \begin{array}{cc}
\sigma + j\omega \varepsilon & 0 \\
0 & \sigma + j\omega \varepsilon
\end{array} \right]
\]  

(2.10)

By using the Gauss-Lagrange rule, (2.8) can be converted into the following format for the ease of calculations. We get

\[
[K_e] = \sum \sum [B]^T [P] [B] |J| C_i C_j
\]  

(2.11)

where \(C_i\) and \(C_j\) are the weights of the Gauss-Lagrange rule and \(|J|\) is the determinant of \([J]\).

In the simulations, the element matrix is constructed for each element in the system using (2.11). These element matrices are assembled to create the system matrix \([KK]\). The system matrix is banded, sparse and symmetric. Hence to solve (2.6), it is modified by introducing the boundary conditions to the system, and solved using the Gaussian Elimination Method. Electric field or Potential gradients are calculated using (2.9) for the problem region. Maxwell's equations can then be used to calculate the electric field strength \(E\) as follows.

\[
E = -\text{grad}(\phi)
\]  

(2.12)

As shown in this thesis, this analysis can be used to determine the high risk areas where creeping discharges can occur in a wooden utility pole, especially the wooden members subjected to high electric field, in order to understand the formation of pole-top fires. Next
section presents a brief description about pole-top fires and the cost effective methods used in the power industry to overcome the issue.

### 2.5 Pole-top Fires

Pole-top fires that occur on wooden poles are a major concern in the power industry [29-33]. There are more than five million hardwood timber poles installed in the Australian power network, but unfortunately, there have been more than hundreds of pole-top fire events recorded over the past years. Finding a solution for the pole-top fires in order to ensure the safety of power delivery systems has become a major research focus over the past years.

According to past research, the main causes of wood pole fires are believed to be dry band arcing and leakage current of high voltage (HV) insulators [11, 13-17]. Dry band arcing occurs if a small portion of the pole is dry, which is a common occurrence after a light shower on a windy day. The resistance of wood becomes very low when wet because of the increased moisture content [12, 15] and the wet part makes a series connection with the dry parts having a very high resistance. The concentration of the voltage drop across the dry areas leads to electric breakdown and forms carbonized paths along the wooden pole. [100] shows that small current flows through the wooden pole ignite these carbonized paths. The leakage current of HV insulators, which is considered as the other major cause, also generates heat in the structure due to the resistance variations. Ross found out that during prolonged dry periods, contamination accumulates on the insulator surfaces, and if followed by fog, rain mist or snow, the surface resistance reduces and allows leakage current to flow through the insulators to wood [13, 14].

Wickham et. al. studied the various factors contributing to pole-top fires under controlled conditions in a laboratory [101]. Artificial contamination and fogging was used to represent the actual service conditions of a wooden pole. Pole fires were observed under these conditions,
2.5 Pole-top Fires

and the resulting burning was similar to the pole-top fire events that occurred in the field. Their conclusion was that pole-top fire occurrences cannot be attributed to a single factor, but are in fact the result of a combination of several factors that need to be fulfilled simultaneously. The factors include leakage current, overall surface resistances, light wind and moisture. Also the results show that 50% of a voltage gain occurred in the small section where cross-arm is connected to the pole.

2.5.1 Mathematical Models

Over the past few decades, extensive studies have been carried out in order to find the causes of pole-top fire, and to find a solution. The majority of pole-top fires are known to occur at the king bolt which joins the cross-arm to the pole. It has also been shown that pole-top fires are more likely to occur on aged wooden utility poles due to the change in electrical properties of wood as a result of wood decay [102]. The weather conditions play a major role as well [12]. Fires normally occur during the summer periods when light rain or mist is present. At wet weather condition, the conductivity of wood increases, which changes the overall resistance of the wooden pole. Therefore, higher leakage currents pass through the structure, and it is believed that the pole-top fires start due to the joule heating ($i^2R$) at the metal insertions in the structure, especially at the king bolt which connects the cross-arm to the pole. Sachin et al showed that a leakage current of around 5 mA is sufficient to heat the area around the king bolt to a temperature of around 60$\degree$ C which may cause burning. Experiments carried out by Filter showed that fires can start at the king bolt with a leakage current of 2 mA – 15 mA, depending on the wood species and preservative treatments used. These experiments indicated that for poles treated with water-borne preservatives such as Ammonia Copper Arsenate (ACA) and CCA, fire inception currents are two to three times greater than pentachlorophenol-treated
2.5 Pole-top Fires

poles. For poles treated with water-borne preservatives, 4 mA to 6 mA leakage currents could flow through the pole during wet weather condition, and as a result of polluted insulators.

To this end, Rahmat used the modified ladder network model to calculate the leakage current distribution through the structure. He showed that the majority of the leakage current flows through the heartwood of the pole, and the current concentrates in wood where the metal objects such as king bolts are inserted. Laboratory experiments were used to study the temperature increase at the king bolt for different magnitudes of leakage current. A CCA treated pole was used in these studies, and he showed that the temperature of the king bolt increases with the increase in the leakage current [95].

2.5.2 Pole-top Fire Mitigation

Several pole-top fire mitigation techniques have been proposed by researchers and by the power industry. Table 2.1 summarises the current pole-top fire mitigation guidelines proposed by the Energy Networks Association (ENA) to prevent pole-top fires in Australia [103].

Most of these mitigation techniques either provided a short term solution to the pole-top fire problem, or did not have the capability of solving the issue at service conditions. When it comes to solution procedures it should be noted that the methods should be thoroughly investigated before being utilized in the power networks since they may have some drawbacks as well. The drawbacks of the ENA guidelines and the solutions proposed by the researchers are discussed below.

A common approach taken by the electricity distribution companies to improve the operational reliability of the system is the replacement of the existing insulators with low leakage current insulators. In addition, other methods are proposed to enhance the insulation capabilities of the existing insulators, for example, adding creepage extenders to improve the electric strength of
2.5 Pole-top Fires

the insulators and reducing the leakage current flow in the utility poles. However, replacing the
insulators is a costly option and it requires the lines to be de-energized during the replacement
process. Another method of pole-top fire mitigation is replacing the wooden cross-arms with
steel or fibreglass cross-arms. Replacing all the wooden cross-arms in the network with steel or
fibreglass cross-arms may prove to be effective in the long run. However, several pole-top fire
incidents were still recorded in utility poles having galvanized steel cross-arms. On the other
hand, fibreglass cross-arms were not in use in the field for that long and they might prove to be
ineffective and might fail due to factors such as pollution, UV exposure. No conclusive ageing
tests have been conducted in order to determine the performance of the fibreglass cross-arms in
a high voltage environment, and therefore, it is too soon to comment on the reliability of the
fibreglass cross-arms. Replacing the cross-arms in an entire network is a highly expensive task
and the lines have to be de-energized in order to complete this kind of an installation.

Gang nailing around the bolt attachments and insulator bonding is proposed as a method of
diverting the leakage current from the high risk areas such as king bolts and stay connectors,
and spreading the current concentration across a larger area of the pole. However, these
methods might lead to current concentration and high electric stress on other areas of the pole,
which may lead to fires in these areas. Reducing the number of circuits in a utility pole can
lessen the risk of pole-top fires as well since this reduces the number of leakage current
sources. However, this can again be a costly option given the amount of changes that should be
made in the network to achieve this objective.

Another approach that is being taken up by the utility companies is washing the insulators
regularly using pressured water to clean the surface of the insulators and get rid of the surface
pollutants. However, this method may not clean the whole surface of the insulator, and may
leave conducting particles behind. Frequent washing of the insulators is required in some areas,
2.5 Pole-top Fires

proving the process to be costly as well. It is also recommended to spray nonconductive, hydrophobic, pollutant retardant coatings such as Room Temperature Vulcanizing (RTV) silicon or silicon grease on the insulator surfaces which will enhance the insulation properties of the structure. However, like the line insulator washing procedure, this might not cover the whole surface of the insulator and might be ineffective and costly.

There are few more methods proposed over the past years as pole-top fire mitigation techniques. Most of these techniques include pole bonding to eliminate voltage concentration at the metal insertion in the structure. In many configurations, a copper plate has been connected to the king bolt and bonded with the cross-arm in order to prevent the leakage current concentration. However, these attachments and connections become imperfect and loose, leading to worsen the electrical contacts between the bonding and the wood [37]. Rahmat proposed another shunting arrangement where a mid-pole bonding system was used to divert the leakage currents from the king bolt. In this arrangement, insulated wires were used to bypass the leakage current from flowing through the king bolts to a point several meters below on the pole to a heat sink made out of Aluminium fins located several meters below the bolt [95]. The laboratory studies done under controlled conditions proved to be effective, however, further studies are required in order to study the feasibility of this technique. A main drawback of this system is the reduced basic impulse insulation level of the utility pole.

Line pole grounding is another popular method which has been used to overcome pole-top fire. All metal fittings such as king bolts, insulator pins, stay connectors and other steel fittings are shunted through grounding cables to the earth rod. This diverts the leakage current to ground instead of flowing through the wooden members of the utility pole. The main drawbacks of this solution are diminution in basic impulse insulation of the structure, and the high cost of installation.
Table 2.1: ENA Guidelines for the mitigation of pole-top fires [103].

<table>
<thead>
<tr>
<th>Mitigation Option</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low leakage current insulators</td>
<td>Low leakage current insulators limit the leakage current by either lengthening the leakage path or having insulator material that maintains a high resistance to leakage current. (For example, replacing fog pin insulators with post insulators).</td>
</tr>
<tr>
<td>Steel Cross-arms</td>
<td>Insulators attached to wood cross-arms are prime areas for leakage current damage as the cross-arm is thin at such attachment points. By eliminating the flammable material, using a steel cross-arm instead of wood, will prevent cross-arm fires. Care must be taken to ensure where the steel cross-arm attaches to the pole the contact area is kept large to avoid leakage current concentration and burning.</td>
</tr>
<tr>
<td>Gang Nailing around bolt attachments</td>
<td>The use of a gang nail with a spring washer under the insulator bolt attachments will reduce the current density at this point by providing a larger contact point.</td>
</tr>
<tr>
<td>Bonding insulators</td>
<td>Bonding can be used to direct leakage current away from the surface of a wood cross-arm, by using a conductive material connecting the bolts of the insulators and attaching the conductive material to a large surface area on the pole.</td>
</tr>
<tr>
<td>Reducing the number of circuits</td>
<td>As the number of circuits on a pole increase, the number of leakage sources also increase. Consideration should be given to reducing the number of circuits on each pole in order to reduce the potential for leakage and to increase reliability, as less number of circuits are affected by the fire.</td>
</tr>
<tr>
<td>Regular washing programme</td>
<td>The insulators conduct high leakage current when covered with pollutants in wet conditions. Removing these pollutants by a washing program is the key to reducing the leakage current. Build-up of pollution in certain environments (such as coastal sea spray, heavy industry smoke, dust etcetera) and very long dry spells makes insulator washing an option for mitigating against current leakage. The longevity of this solution can be very limited, where the pollutants are ever present or in large supply.</td>
</tr>
<tr>
<td>Pollutant Retardant Coating</td>
<td>Coating insulators with nonconductive or hydrophobic properties (RTV silicon or silicon grease) will reduce the effect of pollutants on the insulators and will mitigate the source of the leakage current. Any applied coating may need to be replaced periodically.</td>
</tr>
<tr>
<td>Structural Tightening</td>
<td>Heat developed between surfaces increases directly with resistance to current. A technique to lower the resistance has been to tighten any structural components. However, this can have a limited effective life depending on the environmental conditions. Where the ambient temperature and moisture levels vary significantly, wood tends to swell and contract more and thus increase the likelihood of the structural components becoming loose.</td>
</tr>
</tbody>
</table>
2.5 Pole-top Fires

However, even when the leakage current in the system is diverted to ground via direct bypass in these kind of arrangements, pole-top fires were still recorded. This proves that leakage current is not the only cause of pole-top fire, and eliminating the effect of leakage current solely does not prevent the risk of a pole-top fire occurrence. Therefore, using these kind of methods does not eliminate the risk of pole-top fires fully, and it is important to find a cost effective, durable and long term solution to the pole-top fire issue. This thesis is focused on finding a second phenomenon which can start a pole-top fire under a high voltage environment. The study is mainly focused on the creeping discharges that can develop into arcing and burning on cellulose fibre surfaces leading to pole-top fires.
Chapter 3

Study of Leakage Current and Voltage Distribution in a Wooden Supporting Structure using a Three Dimensional Ladder Network Model

3.1 Introduction

Wood is a widely used material for the fabrication of utility poles used in power distribution networks. The low initial cost, environmental impacts, and structural and electrical properties make them advantageous over alternative types such as concrete, steel, and fibreglass reinforced composite poles. In Australia, there are more than 5 million wooden poles used in energy networks, and in Victoria the number exceeds 0.8 million, which is 74% of the total number of service poles used in the state [34]. The main disadvantage of using wooden poles in energy networks in term of the safety is the formation of pole-top fires, as discussed in the previous chapters. It is obvious that these fires affect the reliability of the electricity network as the fires cause interruptions supply. In addition, the pole-top fires could also become a possible cause of bushfires [29, 30, 33]. In Victoria and other parts of Australia, pole-top fires are
3.1 Introduction

known to have destroyed forest and wildlife and have also caused loss of human life in the past decade.

The annual wood pole failures in some parts of Australia is well above industry norms with the Western Australian network having between 1.88 to 4.34 failures per 10000 poles per year, in comparison with the industry target of 1 per 10000 poles per year [24]. Considerable amount of research has been done in finding a solution to this problem, but the research focus has mainly centred on the physical properties of wood and reliability assessment [5-10, 13-15]. These previous works include the introduction of wood preservatives to reduce the possibility of fire, and the study of effects of humidity levels on fire formation in wood.

This thesis focuses on the electrical properties of the wooden pole, which undoubtedly has a huge influence on the development of pole-top fires. The insertion of the metal bolt, which connects the supporting cross-arm to the pole, alters the resistance of the structure as a whole and causes a considerable current flow through the wooden pole. A high proportion of this current flows through the king bolt due to its conductive property. The current and the resistance variations in the pole may cause the structure to heat up, and ultimately, this heat may cause fire at the interface of wood and metal [14-16].

The leakage current flow through the structure was studied previously [15-17], but the current flow analysis deviates from the actual current distribution along the pole due to its two dimensional (2D) limitation. In a two dimensional model, it is assumed that the king bolt is inserted across the total cross section of the pole. However, in reality, the bolt touches only a very small amount of wood, and hence, the king bolt should only be modelled in parallel with a small area of the cross section of the pole. In addition, due to this assumption, the results from the current flow analysis indicate that the leakage current, which flows through the bolt and its connecting resistances, also flows through the entire cross section, which spans across 1.5 m of
3.2 Ladder Network Model of a Wooden Utility Pole

A ladder network model was developed in order to determine the electrical characteristics of a wooden utility pole under various operating conditions. The influence of moisture content, treatment type, wood species, pole dimensions and the effect of weather conditions are included in the model.

The ladder network model consists of three types of wood resistances, namely Sapwood Resistance ($R_s$), Heartwood resistance ($R_h$) and Radial resistance ($R_r$) as shown in Fig. 3.1. The configuration provides suitable connection points for other resistances representing pole hardware such as the cross-arm or the metal insertions. Rainy weather is modelled using suitable external bridging resistors $R_w$, which are connected between the nodes of sapwood resistances along the length of the pole. The values of resistances in this model are determined by factors such as the wood species, type of preservative treatment and moisture content percentage (MC)% of the pole. The relationship between the wood resistivity ($\rho$), moisture content (MC%) and type of treatment can be described by following equations.
3.2 Ladder Network Model of a Wooden Utility Pole

Untreated wood: \[ \rho = 10^{(-0.137(MC\%)+7.27)}(\Omega m) \] (3.1a)

Penta Treated wood: \[ \rho = 10^{(-0.135(MC\%)+7.36)}(\Omega m) \] (3.1b)

CCA treated wood: \[ \rho = 10^{(-0.25(MC\%)+9.12)}(\Omega m) \] (3.1c)

ACA treated wood: \[ \rho = 10^{(-0.303(MC\%)+9.51)}(\Omega m) \] (3.1d)

For a CCA treated wooden pole, the resistances of sapwood and heartwood (in \( \Omega \)) are calculated using the following equation.

\[ R_s = R_h = \rho l \frac{l}{A} = (10^{(-0.25(MC\%)+9.12)}) l \] (3.2)

The radial resistance is approximately 1.83 times the sapwood resistance [16] resulting in

\[ R_r = 1.83 R_s \] (3.3)

It is known that the moisture content varies along the length of the pole [6] and the moisture gradients relative to the sapwood and heartwood along the wooden pole are shown in Table 3.1. As a result of ground moisture absorption into the wood, the lowest section of the pole above the ground line has high moisture content compared to the rest of the pole. Therefore, the bottom section of the wooden pole (up to 1.5 meters) is considered to have a high moisture content in the resistance calculations. On the other hand, the top of the wooden pole has lower moisture gradient due to regular airflow and sunlight. Thus, the moisture content in the top section of the pole is lower compared to the middle sections of the pole. The construction of the three-dimensional resistance model and the leakage current flow through the pole for different scenarios are presented in Section 3.2.1.
3.2 Ladder Network Model of a Wooden Utility Pole

3.2.1 Three Dimensional (3D) resistance model

A wooden pole with a height of 12 meters is presented using an 8-section model, where each section is 1.5 meters in height, as shown in Fig. 3.2(a). Section 1 is the section closest to the ground and Section 8 is the section at the top of the pole. The cross section of the pole is further

Table 3.1. Moisture Gradients Relative to Sapwood and Heartwood along the Wooden Pole.

<table>
<thead>
<tr>
<th>Location on Pole</th>
<th>Moisture Content</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Top 1.5 m</td>
<td>MC %</td>
<td>MC + 5 %</td>
</tr>
<tr>
<td>Central portions</td>
<td>MC%</td>
<td>MC + 9 %</td>
</tr>
<tr>
<td>Bottom 0.75 – 1.5 m</td>
<td>MC + 5 %</td>
<td>(MC/2) + 19.5 %</td>
</tr>
<tr>
<td>Bottom 0.00 - 0.75m</td>
<td>MC + 5 %</td>
<td>30 %</td>
</tr>
</tbody>
</table>

Figure 3.1: Resistance of wooden pole with king bolt insertion.
3.2 Ladder Network Model of a Wooden Utility Pole

divided into four equal sub-sections as in Fig. 3.2(b) and the king bolt is inserted at sub-section 4 of section 6.

Figure 3.2: (a) The model of the utility pole consisting of eight sections and (b) four subsections.

Fig. 3.3 shows the three-dimensional ladder network, which is used in this study. The resistance of the king bolt is represented by $R_{kb}$ and is connected in parallel with the radial resistance $R_{r34}$. The resistance of the supporting cross-arm is neglected in the model for simplicity of calculations, as this does not have much effect on the current and voltage calculations [17]. The resistance values are determined by the wood species, the preservative treatment and the moisture content (MC %) of the pole. $R_{s11}$ represents the sapwood resistance of the first sub-section of section one. Section 1 consists of sapwood resistances $R_{s11}$, $R_{s12}$, $R_{s13}$ and $R_{s14}$, heartwood resistances $R_{h11}$, $R_{h12}$, $R_{h13}$ and $R_{h14}$, and radial resistances $R_{r11}$, $R_{r12}$, $R_{r13}$ and $R_{r14}$ as shown in Fig. 3.3. Current distribution of the wooden pole is simulated and analysed.
3.3 Results and Discussion

using this resistance model. For the simulations, a utility pole without a cross-arm is considered. The top and bottom radii of the pole are 11cm and 18cm, respectively, and the top and bottom heartwood radii are 8.15cm and 14.2cm. The pole is assumed to be treated with chromate copper arsenate (CCA), and the king bolt has a resistance of $3\mu\Omega$.

3.3 Results and Discussion

3.3.1 Resistance of the pole

The resistance of the pole varies along its height due to the varying radius and the moisture gradient. The radial resistance at Section 4 differs from that of the other sections due to the insertion of the kingbolt. Fig. 3.4 and Fig. 3.5 show the resistance variation of Section 4 of the pole model at two different weather conditions, and the resistance values are calculated using (3.2) and (3.3). Dry and wet weather conditions are modelled using 11.7% and 22% moisture contents, which are the equilibrium moisture contents at 27°C at relative humidity of 65% and 100%, respectively [104]. The moisture content of the pole in dry weather condition is 11.7%, and the sapwood, heartwood and radial resistances at the top of the pole are 563 MΩ, 21.2 MΩ and 1030 MΩ, respectively. For wet weather condition, i.e., when the moisture content increases to 22%, these resistances reduce to 1MΩ, 37.7kΩ and 1.83MΩ, respectively. This reduction in resistance causes an increase in the leakage current flow through the pole. The above-mentioned figures (i.e., Fig. 3.4 and 3.5) clearly show the effect of the metal insertion, and a comparatively higher current can be expected around the bolt because of the reduction in resistance. It can also be seen that the heartwood resistance of the pole is the smallest out of the three. This is due to the high moisture content in heartwood as shown Table 3.1.
3.3 Results and Discussion

Figure 3.3: Three dimensional resistance model of the utility pole.
3.3 Results and Discussion

3.3.2 Leakage Current flow along the Pole

It is important to analyse the leakage current flow through various pole sections to understand the pole fire formation. Since the king bolt is inserted at Section 4 of the model, analysing the current distribution along radial, heartwood and sapwood resistances of this section is essential. This analysis is presented in Fig. 3.6. A pole at wet weather condition is considered in this analysis since these conditions make the pole more vulnerable to fire as discussed in Section 2.5. A current spike can be observed in the radial resistance at Section 6 where the kingbolt is inserted. However, at all other sections, the current is in general lower compared to Section 6 due to the higher radial resistance. It can be predicted that the radial current spike at the king bolt insertion may have a high impact on pole-top fire formation. Furthermore, it can be seen that the comparatively small heartwood resistance results in a higher current through heartwood at the lower sections of the pole to the ground. On the other hand, the current through sapwood gradually decreases with the length of the pole because of its high resistance. The current in lower heartwood sections flows through a larger cross section of wood, resulting in a very low current density in heartwood. This negligible current flow through outer sapwood and inner heartwood sections makes the effect of this current minimal at the lower sections of the pole.

3.3.3 Analysis of Radial Current

Normally, fires are ignited at the metal-wood junction on a wooden pole where the king bolt is inserted. The resistance of this king bolt is connected in parallel with the radial resistance of the pole. Since the radial currents have the highest impact on pole-top fires as discussed above, the change in the current flow through the pole for different scenarios is observed. The radial current distribution along Section 4 with and without the king bolt insertion is shown in Fig. 3.7. The results in this figure clearly show that the insertion of the bolt causes an increase in the
3.3 Results and Discussion

current from 0.65 mA to 2 mA at section 6. However, the insertion does not have similar effect on the other sections of the pole.

In order to study the effect of moisture on fire formation, Fig. 3.8 presents the radial current flow along the pole under dry and wet weather conditions, where the moisture content is at 11.7% and 22%, respectively. The current distribution along the whole pole becomes comparatively larger with the increase in moisture content. This is in line with the results presented in [12, 15] using other resistance models. The result in Fig. 3.8 gives clear evidence to the fact that wooden poles are more susceptible to fire in wet condition due to high current flow through the pole. It is known, that in an actual network, pole-top fires are prone to happen soon after a shower or near coastal areas [11].

Figure 3.4: Radial, Heartwood and Sapwood resistances at Subsection 4 in dry weather condition.
3.3 Results and Discussion

Figure 3.5: Radial, Heartwood and Sapwood resistances at Subsection 4 in wet weather condition.

Figure 3.6: Radial, Heartwood and Sapwood current distributions at Subsection 4 in wet weather condition.
3.3 Results and Discussion

Figure 3.7: Radial current distribution at Subsection 4 with and without the king bolt insertion.

Figure 3.8: Radial current distribution at Section 4 under wet and dry weather condition.
3.3 Results and Discussion

Based on the results presented in Figs. 3.4, 3.5, 3.6, 3.7 and 3.8, the current distribution of the pole is clearly affected by the king bolt insertion. This leads to another interesting question on how the actual position of the king bolt affects the leakage current. Our results show that the flow of leakage current also alters as the location of the king bolt in the pole is varied. Fig. 3.9 shows the radial current flow through the pole for four different locations of the bolt, which are Sections 4, 5, 6 and 7, respectively. In each case, an increase in current can be observed at the corresponding pole section. However, as the king bolt is shifted down the pole, the magnitude of the current reduces. This is due to the resistance variation along the length of the pole created by the moisture gradient. Since the king bolt resistance $R_{kb}$ is connected in parallel with a radial resistance ($R_{r64}$, $R_{r54}$, $R_{r44}$ or $R_{r34}$) as shown in Fig. 3.3, the current that flows through the bolt not only depends on its low resistance, but it is also dependent on the high radial resistance (i.e., a higher current when in parallel with a higher resistance. Therefore, the current reduces at the lower sections because the radial resistance of the pole reduces along its length from top to bottom.

With an understanding of the resistance and current flow in each of the pole sections, the analysis in the next section is focused current flow variations in each of the subsections. Fig. 3.10 shows the distinctive patterns of the radial current distribution of the four pole subsections. In Subsection 4, the radial current is higher at section 8 where the leakage current enters the pole. The current reduces at section 7 because of the comparatively high resistance in sapwood, and then increases vastly due to the king bolt insertion at section 6, before reducing to almost zero at the lower sections. It is shown in Fig. 3.6 that a large portion of the current flows through the heartwood resistances in these lower sections. Therefore, it can be seen that there is a current concentration due to the king bolt insertion at section 6, which can lead to heating the
3.3 Results and Discussion

resistance elements around the bolt. It can be also be seen that the radial current of the other subsections are very small due to their total resistance being higher compared to subsection 4.

The model in [15] assumes that the same leakage current flows through the entire cross section. The results in Fig. 3.10 clearly shows that this observation is not true in a practical setting since the radial current flow in the other three subsections are clearly different from that of subsection 4. The reason for this is that in the actual scenario, the bolt only touches a very small amount of wood. To further prove the usefulness of the three dimensional model, the currents of each of the models are compared. For the comparison, a 12 meter utility pole which is represented by 16 sections of 0.75 meters each has been considered for the two dimensional model, similar to the one in [15]. To be consistent in the comparison, the three-dimensional model in Fig. 3.3 is modified such that the number of sections and the step size of the two models are equivalent. The current distributions in the two models are shown in Fig. 3.11. As

Figure 3.9: Radial current distributions for different locations of the king bolt.
3.3 Results and Discussion

shown in this figure, the magnitude of the radial current through the king bolt is smaller in the three-dimensional model due to the difference in resistance values in its adjacent elements in the two models. The resistance between these adjacent elements or connecting resistance is defined as the resistance between the surface of the king bolt and the wood which is in contact with the king bolt. Since the king bolt has a very small surface area and it touches only a small area of wood, the connecting resistance is therefore higher. When comparing the two models, the connecting resistance of the three dimensional model is four times higher than that of the two dimensional model since the cross section is divided into four subsections. This results in an increase in the total resistance around the king bolt compared to the two dimensional model, which leads to a lower current attraction towards the metal insertion in the actual case.

![Figure 3.10: Radial current distributions of the four subsections.](image)
3.3 Results and Discussion

3.3.4 Voltage Distribution along the pole

When analysing the current distribution along the pole and the current flow through the king bolt obtained by the ladder network model, it can be seen that the current flow through the king bolt is very low in magnitude, and varies from 0.7 mA – 2 mA as reported in Section 3.3.3. It is safe to assume that even though it might be an important factor when it comes to pole-top fires, the leakage current cannot be the only contributing factor that may lead to the fires initiating at the king bolt. Therefore, it is important to explore other factors which could have a role in initiating the burning fire.

When looking at other factors, voltage distribution along the pole and the voltage of metal contacts can be a contributing factor when it comes to the development of pole-top fires. The wooden utility pole is in a high voltage environment and the resistivity of most of the structure is high except for metal fittings such as king bolts, bonding and stays. These resistance
3.3 Results and Discussion

variations in the structure can result in comparatively high voltages to be present at the lower resistances such as metal fittings. Therefore, it is important to analyse the voltage distribution of the structure using the three-dimensional ladder network model as well.

Again, a wooden pole at wet weather condition is analysed, and the results for voltage distribution along subsection 4 are presented in Fig. 3.12. An effective creepage distance of 0% is used for the simulations in order to model highly polluted conditions. Since the king bolt is inserted at subsection 4 of the model, analysing the voltage distribution along resistance components of this section of the pole is essential. Voltage in the heartwood section is high at section 8, since this is the closest resistance to the HV insulator. The voltage of the lowest sections decrease rapidly because of their close proximity to ground. However, from section 7, an evenly distributed voltage can be observed along the length of the pole, except for the minor deviation in Section 6. The king bolt is inserted in this section and is connected in parallel with the radial resistance, resulting in a low total resistance at section 6. Looking at the voltage at each section, it can be seen that the voltage of the metal king bolt is 4.54kV at wet weather condition. The effective creepage distance of the insulator is 0%. The metal bolt energized with high voltage can act as an electrode in the setup where rest of the material attached to the king bolt are dielectric in nature. The electric field induced by the high voltage of the metal bolt can initiate ionisation of the surrounding dielectric material such as air, wood and other insulating material leading to surface discharges, partial breakdown and arcing around the king bolt. The energy stored in these arcs has the ability to generate sufficient heat to start burning the cellulose fibre around the bolt leading to fires at the metal / wood junction.

As reported in the literature which is discussed in Section 2.5, pole-top fires are common after a light shower during summer. As discussed above, resistance of the wood changes with the change in moisture content and the wooden utility poles prove to be more conductive at wet
3.3 Results and Discussion

weather condition. Therefore, in order to analyse the change in voltage at different weather conditions, voltage distribution along the pole for dry and wet weather conditions are presented in Fig. 3.13, that is, 11.7% and 22%, moisture contents respectively. This shows that the voltage across the wooden segment of the structure has increased at wet weather condition, in turn increasing the voltage of the king bolt from 2 kV to 4.54 kV. The total resistance of the wooden pole changes with the change in moisture content as presented in Section 3.3.1. In addition, resistance of the insulators decrease due to the presence of moisture on the insulator surface, which in turn increases the conductivity of the insulator. The resistivity of the insulator surface can reduce if there is surface pollution on the insulators, resulting in a lower voltage drop across the insulators and higher portion of the voltage sustained across the wooden pole. The 3D resistance model is used to analyse the change in voltage at the king bolt with the change in creepage distance of the insulator, and the results are presented in Fig. 3.14.

The change in voltage distribution pattern at Section 6 of the pole can be clearly seen at dry weather condition. These characteristics can be observed due to the change in resistivity of the whole structure. The voltage of the king bolt is dependent on the resistance of sapwood, heartwood and radial resistances. When the moisture content of wood increases, it increases the conductivity of wood and reduces the gap between the resistances of metal and connecting wooden objects. Therefore, the deviation of the voltage distribution along the length of the pole is much lower as shown in Fig. 3.13. It can be clearly seen that the voltage of the king bolt has increased at wet weather condition. Therefore, it is very important to analyse the effect of voltage on pole-top fires in order to identify all the factors that can lead to pole-top fire formation as well.
3.3 Results and Discussion

Figure 3.12: Voltage distributions at Subsection 4 in wet weather condition.

Figure 3.13: Voltage distributions at Subsection 4 in dry and wet weather conditions with and without the king bolt.
3.3 Results and Discussion

3.3.5 Discussion of Results

The comparison between the current distribution results using the 8-stage model and the 16-stage model proves that in order to obtain more accurate results, the division pattern should have a closer resemblance to an actual wooden pole. The 8-stage model discussed in this chapter has a current of 2mA flowing through the king bolt, but in the 16-stage model, the current is reduced to 0.7mA. This, along with the comparison of the two and three dimensional models, suggests that for more accurate results, the division pattern along the length of the pole and the cross section should be modified. The optimal solution is to divide the pole along its cross section to match the size of the king bolt, i.e., each subsection should have a cross sectional area equal to the size of the king bolt. Even though this can be achieved using the three dimensional resistance model, this consumes a lot of time and requires additional resources. Another limitation of this model is that it does not take the dielectric nature of a wooden pole in to account. Therefore, the actual current and voltage distribution through the

Figure 3.14: Voltage of the king bolt in wet weather conditions for changing creepage distance of the high voltage insulators.
wooden pole may deviate from what is calculated using a 3D resistance model. Therefore, finite element analysis can be used to overcome the limitations of the model discussed here. The number of steps in the model can be varied with a trade-off between accuracy and computational speed. This can be achieved using finite element analysis where the total structure is divided into finite number of elements and then the applicable electromagnetic equations are solved for each of these elements to achieve the electrical behaviour of the total structure. The model can also be further extended to analyse the actual wooden pole model with the supporting cross-arm included. In addition, more complex structures used in transmission lines such as H frames, poles with supporting steel bars, can be analysed using this three dimensional model.

3.4 Conclusions

Many power transmission and distribution networks use wooden poles as the supporting structure for the power lines. One of the main disadvantages of using wooden utility poles is the formation of pole-top fires. These fires not only affect the reliability of a power supply, but also have become a main safety concern, causing catastrophic events such as bushfires. In this study, a three-dimensional resistance model of a wooden pole based on the electrical ladder network has been proposed to analyse the leakage current distribution along the pole. The analysis showed that a considerable amount of the leakage current is passed through the heartwood to the ground. The current concentration along the radial resistance was increased in the section where the king bolt was inserted. Otherwise, the current flow from inner heartwood to the outer surface of wood was negligible. The analysis has shown that all three resistances (i.e., sapwood, heartwood and radial) reduce when the moisture content increases, resulting in a higher leakage current. This made the wooden pole more vulnerable to fire inception at the metal-wood interface. The leakage current distribution was affected by the location of the bolt.
3.4 Conclusions

and the current was reduced when the location of the bolt was varied along the length of the pole from top to bottom. The results presented in this chapter also proved to be more accurate than the results obtained from the two-dimensional model, with a clear deviation in the actual current flow patterns. Even though a high proportion of the leakage current was passed through the king bolt, this current is not sufficient to heat up the king bolt or the surrounding wooden members. It can be construed that in a distribution or sub-transmission network, the current flow through the bolt alone may not be able to produce adequate heat to start a pole-top fire. Therefore, the voltage distribution of the wooden pole was also analysed in this chapter in order to determine the other factors which may contribute to pole-top fires. The study showed that there is a high voltage present at the metal bolt which has the ability to act as an electrode. Furthermore, the voltage at the king bolt increases at wet weather conditions, increasing the risk of surface discharges, arcing, and burning at the wood-metal junction. Therefore, a thorough analysis of the behaviour of the wooden supporting structure in an electromagnetic environment is necessary in order to uncover the actual cause of pole-top fire, which is discussed in the following chapters.
Chapter 4

Study of Electric Field and Voltage Distribution in a Wooden Supporting Structure using Finite Element Method

4.1 Introduction

The current and voltage distribution in the wooden pole was analysed using a three-dimensional ladder network model in the previous chapter. The comparison between the two and three dimensional ladder network models proved that for more accurate results, the division pattern of the pole should be modified to resemble an actual pole. Another limitation of the ladder network model is that the wooden structure was assumed to be purely resistive. In reality, a wooden structure has both conductive and dielectric properties and these electrical properties change with the moisture content of wood [12, 15]. Therefore, it is vital to analyse the behaviour of the wooden pole in a high voltage environment considering every aspect in order to investigate the actual cause of a pole-top fire.

A typical wooden pole structure in the power distribution networks consists of materials of various sizes and electrical properties and it is important to analyse the objects of smaller sizes such as metal insertions and insulators. Hence, finite element analysis is used in this chapter to
calculate the potential distribution, electric field and the current distribution in the wooden structure. Finite Element Analysis and its meshing techniques are used to overcome the limitations of the ladder network model. The complete pole structure can be divided into finite number of elements and the applicable electromagnetic equations will be solved for each of these elements to calculate the electrical characteristics of the total structure. In this chapter, the finite element analysis of the wooden supporting structure based on the axisymmetric model as well as the three-dimensional finite element model will be carried out.

4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

In this section, a cylindrical wooden pole with a height of 12 metres and a constant diameter from top to bottom is modelled using Finite Element Analysis. To simplify the calculations, the pole is considered axisymmetric. As shown in Fig. 4.1, the wooden pole is divided into 595 sections for finite element analysis. The king bolt is considered as a metal insertion in the upper part of the pole at 9 m from the ground level, and there is a thin air gap in between the wood and metal interface. The thin air layer has a thickness of 0.1 mm. Each section towards the bottom of the pole has a height of 50 cm and the height of each section around the metal insertion is 0.5 cm. An epoxy insulator, which has a diameter of 12 cm and a height of 20 cm, is placed on top of the pole.

In this analysis, the pole is placed between two circular plate electrodes, which represent the high voltage line and ground plane that are placed 12.2 m apart. The top high voltage electrode has a diameter of 5.5 m and the ground electrode has a diameter of 10 m. The pole is placed in a uniform field between the two electrodes and connected to the centres of the circular plates. As shown in Fig. 4.2, the king bolt is modelled as a metal ring insertion in the wooden pole to
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

maintain the axisymmetric nature of the model, and has the same volume as a normal king bolt. A thin air gap is introduced around the metal insertion to model the typical contact between the wood pole and the king bolt. The axisymmetric model, which consists of the two electrodes and the pole, is shown in Fig. 4.3. The area under investigation is divided into 3875 quadrilateral elements and the number of nodes in the division pattern is 4032, which represents $n$ in (2.5). The potential distribution in the system is determined by solving (2.6) with boundary conditions as illustrated in Fig. 4.3. The top electrode is energized at 11 kV and the ground electrode is energized at 0 V as shown.

Figure 4.1: Dimensions and division pattern of the pole model.
In this axisymmetric model, the complex permittivity matrix ($[P]$ in (2.8)) of each element of the model is defined using the data published in [84, 105]. The conductivity and the permittivity of the wood will affect the current low through the pole. The electrical properties of wood for various moisture contents as discussed by Darveniza [84] are presented in Table 4.1. A typical king bolt is made of galvanised steel. The electrical properties of steel with a conductivity of $1.16 \times 10^6$ S/m and relative permittivity of 3.1 are applied for the calculations [105].

### Table 4.1: Conductivity and Permittivity according to Moisture Content of Wood.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Conductivity, $\sigma$ (S/m)</th>
<th>Relative Permittivity, $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.7%</td>
<td>$1 \times 10^{-6}$</td>
<td>7</td>
</tr>
<tr>
<td>18%</td>
<td>$1 \times 10^{-5}$</td>
<td>8</td>
</tr>
<tr>
<td>22%</td>
<td>$5 \times 10^{-4}$</td>
<td>9</td>
</tr>
</tbody>
</table>
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

4.2.1 Current Density around the Metal Object

The current density distribution, $J_i$ on the surface of the wooden pole for moisture contents of 11.7%, 16.7% and 22% is calculated using Eq. (4.1). The current density

$$J_i = (\sigma + j \omega \varepsilon)E_i$$  \hspace{1cm} (4.1)

Where $\sigma + j \omega \varepsilon$ is the complex conductivity of the element. $E$ is the electric field and the subscript $i$ is used to represent the $i$th element.

The current density distributions along the length of the pole at 11.7% and 22% MC are shown in Fig. 4.4 and Fig. 4.5 respectively.
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

Figure 4.4: Current density distribution on the surface of the pole at a moisture content of 11.7%.

Figure 4.5: Current density distribution on the surface of the pole at a moisture content of 22%.
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

These results show that the current density around the metal insertion is high, and the magnitude of current density increases with the increase in moisture content. Current flow in each component of the structure can be calculated using the current distribution results.

Fig. 4.6 shows the increase in current flow in the bolt due to the varying moisture content of wood. The current flow in the metal insertion increases from 1.13µA to 0.35mA with the increasing moisture content. Even though the current flow in the bolt increases, the current magnitude is very low in each case. Therefore, this current may not contribute to heat generation at the wood / metal interface.

![Figure 4.6: The current flow in the bolt at various moisture contents.](image)

4.2.2 Electric field and Voltage Distribution near the Metal Object

The current flow in the structure showed limited signs of being able to start a pole-top fire due to its low magnitude. However, when analysing the potential distribution and potential gradient around the metal insertion and the thin air gap, the characteristics of the voltage and electric
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

field around the area where the metal is inserted showed to be more significant. The voltage along the pole length is calculated as discussed in Chapter 2, and the voltage distribution along the surface of the pole for moisture contents of 11.7% and 22% are shown in Fig. 4.7 and Fig. 4.8, respectively. At dry weather conditions, the voltage decreases gradually from 8 kV to 0V along the length of the pole and it decreases from 10.5 kV to 0 kV at wet weather conditions. It can be seen that the metal insertion is at very high voltage in both dry and wet weather conditions. This is due to the location and the close proximity to the high voltage energized conductor. The metal object starts to act as an energized conductor due to this high voltage. This high voltage can lead to ionization of surrounding dielectric material such as wooden objects, insulation materials and surrounding air. A high electric field can specially be present at the air layer trapped between the metal / wood interface and this can lead to partial arcing inside the air gaps resulting in high energy dissipation. This in turn may lead to fire ignition at the metal insertion. Therefore, it is vital to also analyse the electric field distribution of the wooden utility pole.

The electric field around the metal insertion at various weather conditions are calculated using (2.9), and the results obtained for 11.7% and 22% MCs are shown in Fig. 4.9 and Fig. 4.10 respectively.

The electric field of the air gap is very high and the magnitude of electric field varies with increasing moisture content. The electric field is the potential gradient of the object, which in this case, depends on the moisture content of wood. The electrical properties of wood changes with the change in moisture content, and this alter the potential distribution of the structure for each case. The potential of the metal object depends on the potential distribution of the adjacent elements, which are wood and air. This high electric field can ionize the air and wooden members around the metal insertion, which maybe the initial step of starting a pole-top fire.
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

Results obtained for the Current flow through the king bolt and voltage distribution along the pole using the ladder network model and finite element analysis showed similar characteristics for each weather condition such as a current spike and voltage deviation at the king bolt. It is important to further analyse the electrical characteristics near the king bolt insertion of the utility pole. Therefore, a comparison of the calculations using the ladder network model and the finite element model is shown in Table 4.2.

Table 4.2: Current and Voltage values at the king bolt using the ladder network model and the finite element model.

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Current at the king bolt</th>
<th>Voltage at the king bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3D Ladder Network</td>
<td>FEM</td>
</tr>
<tr>
<td>Dry weather</td>
<td>0.925 µA</td>
<td>1.13 µA</td>
</tr>
<tr>
<td>Wet weather</td>
<td>0.7 mA</td>
<td>0.35 mA</td>
</tr>
</tbody>
</table>

Figure 4.7: Voltage Distribution along the surface of the pole at dry weather condition (11.7% MC).
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

Figure 4.8: Voltage Distribution along the surface of the pole at wet weather condition (22% MC).

Figure 4.9: Electric Field on the surface of the pole at dry weather condition (11.7% MC).
4.2 Finite Element Analysis using an Axisymmetric Model of the Wooden Supporting Structure

Even though the current and voltage distribution patterns looks similar for these two models, the values obtained for current flow and voltage at the king bolt are different. It can be seen that the current flow patterns vary for the two models when the electrical properties of heartwood and sapwood change with the moisture content. However, the calculated values are different, which can be explained using the dissimilarities between the ladder network and finite element models. Ladder network model uses a purely resistive model, and it does not take the capacitance of the structure into account when calculating the current and the voltage. However, an actual wooden pole has both conductive and dielectric properties, and these attributes are captured in the finite element model. Therefore, when the conductor is energized at 11 kV, the voltage is distributed along the two models differently according to their individual impedances. Due to the different voltage distributions, the current flow in each impedance element is different from each other, which explains the deviation in the results in

Figure 4.10: Electric Field on the surface of the pole at extremely wet weather condition (22% MC).
the two models. Another factor which creates this deviation is the very distinct division patterns in the two models. The ladder network considers the king bolt to be parallel to a large wooden block represented by a large resistance, even though in reality, the king bolt touches a very small portion of the utility pole. These attributes are also catered for in the finite element model, where the wooden pole is also divided into smaller sections around the metal insertion. From these observations, it can be concluded that the finite element model is more reliable when it comes to analysing the electrical characteristics of a wooden utility pole. Therefore, finite element analysis is used in the following sections in order to analyse the behaviour of a wooden utility pole in a high voltage environment.

Even though the results obtained using the axisymmetric model gives a basic idea about behaviour of the wooden supporting structure in a high voltage environment, it is hard to base conclusions on these results. The results are not 100% accurate due to the three dimensional limitations of the structure used for the potential distribution and electric field calculations. Hence, finite element analysis software ANSOFT MAXWELL is used to calculate the potential distribution, electric field and current distribution using a three dimensional model equivalent to an actual wooden supporting structure.

4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Up to this point in this thesis, two methods were used to analyse the current distribution in a wooden supporting structure. The leakage current distribution in the wooden pole was studied using a three dimensional ladder network model and the current densities near the king bolt were studied using an axisymmetric model of a wooden supporting structure. In the leakage current study, the structure was assumed to be purely resistive even though an actual wooden
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

pole consists of both resistive and dielectric elements. In the finite element analysis of the structure in the previous section, even though a three dimensional analysis was performed, the model of the pole was considered axisymmetric, eliminating some important geometrical aspects of the structure such as the cross-arm and the three phase conductors. In this section, the behaviour of the metal / wood interface under an electromagnetic environment will again be analysed using finite element analysis. However, unlike the previous section, this section simultaneously takes into consideration the resistive and capacitive properties as well as the three dimensional geometry of the wooden pole, making the model almost similar to the actual wooden pole structure.

The metal / wood contact where the king bolt is inserted may not be perfect due to manufacturing methods, thus air or other gasses maybe present in the gaps between the bolt and the wooden pole. Partial arcs can develop in the air trapped between wood / metal interfaces. Another phenomenon that may lead to partial arcing at the wood / metal interface is the creeping discharges that develop on the cellulose fibre surfaces due to its dielectric properties. The development of creeping discharges can depend on several factors such as voltage of the HV electrode, capacitance of the dielectric, presence of moisture or other conducting dust particles in the surroundings [106]. The energy stored in the arcs and discharges can degrade the wooden members and create carbonized paths that may lead to burning. When it comes to pole-top fires, the arcs that start in the hardwood surface, the air gaps, and the wood / metal interface create the greatest research interest. Therefore, in this section, a wooden pole model is analysed with a thin layer of air inserted around the bolt to model the imperfections in the metal / wood contact.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

4.3.1 Wooden Pole Model

For this study, a chromate copper arsenate (CCA) treated red pine pole is modelled and analysed at different weather conditions. The wooden pole is cylindrical with a height of 10 meters and has a constant diameter from top to bottom as illustrated in Fig.4.11. A height of 10 m is selected due to the limitations of the application used. The galvanized steel king bolt, which has a radius of 15mm, is inserted across the diameter of the pole 0.5 meters from the top. This bolt is used to fix the cross-arm at the top of the pole. The wooden structure consists of two types of wood, namely heartwood and sapwood, which have different electrical properties due to their different moisture contents. The moisture gradient of heartwood is considered 5% higher than that of sapwood at dry weather conditions since it is the interior of the pole and not directly exposed to sunlight (refer Fig.4.11). The resistivity of sapwood and heartwood are calculated using (4.2). The permittivity of wood at different moisture contents are given in [84] as

\[
\rho = 10^{(-0.25(MC\%) + 9.12)} \text{ (\Omega m)}
\]

Dry and wet weather conditions are considered in this study in order to analyse the electrical characteristics of the wooden utility pole. The moisture contents of sapwood and heartwood for each of these conditions are given in Table 4.3. An 11 kV three phase supply is modelled by using three Aluminium conductors which are placed on the top of 11 kV insulators as shown in Fig. 4.11. The conductors A, B and C are energized at 8.98 kV, -4.49 kV and -4.49 kV, respectively. It is known that a structure exposed to a high alternating voltage is subjected to the maximum electric field when the energized conductor is at its maximum peak voltage. Hence, in this study, phase A is energized at 8.98 kV, which represents the peak value of the voltage of one conductor in an 11 kV supply, and the other two phase conductors are energized...
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

at -4.49 kV to maintain the similarity to a three phase supply. The current distribution and temperature increase in the area where the bolt is inserted are analysed using finite element analysis.

![Diagram of the Wooden Support Structure](image)

Figure 4.11: The Wooden Supporting Structure.

Table 4.3: Moisture gradient of sapwood and heartwood at different weather conditions.

<table>
<thead>
<tr>
<th>Weather Condition</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sapwood</td>
</tr>
<tr>
<td>Dry Weather</td>
<td>11</td>
</tr>
<tr>
<td>Wet Weather</td>
<td>18</td>
</tr>
</tbody>
</table>

Finite element analysis and Maxwell’s equations are used in order to calculate the electric field and voltage distribution of the wooden utility pole. The area under discussion is divided into
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

tetrahedral elements as shown in Fig. 4.13 and potential distribution and the electric field are calculated for each of these elements.

Figure 4.12: The wooden supporting structure for the 11 kV three phase supply.

Figure 4.13: Finite Element Mesh created for analysing the structure.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

**Electric Field calculations**: The utility pole discussed in this study has both conductive and dielectric properties. The field equation for a region where materials hold both conductive and dielectric properties is given by (2.1). First, the electric potential is obtained by solving the above equation for the problem region as discussed in Section 2.3.2. Then, Maxwell's equations are used to calculate the electric field as follows:

\[ E = -\nabla \phi \]  

(4.3)

**4.3.2 Results and Discussion**

Creeping discharges can develop into arcing and burning on cellulose fibre surfaces. Therefore, in order to identify the areas where creeping discharges can occur, the electric field of the cross-arm and the pole are analysed using FEM. The results are discussed below.

Electric field of the following four areas shown in Fig. 4.14 are analysed particularly in order to identify the possibility of creeping discharge development at those interfaces.

Area 1 – Contact area between the cross-arm and the king bolt.

Area 2 – Contact area between Insulator B and the cross-arm.

Area 3 - Contact area between Insulator C and the cross-arm.

Area 4 – Contact area between the cross-arm and the wooden pole.

Electric field characteristics of the wooden cross-arm and the wooden pole for dry and wet weather conditions outlined in Table 4.2 are shown in Fig. 4.15 and Fig. 4.16, respectively. The electrical properties of wood calculated using (4.2) and [84], are used as the input parameters in finite element analysis to calculate the voltage and electric field of the wooden pole for each moisture content outlined in Table 4.3. Fig. 4.15 presents the electric field of the cross-arm at
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

dry weather condition. Electric field at Areas 1, 2, 3 and 4 are presented in Figs. 4.15(a) – 4.15(d), respectively. Fig. 4.16 presents the electric field of the cross-arm at wet weather condition. Even though the electric field magnitudes are different, the electric field distribution pattern for all the three areas is similar for all dry and wet conditions.

The highest electric field of Area 1 is present at the edges of the cross-arm and near the king bolt, as shown in Fig. 4.15(b) and Fig. 4.16(b). This high electric field near the king bolt can be present due to several factors such as high contact resistance between the cross-arm and the pole, design and geometry of the structure, different electrical properties of contact material, and the voltage difference due to the three phase conductors energized at high voltage. This high electric field can lead to ionization of wood and air given that sufficient energy is present, and this can also lead to creeping discharge and arcing at Area 1. Even though the electric field of the cross-arm at Area 1 is high, the electric field of sapwood in that area is negligible in this case, suggesting that the first ionization starts at the cross-arm in Area 1. However, once there is sufficient thermal energy and ions in the area, both the cross-arm and sapwood surface can ionize due to effective ionization.

Electric field at Area 2 and Area 3 is also high at the area where the metal insulator pins are connected to the wooden cross-arm. Since the wooden cross-arm acts more like an insulator than a conductor, the insulator pins act as high voltage electrodes connected to a solid dielectric. Therefore, creeping discharge can occur on the wooden cross-arm at the metal insulator pins. Even if these discharges do not survive to start a fire at the insulator pins, they can form carbon tracks on the wooden surface, degrading the wooden material due to the high energy present in the discharges. The electric field calculations carried out using the axisymmetric model showed that there is a high electric field present at the air trapped in the wood / metal interface, and this high electric field can lead to ionization and partial breakdown.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

of air inside the utility pole, leading to a pole-top fire. Therefore, the next step is to analyse the electric field distribution of the air layer at dry and wet weather conditions in order to determine the change in electric field around the metal bolt at different weather conditions.

Figure 4.14: Geometry used for the electric field plot.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Figure 4.15: Electric Field of (a) the wooden cross-arm, (b) Area 2, (c) Area 3 and (d) Area 4, at dry weather condition for a supporting structure using a wooden cross-arm.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Figure 4.16: Electric Field of (a) the wooden cross-arm, (b) Area 2, (c) Area 3 and (d) Area 4, at wet weather condition for a supporting structure using a wooden cross-arm.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Electric field of the air gap at the metal / wood junction at dry weather with no moisture present at the insulator is shown in Fig. 4.17. The current conduction from the conductors to ground is negligible because of the high resistance of the whole structure. Here, the insulators are considered as dry insulators with no surface pollution. It can be clearly seen that the electric field distribution in the concerned area is in the range of $0 \sim 50\text{V/mm}$ and the highest gradient occurs at the interface of wood and air. This high electric field in air is present due to the vastly different electrical properties of wood, air and metal. The galvanized steel king bolt would be at a very high voltage due to its conducting nature and low resistance. The wooden surface which is highly resistive at this point with the additional connecting resistance of air will be at high voltage. The wooden pole will be acting as an insulator distributing the high voltage along its length uniformly. However, the voltage drop across air layer will be steeper due to its high resistance. Hence, the electric field of air between wood and metal will be very high.

To get a clearer idea of the voltage distribution of the structure, the voltages and electric field along the marked lines in Fig. 4.18 are plotted in Fig. 4.19 and Fig. 4.20, respectively. Line AB, which is 0.9 m long, starts at heartwood and then goes through the wood, metal and air interfaces along the pole length. Line CD, starts at the top of the pole and goes down through sapwood along its length. The change in voltage due to the complex conductivity of different materials can be seen in these figures. Along lines AB and CD, the voltage is high at the beginning, and then gradually decreases along the length of the pole. The pole acts as an insulator because of the low resistivity of heartwood and sapwood. The voltage drops rapidly at the air gap because of the high resistance of the thin air gap, and the change in the material properties as discussed above. The voltage becomes constant at the bolt because of its high conductivity.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Figure 4.17: Electric Field of the air gap at dry weather condition for a supporting structure using a wooden cross-arm.

Figure 4.18: Geometry lines used for the electric field and voltage plot.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

With the understanding of the field characteristics at dry weather condition, our analysis next focuses on the behaviour of the electric field at wet weather condition. The electric field of the air trapped in the wood / metal interface at wet weather condition is shown in Fig. 4.21. This
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

scenario can occur at the presence of light showers, causing the moisture content of wood to increase up to 14 – 30%. This increased moisture content changes the properties of sapwood and heartwood, making them more conductive, hence changing the electrical properties of the whole structure. Even though the distribution patterns are the same as dry weather conditions, the magnitude of the electric field of the air trapped at the metal wood interface changes slightly. This happens due to the change in electrical properties of the wooden members. The conductivity of wood increases due to the high moisture content (18% –23%), resulting in a higher leakage current flow in the system. Even though the voltage and electric field values change in magnitude, the distribution patterns are the same for each of the above discussed weather conditions. The maximum electric field of air captivated between the bolt and the pole at wet weather conditions is 130 V/mm.

To get a clearer idea of the voltage distribution and electric field characteristics of the structure at wet weather conditions, the voltages and electric field along lines AB and CD (refer Fig. 4.18) are plotted in Fig. 4.22 and Fig. 4.23, respectively. Voltage of Sapwood is very low due to the conducting nature of sapwood at rainy weather. At this point, the voltage of the metal bolt is lower than the surrounding wooden objects, resulting in a high voltage gradient around the bolt. Hence, the electric field of the air layer around the bolt increases with the increase in moisture content of wood. Since the wood is conducting, leakage current passes through wood to ground, allowing a very low voltage drop in wood.

Because of this high electric field, air and other gases inside the gap between the metal / wood interface can breakdown and lead to arcing inside the air gap. The energy stored in these arcs has the ability to increase the temperature in the cellulose fibre and start a fire at the metal / wood junction near the cross-arm.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

Figure 4.21: Electric Field of the air gap at wet weather condition for a supporting structure using a wooden cross-arm.

Figure 4.22: Voltage Distribution along the length of the pole at wet weather condition for a supporting structure using a wooden cross-arm.
4.3 Finite Element Analysis using a Three Dimensional model of the Wooden Supporting Structure

The high electric field in the air gap can lead to partial arcing inside the structure, which have sufficient energy to start burning cellulose fibre material in the structure. The high energy in the arcs can not only start burning wood, but also can heat up the metal bolt leading to higher thermal energy dissipation at the cross-arm junction. This may in fact lead to pole-top fires in the wooden utility pole.

To get a clearer idea of the electric field in the air gap at the dry and wet weather conditions, electric fields along line XY1 (refer Fig. 4.18) are plotted in Fig. 4.23. It can be seen that the electric field in the air gap is much higher at wet weather conditions, especially near the cross-arm area from 340 – 450 mm.

As depicted in Fig. 4.23, a high electric field is present in the air gap at wet weather conditions. Therefore, it can be construed that the highest risk of arcing and burning at the metal / wood junction will be present at wet weather conditions. In the actuality, this kind of situation can occur during a light shower after a dry period, or a continuing light shower.
4.4 Conclusions

In this chapter, the behaviour of a wooden utility pole under an electromagnetic environment had been studied in a simulation environment. The actual three dimensional geometry of a wooden utility pole used in an 11 kV distribution system was studied using finite element analysis in order to calculate the current flow, electric field and voltage distribution of a wooden pole. The analyses were performed modelling dry and wet weather conditions. The results showed that the electrical characteristics of the utility pole changes significantly with the moisture content of the environment. At wet weather conditions, the current density at the metal / wood interface was high due to the conducting nature of the structure. However, voltage distribution and electric field studies of the structure showed that there is a possibility of arcing development near the king bolt insertion.

![Electric Field along the air gap for a supporting structure using a wooden cross-arm.](image-url)
Chapter 5

Development of Arcing in Cellulose Fibre Due to Creeping Discharge

5.1 Introduction

Creeping discharges occur along the surface of a dielectric material as a result of a localized discharge created by a high alternating or static electric field. The study of creeping discharges on dielectric surfaces has been the subject of many works over the past centuries. Surface discharges were studied by Lichtenberg [47] in the eighteenth century. He discovered the possibility of studying the shape and polarity of surface discharges by using dust figures. His studies lead to works of Toepler, Merril and many other researchers who wished to further understand the discharge mechanism on solid/liquid dielectric interfaces [41, 53, 54, 56, and 57].

Understanding the mechanism of creeping discharge on cellulose fibre surfaces is very important to the electrical power industry. Cellulose fibre materials, most importantly ones that are found in hardwood, are used in many power system applications such as power transformer insulations and utility poles [3, 46, 83]. Hardwood timber is the popular choice of material for supporting structures in power networks in Australia, USA, Canada and South Africa. Using
5.1 Introduction

Hardwood poles in power networks is economically and environmentally advantageous over other materials such as concrete, composite fibreglass and galvanized steel. However, fires that occur on wooden poles are a major concern in the power industry [30, 32, 33]. There are more than five million hardwood timber poles installed in the Australian power network, but unfortunately, there have been hundreds of pole-top fire events recorded over the past five years, affecting the reliability of the system. Finding a solution to the pole-top fire issue, in order to ensure the safety of power delivery systems around the world has become a major research focus over the past years.

According to the literature, the main causes of pole-top fires are believed to be dry band arcing and leakage current of high voltage insulators [12-15]. Dry band arcing occurs when there are both dry and wet parts on the surface of the pole, which is a common occurrence after a light shower. The moisture makes a series connection with the dry parts having a very high resistance. The concentration of the voltage drop across the dry areas leads to electric breakdown and forms carbonized paths along the wooden pole. It is shown that small current flows through the wooden pole can ignite these carbonized paths [100]. Experiments have shown that partial arcing can occur in the air trapped inside the voids of the utility poles. These arcs have the ability to degrade the wooden members and create carbonized paths in wood. Continuous arcing can lead to burning the cellulose fibre material due to the energy stored in the arcs. The leakage current of high voltage insulators, which is believed to be the other major cause, also generates heat in the structure due to the resistance variations. However, recent field experience and research work has shown that burning at the cross-arm starts as a tree like burning pattern and then develops into pole-top fire. Fig. 5.1 shows the burning patterns at the cross-arm and the king bolt in a recent pole-top fire in South Africa [37]. These tracking and burning patterns are similar to the burning patterns that occur due to creeping discharges and
5.1 Introduction

partial discharges in dielectric equipment [107]. Therefore, in this study burning of cellulose fibre material due to creeping discharges are studied for various scenarios. This study shows that the burning of cellulose materials could also be initiated by creeping discharges on the hardwood fibres, which is caused by the potential difference between the dielectric and conductive components.

It is known that hardwood has both conductive and dielectric characteristics depending on the amount of moisture content in the cell walls and lumens. Hardwood is mainly made of elementary fibres which are grouped into bundles called microfibrils [108]. Groups of microfibrils will construct the major structural components of wood called the cell walls. Moisture content of wood depends on the amount of both free water and bound water in the wood cells. Free water is found in lumens or cell cavities, and bound water is held between microfibrils of the cell walls.

![Figure 5.1: Burning patterns (a) on the surface of a cross-arm and (b) at a king bolt.](image)

This chapter discusses experimental work carried out in order to identify the creeping discharges and arcing development on cellulose fibre surfaces. This chapter is divided into two sections. In Section 5.2, different creeping discharge patterns and arcing development under HVAC and HVDC are discussed for hardwood specimens with different moisture contents. In
Section 5.3, development of arcing in cellulose fibre, especially in microfibrils found in hardwood, caused by the creeping discharges is studied under HVAC for different hardwood specimens.

5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

In this section, the development of creeping discharges in microfibrils found in hardwood is studied under HVAC and HVDC. Three Yellow Stringybark hardwood timber specimens with three different moisture contents are used for the experiment. Voltages up to 16kV are applied to the specimens using a flat-plane electrode arrangement, until creeping discharges and later arcing between the electrodes occur. Experimental results based on the type of energization and the polarity will be presented in the following sections. The creeping discharge patterns for HVAC, positive and negative HVDC have a clear deviation from each other. Creeping discharges developed into sparks under all the voltages, and these sparks lead to arcing on the cellulose fibre surface. The time taken for the creeping discharges to develop into arcing was different for the three different types of energization. These results will be presented based on the voltages and moisture content of hardwood specimens.

5.2.1 Experimental Setup

In this experiment, the creeping discharges on the cellulose fibre surfaces are observed for the three Yellow Stringybark (YSB) specimens with different moisture contents. The test setup, as shown in Fig. 5.2, consists of a flat-plane electrode arrangement with the upper electrode energized at high voltage and the lower electrode grounded.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

The test setup is made of clear acrylic to make the visualisation easy. A cylindrical flat brass electrode of 5mm diameter is used as the upper electrode, and a brass plane is used as the grounded lower electrode. The hardwood samples used for the test are of 1 cm in thickness. The tests are done under HVAC and HVDC (Positive and Negative) voltages using a partial discharge (PD) free transformer. For samples of 1cm in thickness, maximum voltage of 16kV was selected since creeping discharges were clearly visible on the fibre surface at this voltage. Even though creeping discharges were visible even at voltages around 5 kV, the distinct patterns at HVDC and HVAC could be clearly identified at 16 kV. The voltage is kept at this value until short circuit through the specimen occurs. A high-definition, high-sensitivity camera is placed above the acrylic cover and connected to a computer via a video acquisition card in order to record the discharge patterns. All experiments in this chapter are carried out at ambient temperature of 22 °C and an atmospheric pressure of 76.1 cmHg.
5.2.2 Results and Discussion

The creeping discharge development observed for Positive and Negative HVDC and HVAC is shown in Figs. 5.3 – 5.5 respectively. These discharge patterns can be explained by considering the direction and space-charge effect of the electronic impact ionization [49].

When the flat electrode is energized at Positive HVDC, the discharges consist of sharp branches that are relatively widely spread as shown in Fig. 5.3. When the electrode is positively charged, primary electrons existing around the positive electrode become accelerated into a field of increasing intensity. The effective guidance of the electron avalanches into the anode by the high field strength leaves behind radial space charge of positive ions. The field becomes concentrated near these charged channels, and new avalanches strike into these subsidiary channels, which lengthen and branch the path. The field in the interspace becomes surrounded by the growing branches, and too weak for effective ionization. Hence the avalanche systems stay separate.

When the flat electrode is energized at Negative HVDC, the discharges consist of broad sectors that are separated by narrow radial dark lines as shown in Fig. 5.4. When the electrode is negatively charged, liberated electrons near the cathode are projected into a field of decreasing intensity. The positive space charge left behind weakens the radial field component and creates a tangential one, spreading the ionization over a sector. Succeeding avalanches concentrate the field more and more into a steep cathode fall at the cathode, while in the positive half cycle the cathode fall remains at the tips of the branches.

When the electrode is energized at HVAC, the discharges consist of sharp branches that are relatively widely spread, and broad sectors that are separated by narrow radial dark lines as shown in Fig. 5.5. The discharge propagation is radial for all the specimens and the discharges
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

are evenly and symmetrically distributed at the initial stage. Ionization starts due to the high field strength and when sufficient primary electrons are present, high intensity avalanches in statistical angular separation can be observed. It can be seen that the creeping discharges observed under HVAC have similar characteristics as those under HVDC for both polarities.

Fig. 5.6 illustrates the formation of electron avalanche and the branching due to ionization, at the electrodes (anode and cathode) for the positive and negative energization, respectively. When the electrode is energized with HVAC, both of these ionization characteristics can be observed at the electrode, at each half cycle.

The creeping discharges on the cellulose fibre surfaces developed into bright sparks after a while under all three voltages as shown in Figs. 5.3(c)-5.3(f), 5.4(c)-5.4(f) and 5.5(c)-5.5(f). The sparks developed when the electrode is energized with positive HVDC progresses continuously along the tortuous path, and sparks that developed when the electrode is energized with negative HVDC starts along a straight path, stops, and jumps at angles as discussed by Merrill and Von Hippel in [49]. The sparks start to develop in a symmetrical fashion, from the points where high field strength enhances the ionization. These patterns are clearly visible in Fig. 5.3(f) and Fig. 5.4(f). When the electrode is energized with HVAC, sparks exhibiting both these characteristics could be observed around the electrode. However, a single spark started developing, increasing in length at normal atmospheric pressure under alternating voltage. The spark development under HVAC is discussed in detail in the next section. The bright sparks disappeared under the cellulose fibre surface eventually, and developed into arcing under each voltage, as shown in Fig. 5.7.

Arcing and smoke at the high voltage electrode could be observed on all specimens ultimately, and later, the fibre surface started burning due to the arcing. Experiment was carried out on five
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

different spots of each specimen for each energization, and the average time taken for arcing and burning to occur is presented in Fig. 5.8. The moisture contents of hardwood vary from species to species, and the moisture content (MC) of each specimen and the average time taken for arcing and burning to occur is presented in Table 5.1.

In the specimens with high moisture levels, the time taken for the creeping discharges to develop into arcing and burning was less, as shown in Fig. 5.8. It can also be seen that the time taken for arcing under HVAC is approximately double when compared to both positive and negative HVDC. This can be explained by the nature of ionization when an HVAC waveform is applied. The electrode oscillate between an anode and a cathode in each half cycle, creating ionization patterns of both polarities as shown in Fig. 5.6. The change in polarity does not neutralize the ions. However, the effective ionization is delayed due to the change in polarity, taking more time for the creeping discharges to develop under HVAC. However, the time taken for arcing to develop is considerably less when higher moisture content is present in the cellulose fibres as shown in Table 5.1 and Fig. 5.8. The moisture provides a conductive medium around the dielectric, enhancing the ionization. Therefore, it can be seen that if high moisture content is present, creeping discharges can develop into arcing and burning even under HVAC.

Fig. 5.9 presents the timber specimens after burning. It can be seen that the burning pattern is similar to the creeping discharge patterns developed at each energization. It can also be seen that the highest degree of damage was done at positive HVDC. This is because of the high energy stored in the electron avalanches and the plasma created in the ionization process. To further analyse the different discharge and burning patterns under HVAC and HVDC, the electric field of the setup is analysed using finite element method.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

Figure 5.3: Stages of creeping discharge development under 16 kV Positive HVDC.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

Figure 5.4: Stages of creeping discharge development under 16kV Negative HVDC.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

Figure 5.5: Stages of creeping discharge development under 16kV HVAC.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

Figure 5.6: Ionization under (a) positive and (b) negative energization.

Figure 5.7: Arcing development when the electrode is energized at (a) Positive HVDC, (b) Negative HVDC and (c) HVAC.
5.2 Comparison of Arcing in Cellulose Fibre due to Different Creeping Discharge patterns under HVAC and HVDC

Simulations are carried out using ANSOFT Maxwell software package, and the results are shown in Fig. 5.10. A wood sample with a moisture content of 11.7% is used for the simulations and the electrical properties of wood is calculated using (4.2) and [84] as the input parameters in finite element analysis to calculate the voltage and electric field of the sample. It can be seen that the electric field around the electrode is uniformly distributed and there is high field strength at several points of the electrode as shown in Fig. 5.10. Ionization process can start from these spots with high electric field and then lead to effective ionization of the

Table 5.1: Moisture content of wood at the electrode before and after the experiment.

<table>
<thead>
<tr>
<th>Energization</th>
<th>Average Time Taken to start Arcing (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen 1 (7.6% MC)</td>
</tr>
<tr>
<td>HVAC</td>
<td>12:40</td>
</tr>
<tr>
<td>Positive HVDC</td>
<td>5:50</td>
</tr>
<tr>
<td>Negative HVDC</td>
<td>7:20</td>
</tr>
</tbody>
</table>

Figure 5.8: The average time taken for creeping discharges to develop into arcing in the three samples, for each energization.
surrounding material. There can be highly ionized channels on the cellulose fibre surface because of the high electric field at these spots. This coincides with the discharge and burning patterns observed in the experiment.

5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

In this section, the development of creeping discharges in microfibrils found in hardwood is studied under HVAC. The same test setup discussed in Section 5.2.1 is used for this experiment. The three most common types of cellulose fibre in hardwood timber in Australia are Yellow Stringybark (YSB), Ironbark (IB), and Grey Gum (GG). In this experiment, the creeping discharges on the cellulose fibre surfaces are observed for these three hardwood specimens. Voltages up to 16kV are applied to the specimens using a flat-plane electrode arrangement, until creeping discharges and later arcing between the electrodes occur. Experimental results based on the vertical and horizontal grain alignment will be presented. A major streamer-like discharge was observed in all of the specimens towards the end of the discharge process, which then developed into a major spark leading to arcing on the fibre surface. The location of the streamer seems to coincide with the position where the highest field strength was observed, and simulation results will be presented to verify these observations.

Figure 5.9: Burning of hardwood timber due to (a) HVAC (b) HVDC negative voltage (c) HVDC positive voltage.

5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

In this section, the development of creeping discharges in microfibrils found in hardwood is studied under HVAC. The same test setup discussed in Section 5.2.1 is used for this experiment. The three most common types of cellulose fibre in hardwood timber in Australia are Yellow Stringybark (YSB), Ironbark (IB), and Grey Gum (GG). In this experiment, the creeping discharges on the cellulose fibre surfaces are observed for these three hardwood specimens. Voltages up to 16kV are applied to the specimens using a flat-plane electrode arrangement, until creeping discharges and later arcing between the electrodes occur. Experimental results based on the vertical and horizontal grain alignment will be presented. A major streamer-like discharge was observed in all of the specimens towards the end of the discharge process, which then developed into a major spark leading to arcing on the fibre surface. The location of the streamer seems to coincide with the position where the highest field strength was observed, and simulation results will be presented to verify these observations.
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

5.3.1 Results and Discussion

The creeping discharge patterns observed for the three specimens are shown in Figs. 5.11 – 5.14. The discharge propagation is radial for all the specimens and the discharges are evenly and symmetrically distributed at the initial stage. Ionization starts due to the high field strength and when sufficient primary electrons are present, high intensity avalanches in statistical angular separation can be observed. The creeping discharges observed in this study have similar characteristics as those under HVDC for both polarities [49]. The discharges consist of sharp branches that are relatively widely spread, and broad sectors that are separated by narrow radial dark lines as shown in Fig. 5.15.

The discharge patterns can be explained by considering the direction and space-charge effect of the electronic impact ionization. When the voltage waveform is in its positive half cycle, primary electrons existing around the positive electrode become accelerated into a field of
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

increasing intensity. The effective guidance of the electron avalanches into the anode by the high field strength leaves behind radial space charge of positive ions. This is similar to the situation where the electrode is energized with positive HVDC as discussed in the previous section. When the waveform is in its negative half cycle, liberated electrons near the cathode are projected into a field of decreasing intensity. This is similar to the situation where the electrode is energized with negative HVDC as discussed in the previous section.

In the Yellow Stringybark specimen, one of these branches developed into a brilliant spark along the direction of the grain alignment after about seven minutes, as shown in Fig. 5.16 and Fig. 5.17. The spark can develop either in the positive half cycle or the negative half cycle depending on the level of ionization. A spark developed in the positive half cycle progresses continuously along the tortuous path, and a spark that developed in the negative half cycle starts along a straight path, stops, and jumps at angles as discussed by Merrill and Von Hippel in [49]. The sparks develop in a symmetrical fashion, where the high field strength enhances the ionization. In past works, single spark tracks were observed when the pressure in the apparatus was increased. The increase in pressure nourishes the ionization, which in turn feeds the avalanches. However, our experiment shows that a single spark could still be observed at normal atmospheric pressure under alternating voltage. The observed spark as shown in Fig. 5.18 is similar to those reported by Merrill and Von Hippel [49] under increased pressure. In the case of cellulose fibre, the ionization was enhanced without the increase in pressure due to the complex dielectric nature of the wood fibres [109]. Cellulose fibres can be easily ionized with a high electric field since the cells are made up of water and cellulose which have varying conductive and dielectric properties.
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.11: Stages of creeping discharge development in Yellow Stringybark at 16kV (horizontal grain alignment).
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.12: Stages of creeping discharge development in Yellow Stringybark at 16kV (vertical grain alignment).
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.13: Stages of creeping discharge development in Ironbark at 16kV (vertical grain alignment).
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.14: Stages of creeping discharge development in Grey Gum at 16kV (horizontal grain alignment).
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

The frequent channelling of intense electron avalanches over the same path creates these intense sparks. These highly conducting plasmas dissipate very high thermal energy, which results in free water and then bound water leaving the cell cavities, extracting the water from microfibrils around the high voltage electrodes. The temperature rise in wood, which is caused by the thermal energy released by the creeping discharges as well as the dipole polarisation of the water molecules subjected to an alternating electric field, causes water molecules to be extracted from the lumens or cell cavities. In our experiment, the extracted water was concentrated at the two electrodes, which in turn increased the moisture content of the specimen between the two electrodes.

Figure 5.15: Creeping discharge pattern including widely spread branches and broad
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.16: Stages of spark development in Stringybark at 16kV (horizontal grain alignment).
Figure 5.17: Stages of spark development in Stringybark at 16kV (vertical grain alignment).
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

As the concentration of moisture on the surface near the high voltage electrode increases, the spark began to disappear into the cellulose fibre specimen as shown in Fig. 5.16(f) and Fig. 5.17(f). Arcing and smoke at the high voltage electrode could be observed on all specimens eventually, and later the fibre surface started burning due to the arcing.

Experiment was carried out on five different spots of each specimen at 16kV, and the average time taken for arcing and burning to occur is presented in Fig. 5.19. The moisture contents of the hardwood vary from species to species, and the moisture contents at the electrode for each of these samples before and after the experiment are given in Table 5.2.

In the specimens having high moisture levels, the time taken for the creeping discharges to develop into arcing and burning was less, as shown in Fig. 5.19. With the high moisture content present at the surface near the high voltage electrodes, and the continuous air supply, the sparks on the surface develop into arcing in the cellulose fibres and lead to ignition, which then burnt the cellulose fibres. Simultaneously, the water concentration between the two electrodes created a conducting passage between them, which lead to a short circuit through the specimen. Fig. 5.20 presents the specimens after the burning occurred. The water concentration around the high voltage electrode can be seen in this figure. It can also be seen that the burning has focused only at one point, even though a smooth cylindrical electrode was used in the experiment. This coincides with the electric field of the setup shown in Fig. 5.10.

5.3.2 Effect of Applied Voltage and External Moisture

It is shown that the time taken for arcing is low when there is higher moisture content in the cellulose fibre. Another factor that can affect the creeping discharge and arcing development on cellulose fibre surfaces is the presence of external moisture, in the form of atmospheric moisture or the moisture on the timber surfaces. Therefore, in order to analyse the effect of
moisture present on the cellulose fibre surface, a thin layer of water is sprayed on the surface of the specimen. Moisture content of wood was measured before and after adding external moisture to the surface using an LCD Digital Wood Timber Moisture Meter. Moisture content of the dry timber sample was 9%. In the wet timber sample moisture content was 17%. Experiments were carried out using the setup discussed in Section 5.2.1, and voltages up to 12.5 kV were applied to the high voltage electrode in 1 kV steps. Time taken for arcing both before and after water was sprayed was recorded. The dry timber sample took a long time to burn. When the electrode was energized at 12 kV, the time taken to start burning was 16 minutes, and at 11 kV, it was 28 minutes. At voltages of 10 kV and lower, the time taken for burning was more than 1 hour. However, the wood started to burn more rapidly when external moisture was introduced to the timber sample. Time taken for a wet timber sample to start arcing and burning at different voltages is presented in Fig. 5.21. These results show that the creeping discharges can develop on the cellulose fibre surfaces even when the electrode is at 1 kV, and the arcing process is accelerated when moisture is present on the surface of hardwood timbers. Creeping discharges can develop even without the presence of a very high electric field when there are conductive materials such as moisture, dust or highly ionized air, which enhance the ionization [106].

It could also be seen that the length of the creeping discharges are different for different voltages, and the length of the burning pattern has the same characteristics. Therefore, further experiments were carried out in order to measure the final length of the burning pattern. The timber sample was energized at the test voltage and kept at this value until short circuit through the specimen occurs. Final length of the burning pattern for different voltages were recorded for the wet timber sample and presented in Fig. 5.22. Burning patterns for different voltages are
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

presented in Fig. 5.23. It can be seen that the degree of damage is high when the electrode is at higher voltages.

Figure 5.18: The single spark developed due to high ionization.

Figure 5.19: The average time taken for creeping discharges to develop into arcing for each specimen.
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

Figure 5.20: The specimens, (a) YSB-horizontal, (b) YSB – vertical, (c) IB – vertical, and (d) GG – horizontal, burnt due to arcing. Dotted circle shows the position of the electrode.

Table 5.2: Moisture content of wood at the electrode before and after the experiment.

<table>
<thead>
<tr>
<th>Wood Specimen</th>
<th>Moisture Content</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before the</td>
<td>After the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>experiment</td>
<td></td>
</tr>
<tr>
<td>Yellow Stringybark</td>
<td>7.9%</td>
<td>11.4%</td>
<td></td>
</tr>
<tr>
<td>Ironbark</td>
<td>8.2%</td>
<td>11.6%</td>
<td></td>
</tr>
<tr>
<td>Grey Gum</td>
<td>9.8%</td>
<td>12%</td>
<td></td>
</tr>
</tbody>
</table>
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

![Graph showing time taken for creeping discharges to develop into arcing at different voltages on the surface of a wet timber sample.](image)

Figure 5.21: Time taken for creeping discharges to develop into arcing at different voltages on the surface of a wet timber sample.

![Graph showing final length of the burning pattern at different voltages on the surface of a wet timber sample.](image)

Figure 5.22: Final length of the burning pattern at different voltages, on the surface of a wet timber sample.
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

From the above results, it can be seen that the voltage of the electrodes and the weather conditions play a major role in initiating burning on cellulose fibre surfaces. To get a clearer idea of the electrical characteristics of the setup, current flow and the partial discharges of the structure were measured using the test setup presented in Fig. 5.24. A partial discharge free transformer was used for the experiment as discussed in Section 5.2.1. A clamp on ammeter was connected to the primary side of the transformer in order to measure the current flow through the primary windings. First, a dry timber sample was used in the experiment and then, external moisture was introduced to the sample by spraying water from a nozzle. Current flow through the test setup and partial discharges recorded from the test specimen for different voltages are presented in Table 5.3.

Figure 5.23: Burning pattern at (a) 5 kV, (b) 7.5 kV, (c) 10 kV and (d) 12.5 kV on the surface of a wet timber sample.
5.3 Development of Arcing in Cellulose Fibre due to Creeping Discharge under HVAC Voltages

It can be seen from these results that partial discharge levels in the test specimen are very high before the burning started. It can also be seen that there is a very high increase in the partial discharge level at wet weather conditions. On the other hand, no significant change could be observed when comparing the current flow through the structure for dry and wet timber specimens. Therefore, it can be seen that burning on cellulose fibre can start even without the influence of a large current.

![Diagram](image)

Figure 5.24: Laboratory test setup for partial discharge measurements (Presco AG PD-4).

<table>
<thead>
<tr>
<th>Applied Voltage (kV)</th>
<th>Dry Timber Sample</th>
<th>Wet Timber Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current (mA)</td>
<td>Partial Discharge</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>62.2 pC</td>
</tr>
<tr>
<td>2.5</td>
<td>2.249</td>
<td>1.23 nC</td>
</tr>
<tr>
<td>5</td>
<td>4.374</td>
<td>2.29 nC</td>
</tr>
<tr>
<td>7.5</td>
<td>6.408</td>
<td>6.71 nC</td>
</tr>
<tr>
<td>10</td>
<td>8.611</td>
<td>13.6 nC</td>
</tr>
<tr>
<td>12.5</td>
<td>10.723</td>
<td>35.8 nC</td>
</tr>
</tbody>
</table>

Table 5.3: Current flow and partial discharges in the timber sample at different voltages.
5.4 Conclusions

Many power transmission and distribution networks use wooden poles as the supporting structure for the power lines. One of the main disadvantages of using wooden utility poles is the formation of pole-top fires. These fires not only affect the reliability of a power supply, but also have become a main safety issue, causing catastrophic events such as bushfires. In this chapter, the development of arcing in cellulose fibre, caused by the creeping discharges under high ac and dc voltages has been studied using laboratory test results. The main goal was to understand the origin of burning near the wood / metal interface at the king bolt. The results showed that the creeping discharges which occurred on the cellulose fibre surfaces lead to surface arcing and gradual burning of the material. The arcing and burning occurred at the points where the highest electric field was observed, and the burning process was accelerated when the moisture content of wood was increased. It was also shown that the burning process is accelerated by introducing external moisture to the timber sample. The conductive layer provided by water particles increased the ionization of wood due to the high electric field around the timber sample, in turn increasing the possibility of arcing and burning around the electrode.
Chapter 6

Creeping Discharge and Arcing Development in a Wooden Utility Pole due to High Electric Field

6.1 Introduction

Many research activities have been carried out in the past in order to identify the cause of pole-top fires. Experiments show that fire is more prone to occur at the metal and wood interfaces of the structure. Some work has already been carried out to study the effect of leakage current flow through the structure in generating heat at these interfaces. An extensive study of the current flow patterns in the wooden utility pole was carried out using the electrical ladder network of a wooden pole in [95], and it shows that the leakage current of the HV insulators flow through the wooden pole to the ground. This study also shows that there is a high current concentration in the king bolt at the cross-arm junction, and this occurs due to the reduction in the overall resistance of the area as a result of the metal insertion.

However, the heat generation at the king bolt is still not clearly discussed when it comes to pole-top fires. Another mechanism that can lead to arcing and burning of hardwood timber is creeping discharges that develop near the metal insertion in a wooden utility pole. The development of arcing on the cellulose fibre surfaces due to creeping discharges were discussed
in the previous chapter. This study showed that creeping discharges can develop into arcing when the moisture contents are high, and then, they can lead to burning near the electrode. Creeping discharges develop as a result of the high electric field on the cellulose fibre surface near the energized metal insertions. The metal / wood interfaces in a wooden utility pole have similar structural characteristics to the experimental setup discussed in Chapter 5. There are several metal / wood interfaces in a pole-top structure. These interfaces create great interest when it comes to pole-top fires. The interface between the king bolt and the wooden pole, and the king bolt and the cross-arm are two possible fire risk areas, where creeping discharges can develop into arcing and burning. Therefore, laboratory experiments and computer simulations are carried out in order to investigate the electric field, creeping discharge and arcing development at the metal / wood interfaces in a wooden utility pole.

The outline of this chapter is as follows. Section 6.2 discusses the test setup used in the high voltage laboratory to investigate the arcing development in a wooden supporting structure. This section also discusses the experimental and simulation studies carried out in order to measure the electric field of the test setup used for the experiments. This setup was then used to study the creeping discharge and arcing development in a wooden utility pole. Section 6.3 presents the results obtained for creeping discharge and arcing developed near the king bolt using the experimental setup discussed in Section 6.2. A nonconductive king bolt made of high strength fibreglass composite is proposed in Section 6.4. This bolt has the ability to minimise the effect of creeping discharges and arcing in order to prevent pole-top fires. In this section, computer simulations are used to identify the change in electric field with the aid of FEM and laboratory experiments are also used to verify the electric field values and to investigate the creeping discharge and arcing development at the fibreglass king bolt. Section 6.5 concludes the chapter.
6.2 Experimental Setup

6.2.1 Electric Field of the Laboratory Test Setup

The electric field of a complete wooden supporting structure was analysed in Chapter 4. However, it is hard to verify these results using experimental results since it is difficult to measure the electric field of a utility pole due to its dimensions, and health and safety concerns related to high voltage structures. Therefore, a utility pole of a smaller scale is built in the high voltage laboratory, and both simulation and experimental studies are used to analyse the electric field of this setup.

The experimental setup, as shown in Fig. 6.1, consists of a 0.5 m wooden pole, a high voltage insulator to represent the rest of the pole length (≈ 9.5 m), a polymeric post insulator, a cross-arm, a galvanized steel king bolt and three conductors representing the phases of a three phase supply. A full scale pole could not be tested in the laboratory due to space limitations. Therefore, the wooden pole is represented by the 0.5m pole and 0.25 m insulator as shown in Fig. 6.1, where the lower end of the insulator is grounded.

The tests were done under high alternating voltages using a partial discharge free transformer. Due to the limitations in the laboratory, only a single high voltage supply could be utilised for the experiment. Therefore, phase A is energized at high voltage as shown in Fig. 6.1. Phase B and C are energized at low voltage (0 – 20 V) using a potential divider to remove the effect of floating potential to the other two adjacent phases. The electric field is measured using an AC electric field meter which is shown in Fig. 6.2.

Insulators installed in pole-top structures can be subjected to various degrees of surface pollution depending on their environment. Surface pollution such as moisture, dirt and salt reduces the effective creepage distance of an HV insulator [110], reducing the dielectric
6.2 Experimental Setup

The change in creepage distance of the insulator changes the current, electric field and voltage distribution of the complete supporting structure, allowing a higher voltage across a wooden pole and high leakage current flow through the structure. Using the ladder network model and FEM, it was shown in Chapter 3 and 4 that the voltage and the current flow through the king bolt increases with decreasing creepage distance of insulators. This laboratory test setup can be used to investigate the change in electric field along the length of the pole with changing creepage distance of insulators. The weather sheds of the insulator are bypassed as shown in Fig. 6.1 in order to study the electric field at creepage distances 100%, 80%, 60%, 40%, 20% and 0%. Bypassing the weather sheds reduces the effective length of insulation, in turn reducing the creepage distance of the insulator.

Figure 6.1: Phase configuration for the experimental setup.
6.2 Experimental Setup

The laboratory test setup is modelled in a three dimensional environment using the finite element analysis software ANSOFT Maxwell, and the electric field of the structure is calculated in order to verify the simulation and experimental results. The electric fields along the length of the pole obtained using laboratory experiments and computer simulations are shown in Fig. 6.3 and Fig. 6.4, respectively. It can be seen that the electric field results obtained from the finite element analysis software are similar to the electric field measured using the test setup with an accuracy of 84%.

Therefore, it can be construed that the electric field calculations carried out in Chapter 4 can be used to analyse the wooden utility pole under a high voltage environment.

It can be seen from the above figures that the electric field on the surface of the pole decreases gradually from top to bottom until it reaches the cross-arm. The electric field starts to increase again near the cross-arm, and it reaches a maximum value near the cross-arm / pole interface before starting to gradually decrease again. Fig. 6.3 depicts the electric field along the length of the pole when the effective creepage distance of the HV insulator is 20%. The experiment was carried out for 6 different creepage distances as discussed in the previous section, and the maximum electric field at the cross-arm for these creepage distances is outlined in Table 6.1.
6.2 Experimental Setup

Figure 6.3: Electric field of the test setup measured using the AC electric field meter.

Figure 6.4: Electric field of the test setup calculated using finite element analysis.
6.3 Creeping Discharge and Arcing Development in the Structure

These results show that there is a considerable change in the electric field near the cross-arm when the creepage distance of the HV insulator is reduced. Therefore, it can be seen that with the change in creepage distance of the insulators, the chance of arcing and burning at the cross-arm increases due to the high electric field present in the area. It is important to analyse the arcing development at the cross-arm in order to identify the risk factors that may lead to pole-top fires. Thus, creeping discharge and arcing development of the test setup is studied in the next section in order to get a clear idea of how arcing and burning can develop at a metal / wood junction in a pole-top structure.

Table 6.1: Maximum electric field at the cross-arm and the Effective Creepage Distance (CD) of the HV insulator.

<table>
<thead>
<tr>
<th>Creepage Distance</th>
<th>Maximum Electric Field (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>6086</td>
</tr>
<tr>
<td>80%</td>
<td>6090</td>
</tr>
<tr>
<td>60%</td>
<td>6717</td>
</tr>
<tr>
<td>40%</td>
<td>6920</td>
</tr>
<tr>
<td>20%</td>
<td>7410</td>
</tr>
<tr>
<td>0%</td>
<td>16231</td>
</tr>
</tbody>
</table>

6.3 Creeping Discharge and Arcing Development in the Structure

Creeping discharges can develop on cellulose fibre surfaces in a wooden utility pole as a result of the high electric field on the structure. This may happen due to the nearby high voltage sources. These creeping discharges can lead to arcing at the metal / wood interfaces in a wooden utility pole. The high energy in these arcs can then burn the cellulose fibre material, leading to pole-top fires. Since the metal / wood contacts are not perfect due to the manufacturing methods, there can be air and other gases trapped inside the voids between the king bolt and the pole. These gases can breakdown if subjected to high electric field, which may lead to partial arcing inside the structure.
6.3 Creeping Discharge and Arcing Development in the Structure

The main types of arcing that can occur near the king bolt are partial arcing on the cellulose fibre surface and partial arcing in air trapped between the metal / wood interface. When dust, moisture or other conducting particles are present in the area, they provide extra ions, enhancing the ionization of the cellulose fibre. Surprisingly, the effect of the creeping discharges and arcs has not been studied fully when it comes to pole-top fires. Therefore, our analysis next focused on studying arcing development at the metal / wood interfaces at the top of the pole, especially the near the king bolt.

In this section, the development of arcing in a pole-top is studied for various scenarios. A wooden supporting structure is setup in the high voltage laboratory as discussed in Section 6.2. Voltages up to 30 kV are applied to the structure using a high voltage transformer until arcing is visible to the naked eye. Experimental results based on various energization scenarios will be presented in the following sections.

Since two types of arcing are studied in this section, two king bolts are used in the experiment as shown in Fig. 6.6 for visualisation purposes. A normal king bolt is used to observe creeping discharge and arcing on the cross-arm surface as shown in Fig. 6.6(a), and a king bolt without a bolt-head is used in the experiment in order to observe arcing inside the air gap as shown in Fig. 6.6(b). Using a king bolt without a bolt-head ensured the clear visibility of arcing inside the air gap.

Only a single high voltage supply is utilised for the experiment as discussed in the previous section. Therefore, only one phase is energized at high voltage at a time, and the other two phases are energized at a low voltage using a potential divider (0 – 20 V). The setup is tested for visible arcing and creeping discharges under various configurations as outlined in Table 6.2. When the post insulator is installed at phase A and when phase A is energized at high voltage,
6.3 Creeping Discharge and Arcing Development in the Structure

one or more weather sheds of the insulator is bypassed as discussed in Table 6.2 in order to
model the change in creepage distance of the insulator. Voltage applied to the HV conductor is
increased until arcing in the air gap or the surface of the cross-arm is visible to the naked eye.
This voltage is called the arc inception voltage in the following sections. The maximum voltage
applied to the high voltage electrode is 30 kV. The voltage was kept at the arc inception voltage
until smoking and burning near the king bolt occurred.

The experiment was carried out for the wooden pole at both dry and wet conditions. The pole at
dry conditions has a moisture content of 12 %. Since a high amount of pole-top fires that were
recorded have started in rainy conditions, the wooden pole and the cross-arm are sprayed with a
thin layer of water to increase the moisture content of wood to 17%.

The arcing in the structure near the king bolt insertion of a wooden supporting structure has
been observed for the various scenarios outlined in Table 6.2.

6.3.1 Results and Discussion

The arc inception voltages observed for the scenarios outlined in Table 6.2 are shown in Table
6.3. It can be seen from the results that in a wooden utility pole that the arc inception possibility
near the king bolt at normal dry weather conditions is minimal.

No arcing at the king bolt could be observed at configurations where creepage distance of the
high voltage insulator was greater than 50%, at both dry and wet conditions. In these
configurations, a large fraction of the supplied high voltage is sustained by the length of the
insulator. Therefore, the voltage difference experienced by the cross-arm is lower, allowing a
low electric field near the king bolt and the cross-arm where the cross-arm connects to the
wooden pole. However, when more than 50% of the insulator weather sheds are bypassed, arcs
6.3 Creeping Discharge and Arcing Development in the Structure

could be observed even at dry weather conditions. This kind of scenario can occur when the creepage distance of insulator decreases due to pollution on insulator surfaces, or when weather sheds of an insulator are damaged.

It can be seen that the arc inception voltage is lower at wet weather conditions. In wet weather, a significant change in the electrical properties of wood could be observed. The Basic Insulation Level (BIL) of wood can decrease from 75 kV/ft down to 40 kV/ft depending on the weather conditions. When the moisture level of wood is higher, the time taken for arcing to start burning the wood is less, and the burning started within 90 seconds of arc inception.

Creeping discharges and arcing developed on the cross-arm surface near the king bolt are shown in Fig. 6.6, and the arcing developed in the air gap are presented in Fig. 6.7. Blue dotted line outlines the cross-arm and the green dotted line outlines the pole in the figures. Creeping discharges start along the surface of a dielectric material as a result of a localized discharge created by a high electric field. These discharges dissipate thermal energy, accelerating the ionization of air and cellulose fibre. They also have the ability to develop into highly
6.3 Creeping Discharge and Arcing Development in the Structure

Conductive sparks and arcs, which can burn the cellulose material, eventually leading to pole-top fires.

Table 6.2: Electrode Configuration for the experimental setup and the Effective Creepage Distance (CD) of the HV insulator.

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1.1</td>
<td>High Voltage with 100% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C1.2</td>
<td>High Voltage with 80% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C1.3</td>
<td>High Voltage with 60% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C1.4</td>
<td>High Voltage with 40% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C1.5</td>
<td>High Voltage with 20% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C1.6</td>
<td>High Voltage with 10% CD</td>
<td>10 V</td>
<td>10 V</td>
</tr>
<tr>
<td>C2.1</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 100% CD</td>
</tr>
<tr>
<td>C2.2</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 80% CD</td>
</tr>
<tr>
<td>C2.3</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 60% CD</td>
</tr>
<tr>
<td>C2.4</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 40% CD</td>
</tr>
<tr>
<td>C2.5</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 20% CD</td>
</tr>
<tr>
<td>C2.6</td>
<td>10 V</td>
<td></td>
<td>High Voltage with 10% CD</td>
</tr>
<tr>
<td>C3.1</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 100% CD</td>
</tr>
<tr>
<td>C3.2</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 80% CD</td>
</tr>
<tr>
<td>C3.3</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 60% CD</td>
</tr>
<tr>
<td>C3.4</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 40% CD</td>
</tr>
<tr>
<td>C3.5</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 20% CD</td>
</tr>
<tr>
<td>C3.6</td>
<td>10 V</td>
<td>10 V</td>
<td>High Voltage with 10% CD</td>
</tr>
</tbody>
</table>
6.3 Creeping Discharge and Arcing Development in the Structure

Table 6.3: Arc inception voltage for a structure using a wooden cross-arm and a galvanized steel king bolt.

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Effective Creeping Distance of the HV insulator</th>
<th>Arc Inception Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry Condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Setup with the wooden cross-arm</td>
</tr>
<tr>
<td>C1.4</td>
<td>40%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C1.5</td>
<td>20%</td>
<td>30 kV</td>
</tr>
<tr>
<td>C1.6</td>
<td>10%</td>
<td>22 kV</td>
</tr>
<tr>
<td>C2.5</td>
<td>20%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C2.6</td>
<td>10%</td>
<td>30 kV</td>
</tr>
<tr>
<td>C3.5</td>
<td>20%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C3.6</td>
<td>10%</td>
<td>30 kV</td>
</tr>
</tbody>
</table>

Arcing inside the air gap and the creeping discharges on the cross-arm surface can start only when the area is subjected to a high electric field. A high electric field near the king bolt enhances the ionization of the dielectric material. This initializes plasma generation, creeping discharges, partial discharges and arcing, leading to ignition at the cross-arm. It was evident that arcing inside the air gap at the wood / metal interface and arcing on the cross-arm due to creeping discharges lead to pole-top fire at wet weather conditions, provided that there is a reduction in the creepage distance of the HV insulators in any of the three phases. Electric field analysis carried out in Chapter 4 and Section 6.2 showed that there is a high electric field near the king bolt on the cross-arm surface and in the air trapped between the wood / metal interfaces. Therefore, it is important to reduce the electric field around the king bolt in order to reduce the risk of pole-top fires. The current flow, electric field and voltage distribution of a
6.4 Novel Pole Design with a Nonconductive King Bolt

wooden utility pole are taken into account and a nonconductive king bolt is proposed in this thesis in order to prevent pole-top fires. This will be discussed in the following section.

Figure 6.6: Creeping Discharge at the king bolt (at wet weather condition).

Figure 6.7: Arcing developed in the air gap (at wet weather condition).

6.4 Novel Pole Design with a Nonconductive King Bolt

Several methods are currently being followed by the power industry in order to minimize the risk of pole-top fires. Most of these mitigation techniques have either provided short term solutions to the pole-top fire problem have been incapable of solving the issue under service conditions.
6.4 Novel Pole Design with a Nonconductive King Bolt

It was shown in the previous section that the partial arcing near the pole / cross-arm junction where a metal king bolt is inserted plays a major role in pole-top fires. Partial arcing was observed in the following areas of the pole, which in turn lead to burning of hardwood timber, initializing a pole-top fire.

- Partial arcing on the cross-arm surface near the king bolt due to creeping discharges.
- Partial arcing inside the air gaps between the king bolt and the wooden pole or the king bolt and the cross-arm.

An arc can be formed in a gaseous liquid or solid dielectric due to an electrical breakdown of the dielectric material, which occurs as a result of high ionization of the dielectric subjected to high electric field. Partial arcs can occur in a dielectric even without reaching the breakdown voltage when there are conductive materials such as moisture, dust or highly ionized air is present to enhance the ionization. An electric arc dissipates energy to the surroundings, further ionizing the dielectric material and increasing the temperature of the surrounding objects.

Creeping discharges start along the surface of a dielectric material as a result of a localized discharge created by a high electric field. These discharges dissipate thermal energy, accelerating the ionization of air and cellulose fibre. They also have the ability to develop into highly conductive sparks and arcs, which can burn the cellulose material, eventually leading to pole-top fires.

Therefore, in order to reduce the risk of pole-top fires, it is essential to reduce the possibility of arcing inside the air gaps and on the cross-arm surfaces. This can be achieved by reducing the electric field of the concerned areas, especially in the air gap between the king bolt and the pole, and in the cross-arm near the king bolt and insulator pins.
6.4 Novel Pole Design with a Nonconductive King Bolt

The electric field characteristics of a typical wooden supporting structure were discussed in Chapter 4 and the laboratory experiments carried out using a wooden pole were discussed in the previous section. From these studies, it can be seen that partial arcing starts in the small air gaps between the king bolt and the cross-arm. There is a high voltage drop in the air gap as a result of the vast difference in electrical properties of the surrounding objects. This voltage drop can be smoothened out by using a bolt manufactured using a material which has electrical properties similar to wood and air, or by using a nonconductive king bolt with a low dielectric constant.

The creeping discharges started on the surface of the cross-arm, and eventually developed into partial arcing, burning the hardwood timber. In this case, the king bolt was at high voltage. It was acting as an electrode, ionizing the cellulose fibre surface and surrounding air, creating an environment of electron avalanches and positive space charges. Using a dielectric material for the king bolt will reduce the chance of effective ionization near the cross-arm surface, which in turn will reduce the possibility of creeping discharge and arcing development in the structure.

In order to achieve these objectives, a nonconductive king bolt made of fibreglass composites that is commonly used in highly erosive environments is proposed in this study. This will reduce the risk of pole-top fires in wooden supporting structures used in power distribution networks. This fibreglass king bolt has a dielectric constant of 4 and has minimum tensile strength of 100 kN. Conductivity of the fibreglass composite is negligible.

Fig. 6.8 presents the proposed new distribution pole design including the fibreglass king bolt. The greatest advantage of this new king bolt is that it offers a very simple arrangement with low-cost implementation. In addition, this proposed method can be installed in any kind of pole.
6.4 Novel Pole Design with a Nonconductive King Bolt

configuration and retrofitted to wooden pole in service in electrical distribution systems. A simple installation procedure is illustrated in Fig. 6.9.

An extensive study of computer simulations and laboratory experiments was carried out in order to analyse the feasibility of the nonconductive king bolt as a pole-top fire prevention method.

Figure 6.8: Novel Pole-top Structure with the fibreglass king bolt.
This section discusses both simulation and experimental work carried out in order to evaluate the feasibility of using a nonconductive king bolt and other pole hardware as a prevention method for pole-top fires. This section is divided into two sections as both simulation and experimental studies were used to determine the feasibility of using a fibreglass king bolt in a wooden supporting structure. In Section 6.4.1, the electric field characteristics of a wooden pole
6.4 Novel Pole Design with a Nonconductive King Bolt

used in an 11kV three phase distribution system is modelled and studied using Finite Element analysis. The electric field characteristics of the structure using a galvanized steel king bolt and a fibreglass king bolt are analysed separately. This section studies the effectiveness of a fibreglass king bolt in reducing the electric field of the fire prone area, especially in the air gap and the cross-arm. This section also discusses the experimental study carried out in the high voltage laboratory, in order study arcing development at the cross-arm for a wooden pole structure with fibreglass king bolt. These electric field calculation and laboratory test results are used to verify the efficacy of the fibreglass king bolt in reducing the risk of pole-top fires at the king bolt and the cross-arm.

6.4.1 Electric Field Calculations using Finite Element Analysis

The wooden pole model discussed in Section 4.3.1 is used in this study to analyse the electric field of the wooden utility pole. Electric field of the structure using a metal king bolt and a fibreglass king bolt are analysed separately and a comparison of the results are illustrated in Fig. 6.10. It can be seen that the electric field of the air gap has reduced significantly when the galvanized steel bolt is replaced by the new fibreglass bolt. The results show that using a bolt made of an insulating material will minimize the chance of partial arcing inside the air gap near the bolt. This will prevent tree burning and carbon formation inside the walls near the bolt, which will reduce the long term degradation of the wooden structure. However, it is important to test the proposed king bolt in the laboratory in order to complete the feasibility analysis of using a fibreglass king bolt as a solution to the pole-top fire issue. Therefore, experiments are carried out in order to study the characteristics of the structure when using a fibreglass king bolt as well.
6.4 Novel Pole Design with a Nonconductive King Bolt

6.4.2 Experimental Results

In this section, the laboratory test setup discussed in Section 6.2 is used to study the arcing development in a pole-top structure for various scenarios. A new king bolt made of fibreglass composites is used in this experiment, which is shown in Fig. 6.11. Voltages up to 30 kV are applied to the structure using a high voltage transformer until arcing is visible to the naked eye. Experimental results based on various energization scenarios will be presented. The arc inception voltage observed for the scenarios outlined in Table 6.2 are shown in Table 6.4.

It can be seen from the results that when a fibreglass king bolt is used, the possibility of arcing near the king bolt is non-existent. Arcing at the king bolt only occurred in C1.6, C2.6 and C3.6 test configurations. These configurations represent a situation where a total insulation failure has occurred, which has a very low probability of occurrence. Therefore, it can be seen that using a high-strength fibreglass bolt as the king bolt has the capability of preventing the pole-top fires. It is important to test the proposed fibreglass king bolt with a full scale pole in actual
6.4 Novel Pole Design with a Nonconductive King Bolt

service conditions in order to determine the effectiveness of the proposed solution. The proposed solution also can be integrated with the existing solutions such as line pole grounding systems or mid pole bonding systems.

Figure 6.11: Fibreglass king bolt (diameter of 20mm) which is used for the laboratory experiments.

Table 6.4: Arc inception voltage for a structure using a wooden cross-arm and a fibreglass king bolt.

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Effective Creeping Distance of the HV insulator</th>
<th>Arc Inception Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry Condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet Condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Setup with the wooden cross-arm</td>
</tr>
<tr>
<td>C1.4</td>
<td>40%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C1.5</td>
<td>20%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C1.6</td>
<td>10%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C2.5</td>
<td>20%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C2.6</td>
<td>10%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C3.5</td>
<td>20%</td>
<td>No Arcing</td>
</tr>
<tr>
<td>C3.6</td>
<td>10%</td>
<td>No Arcing</td>
</tr>
</tbody>
</table>
6.5 Conclusions

In this chapter, the behaviour of a wooden utility pole under an electromagnetic environment was studied in a laboratory setting. A small scale wooden utility pole was used in the high voltage laboratory in order to investigate the factors leading to pole-top fires. Electric field of this setup was measured using an AC electric field meter, and these results were used to validate the electric field values calculated using finite element analysis. This test setup was also used to investigate the creeping discharge and arcing development near the cross-arm junction at the king bolt. The investigations proved that arcing could occur in the air gap near the metal king bolt insertion, which could in fact lead to burning at the wood / metal junction. It was shown that the highest risk of pole-top fire is at wet weather conditions, when the creepage distance of the insulators has been depreciated due to surface pollution. It is important to minimize arcing inside the air gap near the metal / wood junction, in order to prevent pole-top fire. Therefore, a nonconductive, high-strength king bolt made of fibreglass composite was proposed, and the feasibility of using this king bolt was studied using computer simulations and laboratory experiments. Simulations carried out using Finite element analysis showed that the electric field at the cross-arm is reduced with the fibreglass king bolt. Laboratory experiments showed that the proposed king bolt reduces the risk of creeping discharge and arcing development at the cross-arm. This fibreglass king bolt has significant potential to eliminate the risk of pole-top fire by reducing the electric field of the bolt / cross-arm junction.
Chapter 7

Conclusions and Future Work

Wooden utility poles are commonly used in transmission and distribution networks across the world. Their low initial cost, favourable environmental impacts, electrical and mechanical properties have made them advantageous over alternative types such as concrete, fibreglass and galvanized steel poles. One of the main disadvantages of using wooden poles in power networks is the formation of pole-top fires. These fires not only disturb the power supply, but also have become a main cause of bushfires in Australia. Considerable amount of research has been carried out to uncover the causes of pole-top fires and to find a solution to this problem. This thesis focused on studying the electrical properties of a wooden utility pole in order to identify the causes leading to pole-top fires.

In this thesis, electrical characteristics of a wooden utility pole were studied using finite element analysis and a three dimensional ladder network model. Experimental studies were also carried out to investigate the development of arcing and burning on cellulose fibre surfaces caused by creeping discharges. The influence of high voltage, leakage current and electric field on initiating a pole-top fire were studied in detail, and by using the observations, a nonconductive king bolt was proposed as a solution to the pole-top fire issue.
7.1 Conclusions

An outline of the thesis is given below.

1. A three-dimensional resistance model of a wooden utility pole was developed based on the electrical ladder network to analyse the current and voltage distribution along the structure under normal and polluted conditions.

2. Finite Element Method (FEM) was used to analyse the current flow, electric field and voltage distribution of a wooden utility pole in a high voltage environment.

3. A detailed investigation was performed using a laboratory setup to study the development of arcing and burning caused by creeping discharges on cellulose fibre found in hardwood timber. The effects of moisture content, voltage and presence of external moisture on the process leading to arcing and burning were studied in detail.

4. Laboratory tests were carried out to investigate the creeping discharge and arcing development in a wooden utility pole due to high electric field near metal insertions.

5. A cost effective pole-top fire mitigation method was proposed to eliminate the arcing and creeping discharge on wooden utility poles by reducing the electric field near the metal bolt. Computer simulations and laboratory experiments were carried out to verify the feasibility of installing the proposed design in a power network.

Following sections will present the major findings in this research program, conclusions and recommendations for future work.

7.1 Conclusions

In this thesis, many significant outcomes related to pole-top fires on a power distribution network have been discovered. These outcomes and the contributions of this thesis are presented below.
7.1 Conclusions

Firstly, leakage current and voltage distribution of a wooden pole were studied using a three dimensional resistance model based on the electrical ladder network. Leakage current and voltage of the model were simulated for different scenarios that could occur in practice. The analysis showed that a large part of the leakage current passes through the heartwood to the ground, except in the area of the metal bolt. In this area, a large portion of the current passes through the metal bolt, creating a current concentration in the high resistance wooden members around the bolt. Simulations showed that a high voltage was present at the metal bolt, creating a high voltage electrode connected to the dielectric wooden objects. The current and voltage at the metal bolt increases at high moisture contents making the pole vulnerable to fire. These analyses also showed that more accurate results could be obtained when the division pattern of the resistance model represents an actual wooden pole.

The current flow, electric field and voltage distribution of a wooden utility pole were further investigated using finite element analysis. These results confirmed that the electrical characteristics of the utility pole changes significantly with the moisture content of the environment. These analyses also showed high voltage and high electric field is present at the metal king bolt, and there is a possibility of arcing development near this metal insertion.

With the understanding of the voltage and electric field near the metal / wood interface, this thesis next studied the development of arcing in cellulose fibre. In particular, it focused on arcing in microfibrils found in hardwood. Voltages up to 16kV were applied to hardwood timber specimens using a flat-plane electrode arrangement until arcing between the electrodes occurred. The results showed that the burning of cellulose materials is caused by sparks and arcing developed on the fibre surface. Higher moisture levels in the fibres reduce the time taken for the creeping discharges to develop into arcing, and with the help of a continuous air supply, arcing eventually can lead to burning of the microfibrils. It was shown that the arcing and
7.2 Future Work

burning occurs at the points with the highest electric field, and the burning process accelerates when the moisture content of wood was increased. The results also showed that the development of arcing is directly related to creeping discharges, and that the presence of moisture in the environment accelerated the arcing and burning process.

Having established that the creeping discharges and arcing can lead to burning of the cellulose fibre near a high voltage energized electrode, this thesis next studied the creeping discharge and arcing development near wood / metal interfaces in a wooden utility pole. A small scale utility pole was tested in the high voltage laboratory under various configurations to investigate the development of arcing near the king bolt. The results showed that arcing eventually develops into burning of the wooden surface near the king bolt, especially at wet condition, when the creepage distance of the insulators was reduced due to surface pollution.

Finally, taking all these factors into consideration, a pole top fire mitigation method using a nonconductive, high-strength king bolt made of fibreglass composite was proposed to overcome the pole-top fire issue. The feasibility of using fibreglass king bolts was studied using finite element analysis and laboratory experiments. The results showed that the electric field at the cross-arm is reduced with the fibreglass king bolt, and the proposed king bolt reduces the possibility of creeping discharge and arcing development at the cross-arm. The fibreglass king bolt is considered a low cost solution and can be retrofitted into existing distribution poles. This proposed solution has significant potential to eliminate the risk of pole-top fire by reducing the electric field of the bolt / cross-arm junction. The cost effective solution including the nonconductive king bolt offers simple installation which can be used by the power distribution companies.
7.2 Future Work

Before concluding this thesis, a few recommendations are also given for future work in this area of research. The proposed recommendations are listed below.

1. The ladder network model can be further developed by introducing capacitive and inductive parameters into the resistance model. This will make the ladder network model more accurate, and more similar to a finite element model, making the comparisons between the two models easier.

2. This study can be further extended to analyse the temperature rise near the king bolt due to creeping discharges. A thermal study can be used to study the temperature variation due to high voltage and electric field near the king bolt both using computer simulations and experimental work.

3. The proposed solution can be installed on site in a power distribution network, possibly in an area where pole-top fires were reported in the past. This could provide further understanding of the feasibility of the proposed fibreglass king bolt.

4. The effects of leakage current on starting a pole-top fire were analysed in the past, and pole bonding was suggested as a method of prevention. Solutions such as the mid pole bonding system can be integrated with the proposed nonconductive king bolt, and can be installed in a power distribution system for a more effective outcome.
Bibliography


151


[77] A. Beroual and L. Kebbabi, "Analysis of cumulative number and polarity of creeping discharges initiated at solid/liquid interfaces subjected to AC voltage," in *Proceedings*


M. F. Rahmat, "Study of New Mid-Pole Bonding Mitigation System to Wooden Pole Ladder Network Model to address Pole-Top Fire Issue," Ph.D., School of Electrical and Computer Engineering, RMIT University, 2010.


