# Investigation into effectiveness of a downwire insulator and insulated bonding wire as mitigation measures for pole-top fires in woodpole structures

**Mikhuva Doctor Ntshani**

A research report submitted to the faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science of Engineering

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# ABSTRACT

Woodpole structures are widely used for overhead medium voltage (MV) distribution lines in South Africa. The problem is that wood burning, also known as pole-top fires, occurs on such structures, resulting in undesirable power outages, replacement costs and safety risks to humans and animals. The feasibility of a modified partially bonded woodpole structure with a small downwire insulator instead of the 500 mm gap along the wood in reducing the risk of pole-top fires and bird safety was investigated. Tests were conducted in a natural heavily polluted environment at the Koeberg Insulator Test Pollution Station (KIPTS), where several structures were erected and energised at 22 kV (phase-to-phase). Laboratory tests were also performed to confirm the findings obtained at KIPTS. The downwire insulators have been proven to effectively conduct leakage current to earth under polluted and wet conditions, with very little current flowing through the woodpole. Furthermore, no tracking and/or burning was observed on the woodpoles of all the test structures. The findings are promising and indicate that a downwire insulator may be effective in reducing the risk of pole-top fires. The downfall is that the impedance of the downwire insulators and insulation levels provided by the downwire insulators under such conditions may not be adequate to ensure acceptably low risk of bird electrocution. It may be feasible to design such an insulator that only conducts leakage current when necessary to prevent pole-top fires, while maintaining sufficiently high impedance to prevent bird electrocution. The preliminary specifications of the new downwire are provided.

## DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed on 8 April 2015

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**Mikhuva Ntshani**

## ACKNOWLEDGEMENTS

This *work is dedicated to my wife, Itukiseng and my daughter, Nkotiso for their support and sacrifices that they had to make in order to afford me the opportunity to complete this work. I could not have done it without them.*
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# 1. INTRODUCTION

## 1.1 Background

The most important design criteria for MV lines are acceptable lightning performance, bird safety, voltage impulse withstand strength of the structure, pollution performance and human safety [1-5]. A common practice used in distribution line structures in South Africa is therefore to use woodpoles and to partially bond a structure by electrically connecting all the metallic hardware using a bonding wire and to connect the bonding wire to pole earth electrode via a 500 mm gap along the wood [2, 6, 7]. Figure 1.1 shows typical examples of three-phase partially bonded structures. The bonding wire at the pole-top of the structure connects the metallic hardware of all of the insulators together with the bracing straps, bolts and other conductive hardware as shown in Figure 1.1.

This bonding technique results in an increase of the Basic Insulation Level (BIL) or lightning phase-to-earth withstand voltage by an additional 150 kV (phase-to-earth) provided by the wood along the 500 mm gap. For example, the BIL of a 22 kV line structure is increased from 170 kV (provided by the phase insulators) to at least 300 kV, leading to improved lightning performance, especially against lightning induced over-voltages that rarely exceed 250 kV (phase-to-earth) [6, 7]. This technique also assists in reducing the risk of bird electrocution – the fault current flowing on or through the bird when it makes contact with the live conductor is reduced by the impedance provided by the 500 mm wood gap.

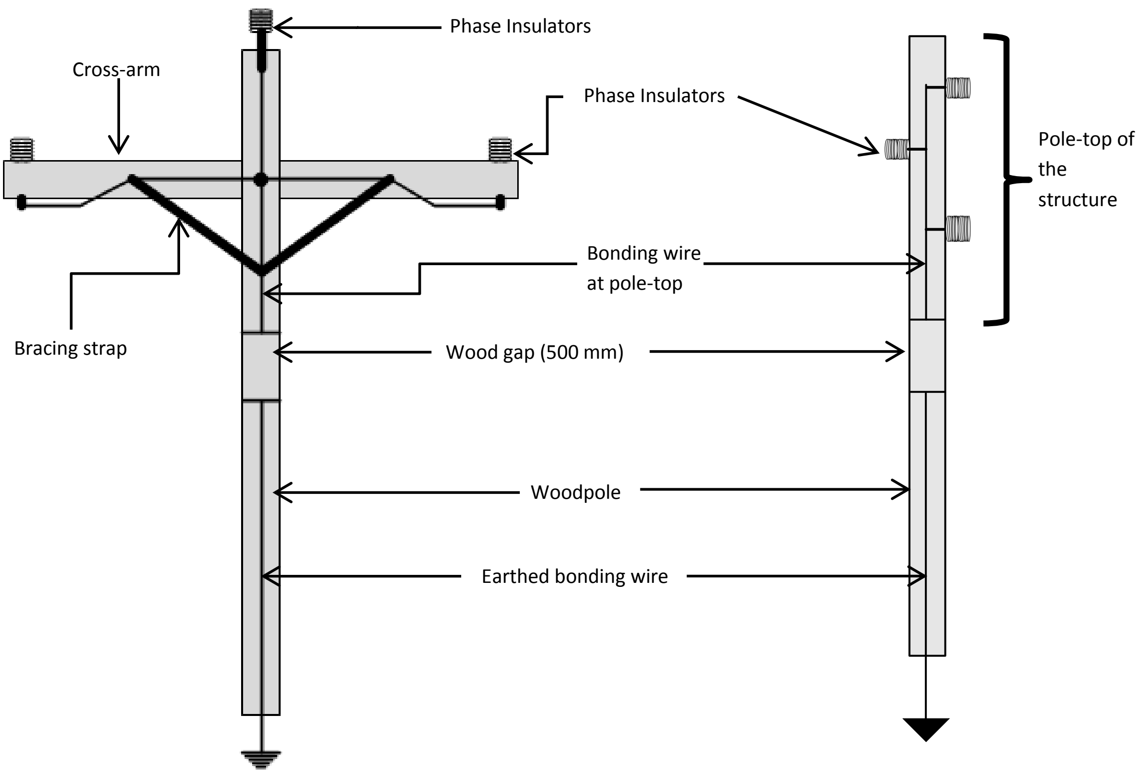



**Figure 1.1: Examples of a partially bonded structure used in South Africa: with a cross-arm to support insulators (left), insulators connected directly to the woodpole (right)**

The problem is that wood burning, also known as pole-top fires, occurs on such structures [1-5]. This problem has been known to occur since the 1940s [3]. Most pole-top fires occur under polluted and light wetting conditions, where sustained low levels of leakage current (in order of milliamps) flows on the surface of the phase insulators and into the structures of the wood. This current may cause wood tracking to occur and consequently burning of the wood. Figure 1.2 shows a typical example of a burnt structure in the field [4].

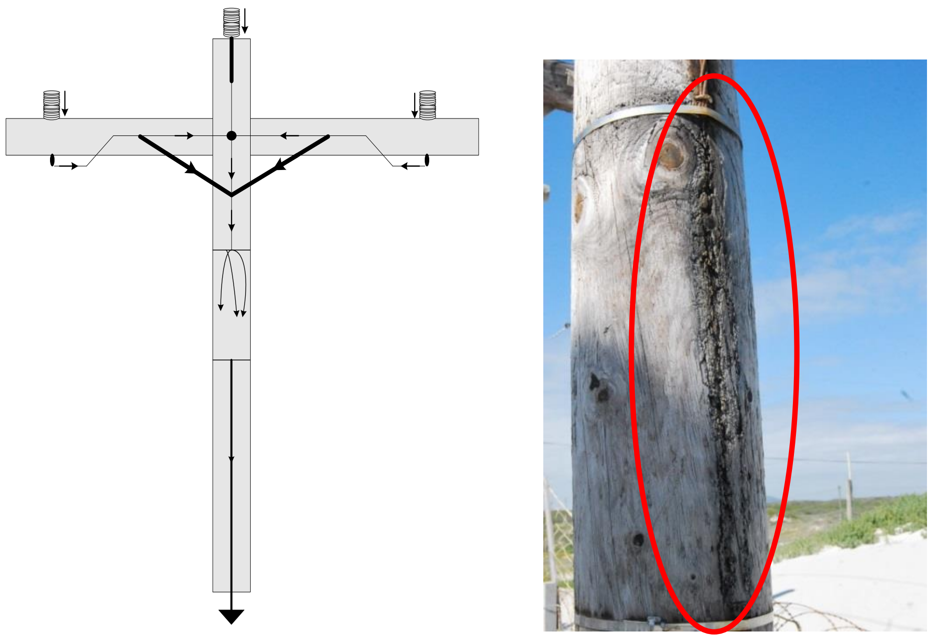
Pole-top fires have several negative consequences, such a low hanging conductor (a live conductor hanging as low as 1 m above ground), a condition that cannot be easily detected, leading to potential safety implications to humans and animals; power outages and replacement costs.

**Figure 1.2: Typical example of a burnt structure in the field [4]**

South African experience is that pole-top fires can occur along the wood directly underneath the phase insulators and along the 500 mm wood gap of a partially bonded structure [2, 4, 5, 8]. The burning underneath the phase insulators (particularly on the cross-arm) is attributed to the fact that the leakage current flowing on the surface of the phase insulators may still pass through and/or over the wood before getting to the metallic bonding [2, 4]. The burning is eliminated by electrical bonding of the metallic hardware (such as the insulator end fittings) and using insulators with suitable conductive end-fittings, in addition to bonding, or by using a steel cross-arm instead of a wood cross-arm [4, 8].

The burning in the wood gap is attributed to the fact that the leakage current flowing on the surface of the insulators and the bonding wire, still needs to pass through or over the surface of the wood gap to get to earth [9]. The problem is illustrated in Figure 1.3 a), with arrows showing the flow of leakage current on the structure. Electrical tracking, which is one of the initial stages of wood burning due to leakage current, was observed in the wood gap of partially bonded structures in the field and at KIPTS [4, 5, 8]. Figure 1.3 b) shows a typical example of such tracking [4, 5, 8].

The burning at the wood gap may be prevented by bonding and directly earthing all the metallic hardware of the structure (i.e. by bridging the wood gap) as proposed by Darveniza [3]. This provides a low resistance path for leakage current to flow to earth without flowing through the wood. This configuration is referred to as a ‘fully bonded and earthed structure’ and has been proven to completely eliminate pole-top fires [8].



a) b)

**Figure 1.3 Illustration of the risk of burning in the wood gap of a partially bonded woodpole structure (a) and electrical tracking observed as a result (b) [4, 5, 8]**

The problem with fully bonded and earthed structures is that their effect on human safety and other factors still needs further investigation [5].

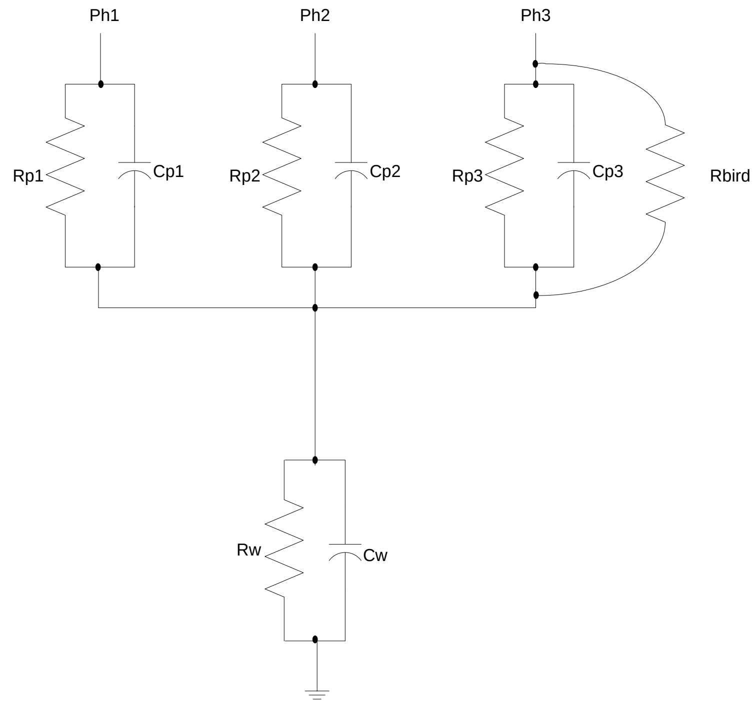
Another problem with fully bonded and earthed structures is that the 500 mm gap also provides additional impedance to reduce the risk of bird electrocution. Figure 1.4 compares the equivalent circuit of a partially bonded structure and a fully (or completely) bonded and earthed structure, with respect to bird safety. A bird (modelled as resistance $R_{bird}$) is assumed to make contact with one of the phase conductors. In Figure 1.4, $R_{p1}$ and $C_{p1}$ are the resistance and capacitance of the insulator connected to phase 1 (Ph1), $R_{p2}$ and $C_{p2}$ are the resistance and capacitance of the insulator connected to phase 2 (Ph2), $R_{p3}$ and $C_{p3}$ are the resistance and capacitance of the insulator connected to phase 3 (Ph3) and $R_w$ and $C_w$ are the resistance and capacitance of the wood across the gap.

For a partially bonded structure (Figure 1.4 a), if a bird perched on the cross-arm makes contact with a phase conductor, the earth leakage current through the bird would be limited by the impedance of the wood across the 500 mm gap, which may be of the order of hundreds of kΩ to MΩ [1, 3]. This may significantly reduce the earth leakage current and therefore limit the risk of the bird being electrocuted to an acceptable level.

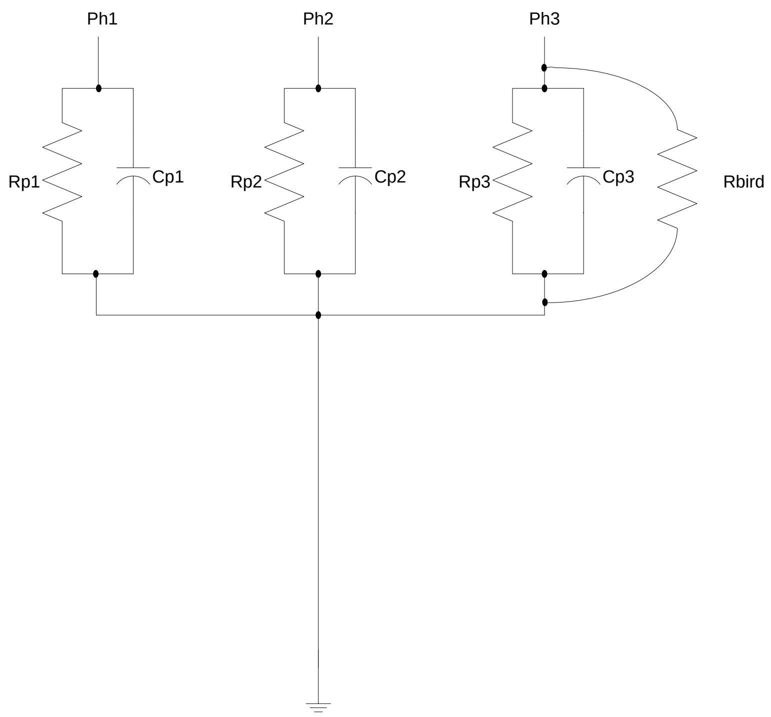
However, for a fully bonded and earthed structure (Figure 1.4 b), the earth leakage current would be limited by the impedance of the bird only, which may be of the order of tens of kΩ. Furthermore, fully bonding and earthing a structure causes the bonding wire at the pole-top of the structure to be at earth potential. Thus a bird perched on the cross-arm and simultaneously making contact with the earthed bonding wire and a live conductor would be subjected to the full phase-to-earth voltage. According to [10], birds with wet feathers may be electrocuted by 5 kV or above. Therefore, full bonding and earthing a structure results in increased risk of bird electrocution when compared to a partially bonded structure.

Thus removing the 500 mm wood gap requires careful consideration of the impact on humans and bird safety.

The objective of the research is therefore to evaluate the feasibility of modifying a woodpole structure to reduce the risk of pole-top fires, when compared to a partially bonded structure, while keeping the risk of bird electrocution at an acceptable level.




a)




b)

**Figure 1.4: Equivalent circuits of a) a partially bonded structure, b) a fully bonded and earthed structure**

## 1.2 Hypothesis

It is hypothesised that the risk of burning at the 500 mm wood gap may be reduced by replacing the wood gap with a small downwire insulator, i.e. the bonding wire is earthed via a small downwire insulator instead of via a 500 mm wood gap. Figure 1.5 shows a schematic and equivalent circuit of the proposed solution, where $R_d$ and $C_d$ are the resistance and capacitance of the downwire insulator and the other parameters are as discussed in Section 1.1. The problem is that woodpole remains in parallel with the downwire insulator, and previous work indicated that wet wood may be relatively conductive [3]. Thus under wet and polluted conditions – under which most pole-top fires were reported [2, 3, 4, 9] – the downwire insulator must allow a significant amount of leakage current to flow to earth, relative to the wood. Thus the selection and design of the downwire insulator is crucial for the effectiveness of the modified structure.

For test purposes, the selection of the downwire insulator was based on Equation 1.1 and previous work conducted at KIPTS [11]. Equation 1.1 indicates that the resistance of the insulator depends on its dimensions (length and area) and the resistivity (insulator material, wetting and pollution accumulated by the insulator) [11]. A conventional porcelain stay wire insulator was selected due to its dimensions (small length and area), material (relatively hydrophobic), robustness and its weight. Previous work indicated that under polluted and wet conditions, a porcelain insulator material offers lower resistances, after cycloaliphatic material, than other materials such as silicone insulator and ethylene propylene diene monomer (EPDM) [11]. However, cycloaliphatic insulator material was not selected since it is prone to erosion and tracking [11].

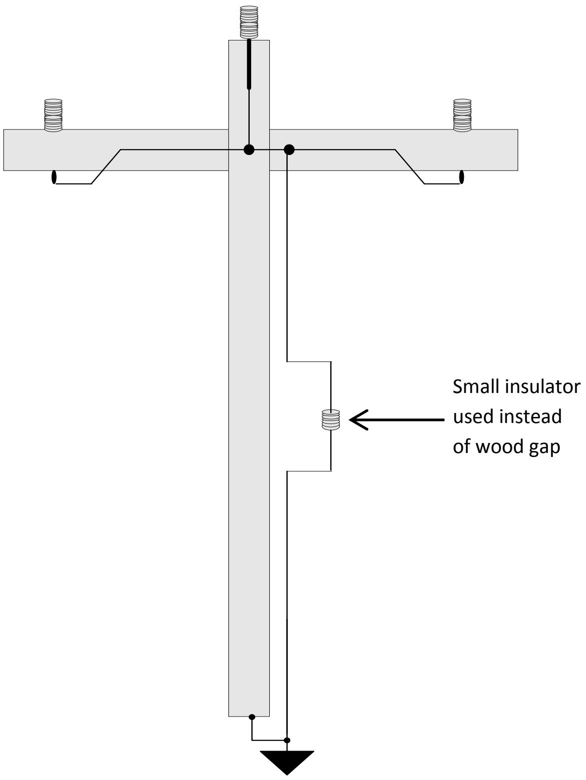
Refer to Appendix A for electrical properties of the porcelain stay wire insulator.

$$R = \frac{\rho L}{A} \qquad \text{(Equation 1.1)}$$

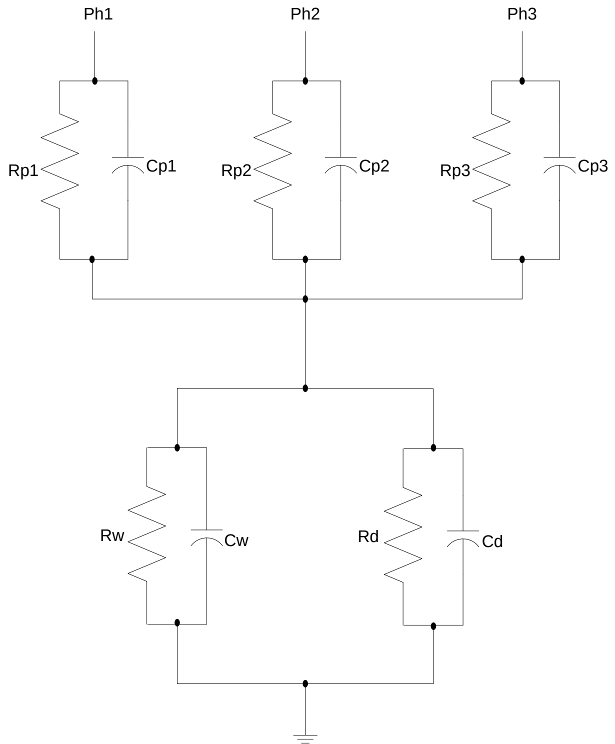
Where $\rho$ is the resistivity of the insulator material, in Ωm
L is the insulator leakage distance, in m
A is the cross-sectional area of the insulator, in $m^2$

An unglazed downwire insulator was also selected to investigate the effect of the downwire insulator surface material. This insulator is similar to a conventional stay wire insulator, except that the glazing was removed. It is postulated that this material may allow pollution to accumulate more easily on the unglazed insulator than on a glazed insulator, resulting in further reduction of insulator surface resistance when the insulator is wetted and polluted. Figure 1.6 shows the differences between the glazed and unglazed downwire insulators used during the investigations.

It is also hypothesised that using an insulated bonding wire instead of the bare bonding wire may also provide additional insulation to reduce the risk of bird electrocution to acceptable levels.




a)




b)

**Figure 1.5: Proposed solution and equivalent circuit: a) schematic diagram [9], b) equivalent circuit**

**Figure 1.6: Glazed (left) and unglazed (right) downwire (stay wire) insulators [9]**

## 1.3 Objectives

The objective of the research was to investigate the effectiveness of using a downwire insulator instead of the 500 mm wood gap to limit the risk of pole-top fires, while still maintaining an adequate level of insulation for bird safety in MV lines.

The research is broken down into answering the following questions:

1. Is the use of a downwire insulator effective in diverting leakage current away from the woodpole? If so, under what conditions is this possible?
2. What is the effect of insulator material on the ability of the downwire insulator to divert leakage current away from the woodpole?
3. What role does the condition of the wood play in the overall performance of the structure to enable leakage current to flow on the insulator instead of on the wood?
4. What insulation level does the downwire insulator provide at the pole-top (i.e. above the downwire insulator)? Are these levels and the levels provided by the insulated bonding wire levels adequate to acceptably limit the risk of bird electrocution?
5. What should the design of the downwire insulator be?

## 1.4 Structure of the report

Section 2 provides the literature review, which details the previous work conducted by other local and international researchers in relation to pole-top fires and insulation coordination of MV lines and their effect on the risk of pole-top fires. Section 3 covers the experiment set-up and rationale for tests in a natural heavy polluted environment and laboratory tests in a controlled environment. Chapters 4 to 6 details the experiment results obtained, with thorough analysis of the results. And finally Section 7 covers the conclusion and recommendations for future work.

# 2. MECHANISM AND INTERNATIONAL EXPERIENCE WITH POLE-TOP FIRES

## 2.1 Introduction

This section is a summary of the literature that was reviewed in this study. The literature survey focusses on the following areas:

- Mechanism of pole-top fires.
- Extent of pole-top fires in South Africa and work conducted by other researchers.
- Experience by other countries.
- Insulation coordination of MV lines, covering amongst others bird safety and lightning performance, especially for South African conditions.

## 2.2 Pole-top fires on MV lines

### 2.2.1 Mechanism of pole-top fires

The mechanism of pole-top fires in wood structures has been known since the 1940s and documented by the Australian researchers [3, 12]. The mechanism is summarised as follows [12]:

- Pollution builds up on the surface of the phase insulators. This normally occurs during dry seasons, where there is little or no rain to wash off the pollution from the insulators. The structures remain dry due to little or no rain.
- In light wetting conditions (fog, mist or dew), the phase insulators are lightly wetted, leading to the flow of leakage current.
- However, certain portions of the wood are shielded from moisture and therefore remain dry even under these light wetting conditions. This causes the shielded areas to have high resistance. Typical examples of such areas are the woodpole to cross-arm interface and the insulator to wood interface for vertically mounted post insulators.
- This causes high voltages to be developed when the leakage current flowing on the phase insulators flows through the highly resistive shaded areas. Furthermore, these areas are generally short in length and therefore high voltage gradients are developed.
- High voltage gradients and current concentration causes heat to be generated ($I^2R$) and sparking to occur on the wood, eventually causing the wood to burn.

The mechanism is similar to the South African experience [2, 4, 5, 8, 9]. Recent work also showed that wood burning occurs when the leakage current flowing on the surface of the phase insulators is allowed to flow on the structures of the wood, whether it is on the pole or on the cross-arm [5, 8].

### 2.2.2 South African experience

Persadh extensively covered the extent of pole-top fires in South Africa, including unpublished work conducted by other local researchers [2]. Loxton investigated the occurrence of pole-top fires in Kwazulu-Natal during the 1990s [2]. The work focussed on partially bonded 22 kV lines since these lines are used more frequently than 11 kV and 33 kV lines in South Africa. Field experience indicated that effective application of the bonding philosophy (i.e. electrical bonding of all metallic hardware of the structure) eliminates burning of the wood cross-arm. The research also investigated the effect of weather conditions (humidity and temperature) and insulator pollution on the leakage current performance of a woodpole structure [2]. The findings showed that leakage current flowing on the insulators increases with pollution accumulated on the insulators, even in lightly wetted conditions. However, humidity in excess of 70% was found to cause higher levels of leakage current to flow on the surface of insulators, even when the pollution accumulated on the insulators was low. This led to the conclusion that pole-top fires may occur even in a lightly polluted environment, provided that the relative humidity is sufficiently high. Loxton also performed measurements of the leakage current on an in-service 22 kV structure [2]. The results indicated that long periods (up to 5 hours) of the day are dominated by low levels of leakage current (in order of 0.5 mA). Higher levels of currents (in order of 9 mA) were also measured when the pollution severity and relative humidity were high. Laboratory tests conducted in conjunction with these tests indicated that lower levels of leakage current (in order of 1 mA) are sufficient to cause burning of the wood [1].

Loxton also investigated the effectiveness of bridging out high resistance zones as a possible measure to reduce pole-top fires [2]. These mitigation techniques were in the form of using a conductive paint around the dry area, guarding (electrically bridging out the high resistive area with a piece of conductor) and banding (similar to guarding, with the conductor connected around the circumference of the wood) and were proposed by Ross and Darveniza [3, 12]. The conductive paint was found to reduce the burning of the wood, but was not found to be sufficiently durable for application in the field [2]. Guarding and banding were found to reduce surface burning but did not eliminate internal burning of the wood. For South Africa, the application of these techniques requires special consideration since they apply to structures that are not bonded or earthed, thus may not be desirable in areas with high lightning activity. As part of this investigation, Loxton also performed laboratory tests to determine the resistance or impedance of the wood cross-arm and the relations to moisture content or wetting of the wood [2]. The tests were performed on a 1 m long wood cross-arm. The result indicated that the wetting has a significant effect on the resistance of wood; where the resistance reduced from 410 MΩ when the wood is dry to 101 kΩ when the wood is heavily wet [2].

Persadh performed further investigations into the occurrence of pole-top fires in Kwazulu-Natal between 2001 and 2007 [2]. Persadh indicated that there were approximately 600 pole-top fires that were reported on 22 kV lines throughout the KwaZulu-Natal province between 2001 and 2007. Most of the pole-top fires were caused by poor application of the bonding technique, although some instances were reported on correctly bonded structures. The results showed that most of the pole-top fires occurred on the cross-arm of the structure (i.e. underneath the phase insulators), with few incidences reported on the woodpole of the structure. The burning of the cross-arms on correctly bonded structures was attributed to the high voltage gradient between the base of an uncapped phase insulator and the wood cross-arm. Persadh measured 300 V between the base of an insulator and the wood cross-arm, which was an equivalent voltage gradient of 60 V/mm. As part of this investigation, Persadh also investigated the effectiveness of using steel cross-arms to eliminate the risk of burning on the cross-arm [2]. The results indicated that a steel cross-arm eliminates cross-arm burning (since steel is used). However, minor leakage current activity (tracking) was observed on the woodpole to steel cross-arm interface, indicating that using steel cross-arm may not eliminate pole-top fires.

Further work performed recently involved field investigations and tests conducted at KIPTS [4, 8]. Field investigations indicated that most pole-top fires occurred on un-bonded or poorly bonded structures. This is consistent with findings of Loxton and Persadh [1, 2]. The effectiveness of a partially bonded structure was investigated at KIPTS. The results confirmed the findings of Persadh [2] that pole-top fires may occur on the wood cross-arm and at the 500 mm wood gap [8]. The results also showed that the burning of the cross-arm may be eliminated by using steel cross-arms. Where wood cross-arms are used, the risk of cross-arm burning may be effectively eliminated by effective bonding and using insulators with suitable conductive end-fittings (capped insulators or collector plate with uncapped insulators). The effectiveness of a completely bonded and earthed structure in eliminating pole-top fires was also investigated [8]. This method was conclusively proven to prevent pole-top fires. However, this option is not currently applied in South Africa due to the increased risk of bird electrocution on some configurations and the fact that the effect on human safety needs further investigations. The problems are detailed in Section 1.1 of this document. Furthermore, the effectiveness of using silicone rubber and silicone rubber coated porcelain insulators in reducing surface leakage current was also investigated. These methods were found to reduce the risk of pole-top fires occurring, but did not eliminate burning at the wood gap of a structure [8].

It follows from the above discussion that at this stage, a partially bonded structure with silicone rubber insulators (provided it has suitable conductive end fittings) provides the best available option to reduce the risk of pole-top fires for South African condition. However, the risk of fire starting at the wood gap of the structure still exists.

### 2.2.3 Australian experience

Australia has experienced pole-top fires since the 1940s [3, 12]. Most pole-top fires occurred at the kingbolt that connects the woodpole and the cross-arm (i.e. the bolt that secure the cross-arm to the main pole). The fires were attributed to the phenomenon of the development of high resistance and high voltage zones in shielded areas – described in Section 2.1.1. The phenomenon described in Section 2.1.1 was first identified by Australian researchers [3, 12]. Proposed mitigation measures were in the form of shunting techniques in order to bridge out the high resistive zones. The shunting technique provided good results during laboratory experiments [12], with certain drawbacks such as corrosion of the shunting conductors and reduced impulse strength of the wood. Some of these techniques were investigated by Loxton with little success as discussed in Section 2.1.2.

Darveniza performed an investigation into the electrical properties of wood and its influence on the occurrence of pole-top fires [3, 13]. The results indicated that the moisture content of the wood has a significant influence on the resistivity of the wood, as expected. Dry wood was found to have a high resistivity, with the resistivity decreasing by a factor of 7 when the moisture content was increased by 60 %. As a result, wet wood was found to be more conductive than dry wood. Other factors such as treatment of the wood were found to have minimal effect on the resistivity of the wood when compared to the moisture content. Darveniza also found that the burning at the metal to wood interface is worsened by the fact that the metal (kingbolt) becomes loose over time and causes a small airgap to exist between the wood and metal. High voltage gradients are generated at this airgap, causing sparking and eventually wood burning [13]. The investigation also showed that using conductive paint to bridge out high resistive areas was feasible and durable, contrary to findings in South Africa. Fully bonding and earthing a structure was proposed as an extreme measure to eliminate pole-top fires since it results in reduced impulse strength of the structure.

Pathak et al conducted a more recent investigation into the occurrence of pole-top fires in Australia [14]. The research was conducted following a pole-top fire incident that occurred on a 22 kV woodpole structure. The structure used a steel cross-arm, with the transformer mounted 3 m below the top of the structure. The burning was reported to have occurred at the bolt that connects the transformer to the woodpole. The results of the investigation showed that the fire was caused by the phenomenon described in Section 2.1.1, where a high concentration of leakage occurred and a high voltage gradient occurred at the bolt, which was shielded from rain by the transformer. Laboratory experiments indicated that relatively low levels of leakage current, in order of 4-5 mA, are adequate to cause wood burning to occur. The investigation indicated that these low levels of currents may cause the temperature at the bolt to reach up to 60 ºC, and the temperature of the wood in contact with the bolt to reach up to 93 ºC, which may cause the wood to burn. The finding that lower levels of leakage current are adequate to cause wood burning is similar to the South African experience as discussed in Section 2.2.2.

Wong et al performed further investigations into pole-top fires that occur at the metal to wood interface [15]. The investigation was in the form of determining the leakage current performance of woodpole structures with kingbolts. A three dimensional resistance model consisting of sapwood, heartwood and radial wood was developed. The results indicated that under wet conditions, wood is capable of conducting substantial leakage current from the pole-top of the structure to earth, with the majority of the current flowing at the centre of the pole. The results also indicated that the presence of the kingbolt and steel bars causes higher leakage current concentration at the kingbolt. The investigation also found that varying weather conditions caused the kingbolt to become loose due to contraction and expansion of the wood. An important finding from this work was that a higher concentration of current at the kingbolt is achievable even if the kingbolt is not loose. Wong's results indicate that an air gap between the bolt and wood is not necessary to cause a higher concentration of the current at the kingbolt. As part of this investigation, Wong also investigated the leakage current performance of aged woodpoles [16]. The results indicate that ageing of a woodpole has an effect on its resistance and ultimately on the leakage current performance of the wood. Aged wood provided lower resistance and hence higher leakage currents were recorded. As a result, it was concluded from this work that older structures are more susceptible to pole-top fires than new structures.

Rahmat et al performed an investigation into the use of a steel cross-arm and its effect on the burning at the kingbolt [17]. The results showed clear differences in the heating effect (or temperature generated) at the kingbolt when steel and wood cross-arms are used, with the steel cross-arm causing the greater heating effect. However, at low magnitudes of leakage current, the difference in heating effects when steel and wood cross-arms are used is minimal. These results indicate that while the use of steel cross-arms eliminates cross-arm burning, their use may not necessarily prevent pole-top fires. This may support Persadh finding where tracking was observed at the woodpole to steel cross-arm interface as discussed in Section 2.2.2.

Wong et al investigated using a shunting arrangement to reduce the burning at the metal to wood interface [18]. Insulated bonding wires were connected to the pins of the phase insulators and terminated at the woodpole away from the critical wood-to-metal interfaces. Laboratory tests provided encouraging results since the leakage current concentration at the kingbolts and at the pin insulator were significantly reduced. However, the method has not yet been tested in the field.

Recent statistics indicate that a total of 186 pole-top fires were recorded in two utilities in Victoria, Australia in 2012 [19], indicating that a solution to pole-top fires has yet to be found.

### 2.2.4 Kenyan experience

Persadh also documented the Kenyan experience with pole-top fires [2]. Pole-top fires were reported on the Mombassa-Malindi 33 kV line, particularly on the section that is closest to the coast. Britten and Kenyan Power Light Company performed an investigation in this regard. The results showed that most of the pole-top fires occurred on the cross-arm [2]. The problem was almost completely eliminated by replacing pin insulators that had a specific creepage of 17 to 22 mm/kV with post insulators that had a specific creepage of 25 mm/kV [2]. Furthermore, steel cross-arms were used instead of un-bonded wood cross-arms. It must be noted that the use of steel cross-arms was later tested in South Africa (refer to Section 2.2.2) with reduced risk of pole-top fires. However, burning was still observed on the 500 mm wood gap in South Africa. The author of this document could not obtain a recent update on the status of pole-top fires in Kenya.

## 2.3 Insulation coordination of MV lines

Insulation coordination plays an important role in the performance of MV lines in relation to pole-top fires. This section summarises the insulation coordination of MV or distribution lines, particularly for South African conditions. Insulation coordination is a study resulting in the selection of insulation strength of the system to match the expected voltage stresses imposed on the system [20]. According to [20], stresses on the electrical system may occur due to pollution, temporary over-voltages and transient over-voltages generated by switching of the system and lightning. Switching over-voltages are not a concern for distribution systems (including MV lines) because the over-voltages generated are lower than the withstand strength [6]. As such, distribution systems in South Africa are designed to withstand the maximum system power frequency voltage and lightning stresses. Factors such as pollution performance and bird safety also influence the design of the MV system.

### 2.3.1 Lightning over-voltages and their effect on MV lines

The author will not cover the theory behind the generation of lightning, but rather covers the effect of lightning on the performance and insulation coordination of MV lines. Lightning flashovers on MV lines can be caused by direct strikes to the line or by induced voltages caused by indirect lightning strikes, i.e. by lightning striking objects in the vicinity of the line [6, 21].

When lightning strikes the conductors directly, the lightning current divides into two components at the striking point, giving rise to two over-voltage surges that travel along the line in opposite directions [21]. The over-voltages depend on the impedance of the line, which is typically between 400 to 500 Ω [21]. As a result, a direct strike carrying 2 kA or higher to MV lines always causes a flashover to occur, even on a partially bonded structure with 300 kV BIL. However, the probability of direct strikes is reduced since the MV lines are generally shielded by nearby tall structures and trees.

Rather, induced over-voltages generated by indirect lighting strikes are responsible for most flashovers on MV lines [21]. This is because indirect strikes to the line occur more frequently than direct strikes to the line. However, lightning induced over-voltages on lines 8 m and higher rarely exceed 250 kV [6, 7], thus flashovers due to indirect lighting strikes may be eliminated by using lines with BIL of above 250 kV (phase-to-earth).

The following options are available to reduce the effect of lightning in MV lines.

#### 2.3.1.1 Unshielded lines with 300 kV basic insulation level (BIL)

In this approach, the MV lines are unshielded (i.e. without shield wires). The aim is to reduce the number of flashovers caused by indirect lightning strikes. As stated above, induced over-voltages caused by indirect lightning strikes rarely exceed 250 kV. The 300 kV BIL approach is thus acceptable to significantly reduce the number of lightning related flashovers. 300 kV BIL is achieved by using insulators with approximately 150-170 kV (phase-to-earth) BIL and bonding all the metallic hardware of the structure together and connecting this to earth via a 500 mm wood gap [6]. The 500 mm wood gap is used as part of insulation and provides approximately an additional 150 kV BIL to earth. Since the wood gap is in series with the insulators, a BIL of approximately 300 kV is achieved between the phase conductors and earth. This approach is called partial bonding and is shown in Figure 1.1. Over-voltages in excess of 300 kV caused by direct strikes on the line cause a flashover to occur on the line structure(s).

Another advantage of using a 500 mm wood gap is that particular types of wood have a good arc quenching capability. This reduces the risk of power frequency follow current when lightning directly strikes the line [6]. According to [6], high voltages are developed during arc quenching if the arc path is large (e.g. inside of the pole), causing wood damage to occur.

The effectiveness of this configuration on pole-top fires has been investigated [8], with pole-top fires occurring on the cross-arms and 500 mm gap along the wood.

This option is widely used in South Africa.

#### 2.3.1.2 Shielded lines to prevent direct lightning strikes to the line

In this approach, shield-wires are installed above the phase-conductors to prevent direct lightning strikes to the phase conductors. The advantage of this options is that using the shield wires prevents direct lightning strikes and reduced magnitude of induced over-voltages caused by indirect lightning strikes [21].The problem is that direct strikes to the shield wires may cause the voltage of the structure to rise above that of the line, causing a back-flashover to the phase conductors to occur [6, 22]. Therefore the effectiveness of this approach requires lower footing resistances (lower than 10 **Ω**) and the shield wire to be earthed at every pole [21]. Depending on soil resistivity, earth trenches may have to be installed to reduce the footing resistance to acceptable level, making this approach expensive (due to high initial capital cost). Surge arrestors may also be installed at various line structures to prevent over-voltages from travelling along the line, thereby posing risk of damaging equipment such as transformers.

#### 2.3.1.3 Unshielded lines with BIL greater than 1 MV

This approach is referred to as the fully insulated approach since there is no earth downwire and the phase insulators may or may not be bonded together. The advantage is that larger wood gaps are achievable with this approach, resulting in an increased BIL to above 1 MV [6, 21]. However, direct strikes to the line may still cause a flashover to occur, which may damage the pole since the arc length is larger [6, 22]. The effectiveness of this configuration on pole-top fires has not yet been investigated.

### 2.3.2 Bird safety

Bird safety is also a very important consideration in the insulation coordination of MV lines in South Africa. Using a 500 mm wood gap between the pole-top and earth electrode of the structure results in a reduced risk of bird electrocution. This is because the 500 mm wood gap provides an additional impedance that limit the earth leakage current through a bird should it simultaneously make contact with the live phase conductor and the bonding, e.g. while perching on the cross-arm. Thus from the options discussed in Section 2.3.1, the fully insulated structure is expected to provide the best performance in relation to bird safety, with the partially bonded structure also offering an acceptable level of safety [5].

Other international researchers have also performed research on this topic. This includes, amongst others, the contributing factors to bird electrocution and various mitigation measures [10, 23]. Harness at al found that bird electrocution occurs on any system that is designed for 69 kV or less due to the reduced phase-to-phase and phase-to-earth clearances when compared to structures operating at larger voltages [23]. The results of the investigation showed that other contributing factors to bird electrocution in MV lines are weather conditions, earthing arrangement of the structure, type of supporting structure used (woodpole, steel and concrete) and tower configuration. It is reported in [10] that in dry conditions, the impedance of the bird feathers is high, and at least 70 kV may be required to cause bird electrocution. However, when the feathers are wet, voltages in excess of 5 kV may be adequate to cause bird electrocution [10].

The effect of concrete pole and steel structures on MV lines instead of woodpole structures on bird electrocution was investigated [10]. The concrete poles are constructed with a reinforcing bar (rebar), which is connected directly to earth. Steel or concrete cross-arms are used and connected to the earthed rebar of the main pole. This effectively causes the cross-arm or the pole-top of the structure to be at earth potential, similar to the steel structure. Harness reported that only one electrocution was noted on woodpole structures over a 90 km long network [10]. However, 68 bird electrocutions were reported on concrete structures (no information was given on how long the section with concrete structures was) [10]. Similar incidences were observed with steel structures. The results, to a certain extent, indicate the effectiveness of woodpole structures to reduce the risk of bird electrocution.

Bird diverters and phase insulator covers were proposed as possible solutions to discourage birds from perching on the earthed cross-arm of the structure [10, 23]. The diverters need to be installed in such a way that they extend over the phase insulators in order to discourage the birds from making contact with a live phase conductor. While bird diverters were preferred, their effectiveness was reduced due to poor installation, birds using them for nesting and the fact that the diverters were removed by birds over time.

### 2.3.3 Pollution (50 Hz) performance

The choice of phase insulators used on a woodpole structure determines, together with the wood properties, the levels of surface leakage current that flows on the structure. Primarily, the insulators are selected based on several factors which include among others, the electrical requirements (i.e. maximum system voltage) and environmental conditions (pollution severity, weather conditions, etc.) in which the line operates [11].

Vosloo investigated the performance of different insulator materials in different pollution severity conditions (light to very heavy) and under different weather conditions [11]. The insulator materials considered for the investigation included high temperature vulcanised (HTV) silicone rubber, room temperature vulcanized (RTV) silicone coating, ethylene propylene diene monomer (EPDM), porcelain, cycloaliphatic epoxy resin and resistive/semi-conductive (glazed). The insulators were tested at KIPTS and energised at 22 kV (phase-to-phase) for a period of one year. Leakage currents flowing on the surface of the insulators were measured over that period. The results indicated that resistive glazed insulators recorded the lowest leakage current, with cycloaliphatic insulators recording the highest. Porcelain insulators and EPDM recorded similar levels. HVT silicone rubber and RVT silicone coating materials resulted in reduced levels of surface leakage currents than porcelain, EPDM and cycloaliphatic insulators.

From the pole-top fires point of view, using phase insulators that limit the surface leakage current may result in a reduced risk of pole-top fires [5, 8]. However, research and experience shows that low levels of current (in order of 1 mA) are adequate to cause burning [1, 8, 14]. Only resistive glazed insulator material is capable of limiting the leakage current to 1 mA, irrespective of pollution or weather conditions [11]. To the author’s knowledge, resistive glazed insulators are not used on electricity distribution or transmission lines because they will contribute significantly to the line losses of 1 mA per insulator at all times. Thus silicone rubber insulators are preferred in this regard.

## 2.4 Summary

The literature survey presented in this chapter indicates that a lot of research has been conducted on pole-top fires on woodpole structures. Despite this research, there is currently no solution that eliminates the risk of burning of the structure on the 500 mm gap provided for insulation coordination purposes, while also taking into account other constraints such as bird safety. The following chapter details the research methodology and experiment setup.

# 3. TEST SETUP AND METHODOLOGY

## 3.1 Introduction

The feasibility of the modified structure was investigated through tests conducted at KIPTS and at Eskom's Corona Cage. Tests at KIPTS were intended to evaluate the effectiveness of the proposed structure in a natural heavily polluted environment. KIPTS was selected as a suitable test location because of the harsh environmental conditions (very heavily polluted and extreme humid conditions) [11] and the availability of measuring equipment required for this testing. Tests at Eskom's corona cage were intended to evaluate the proposed structure in a controlled environment.

## 3.2 Tests at KIPTS

### 3.2.1 Test structures

Three structures, one with a glazed downwire insulator, one with an unglazed downwire insulator and the other fully bonded and earthed, were erected at KIPTS and energised at 22 kV (phase-to-phase) . Figure 3.1 shows the structure with a glazed downwire insulator. Silicone rubber insulators with specific creepage of 31 mm/kV were selected as phase insulators for their ability to limit the levels of surface leakage current. This was based on the literature that indicates that lower levels in the mA range were adequate to cause pole-top fires – thus limiting current would ensure that the effectiveness of the structure is tested accordingly. The specific creepage used was found to be acceptable in limiting the risk of flashover and damage to measurement equipment. Refer to Appendix B for details and the electrical properties of the phase insulators used on the test structures.

The other two structures are similar to this structure and are shown in Figure 3.2.

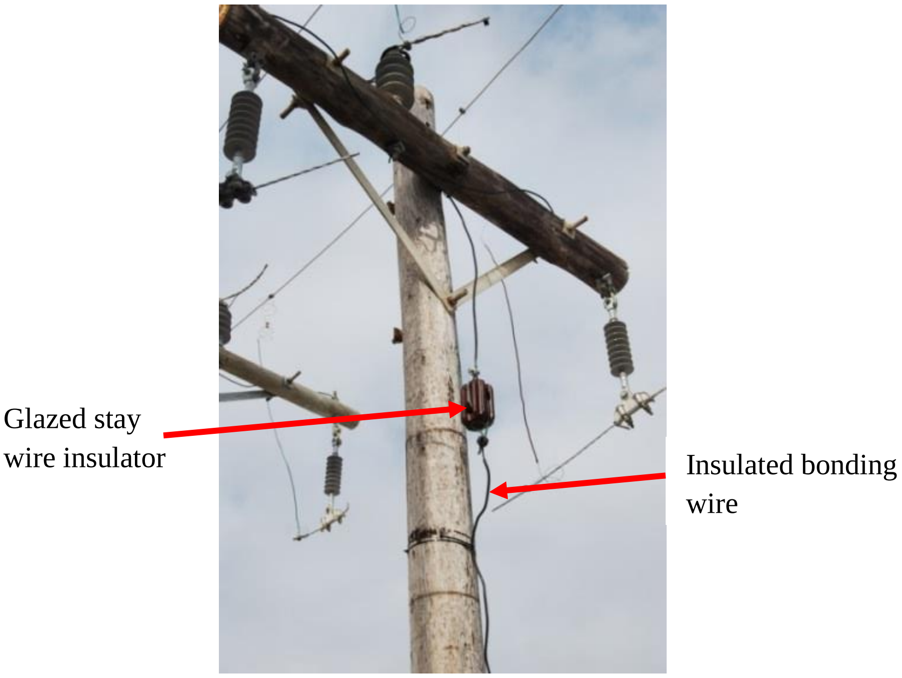



**Figure 3.1: Test structure with a glazed downwire insulator**


a)

b)

**Figure 3.2: Other two structures erected at KIPTS: a) structure with unglazed downwire insulator, b) Fully bonded and earthed structure with no downwire insulator or wood gap**

The test structures were aligned in a horizontal direction, approximately 2.5 m away from each other due to space limitations. The structure with glazed downwire insulator was installed closest to the sea, with the fully bonded and earthed structure furthest from the sea as shown in Figure 3.3. However, there were other structures that are not shown in this figure that were installed and tested at KIPTS, but not relevant to this work.

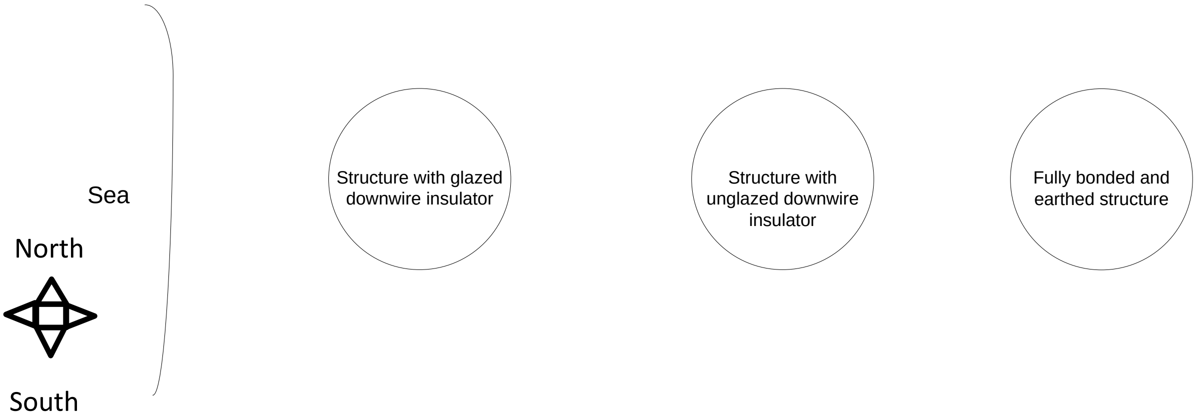



**Figure 3.3: Arrangement of the test structures at KIPTS**

### 3.2.2 Test structure evaluation methodology

The three test structures were energised continuously for approximately four months (between July and December 2012). The structures were evaluated using various methods.

#### 3.2.2.1 Logging and analysis of the leakage current flowing along the downwire

Leakage current sensors were installed on the downwire of each structure. The currents sensors were installed below the downwire insulator and were earthed to station earth via the bonding wire of the structure. The current sensor used was a Hall-effect sensor which is galvanically isolated (up to 6 kV) and has a bandwidth of 100 kHz if the sensing windings have a single turn [24]. However, the KIPTS sensor had multiple turns; therefore the bandwidth was reduced, but was still high enough. The current was sampled at the on-line current analyser (OLCA) system at 2 kHz. The OLCA stores several leakage current parameters every 10 minutes. These include the highest positive and negative peaks, positive and negative average values, root mean square (r.m.s), positive and negative accumulative (integrated) charge and integrated leakage current squared.

The current sensors and the OLCA system were calibrated by the manufacturer before energisation of the test structures. In addition, minor calibrations were performed at times using the DC current sensor to evaluate the condition of the current sensors.

The three test structures were evaluated by analysing the leakage current flowing on the downwire of each structure over the test period.

#### 3.2.2.2 Visual observations of test structures

The feasibility of the modified structure relies on the ability to divert leakage current away from the wood. In such cases, no signs of tracking or burning should be observed on the surface or interior of the wood. This is based on the results presented in [8], where it is stated that no signs of tracking were observed on the fully bonded and earthed structures tested at KIPTS.

Visual observations of the test structure were performed at energisation and thereafter approximately monthly, to determine any signs of tracking or burning on the surface of the woodpole of the test structures. Photographs were taken during visual observations to track the changes on the surface of the wood of each structure. Ultra-violet (UV) recordings and infra-red imaging (IR) were also performed at times using UV and IR cameras to detect any signs of internal heating and leakage activity on the wood.

#### 3.2.2.3 Simultaneous measurement of voltage and current waveforms

The test involved simultaneous measurement of current flowing along the downwire insulator and the downwire insulator voltage (i.e. voltage above the downwire insulator). A 120 Ω shunt resistor was used to measure the current flowing on the downwire insulator as shown in Figure 3.4. The 120 Ω resistor was selected in order to measure lower levels of leakage current (in order of mA). The resistor was connected below the downwire insulator. However, the current flowing along the woodpole was not measured for practical reasons (i.e. unavailability of current sensor with large enough diameter to cover the circumference of the woodpole (approximately 60 cm) and have a low sensitivity (in mA range) to measure the desired current accurately).

A 1000: 1 Tektronix high voltage (HV) probe was used to measure the voltage above the downwire insulator and earth (i.e. the voltage between the bonding above the downwire insulator and earth) as shown in Figure 3.4. As such, the insulator voltage is the difference between the voltage measured by the HV probe and the voltage across the 120 Ω resistor.

The outputs of the resistor and HV probe were connected to the oscilloscope. The oscilloscope was battery-operated and its earth terminal was connected to the test station earth point to ensure that the measurement channels were referenced to a common earth point.

The results of this test were used to estimate the impedance of the downwire insulator and to determine the insulation levels provided by the downwire insulators.

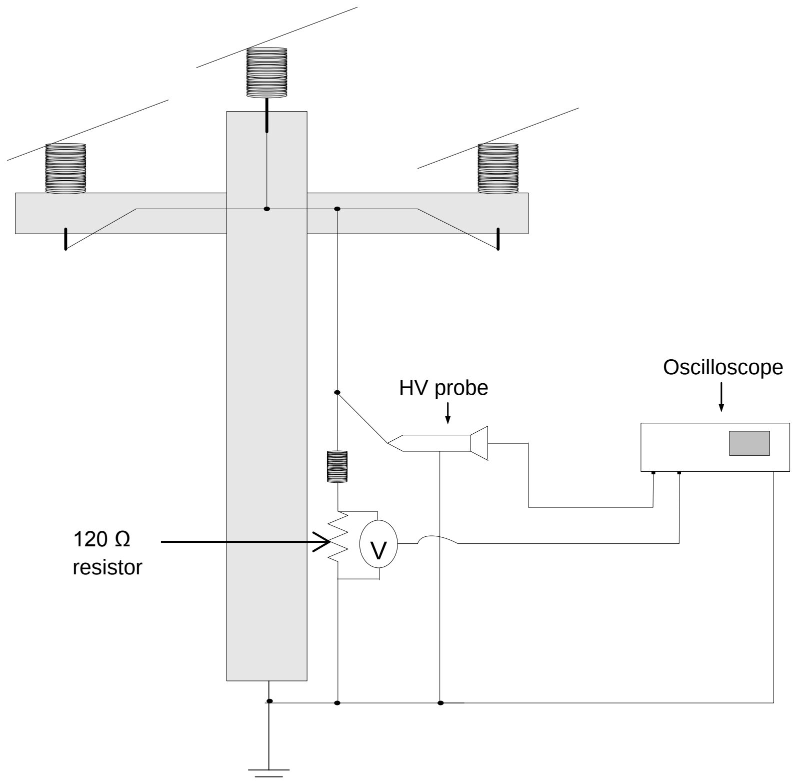



**Figure 3.4: Measurement method for the downwire insulator voltage and the downwire current**

#### 3.2.2.4 Monitoring of the environmental conditions

The objective of monitoring the environmental conditions (pollution severity and weather) was to correlate both the logged leakage currents and the visual state of the test structures to the environmental conditions. The pollution severity of the site was monitored over the entire period of testing in accordance with SANS 60815-1 [25]. However, weather conditions was not monitored bsince the weather sensor installed at KIPTS was not operational during testing.

## 3.3 Tests at the Eskom Corona Cage

The Eskom Corona Cage was selected because of the availability of three 220 V/11 kV single phase transformers (to approximate the 12.7 kV nominal phase-to-ground voltage stress of the 22 kV phase-to-phase systems tested at KIPTS), availability of space for erecting a test structure and its accessibility.

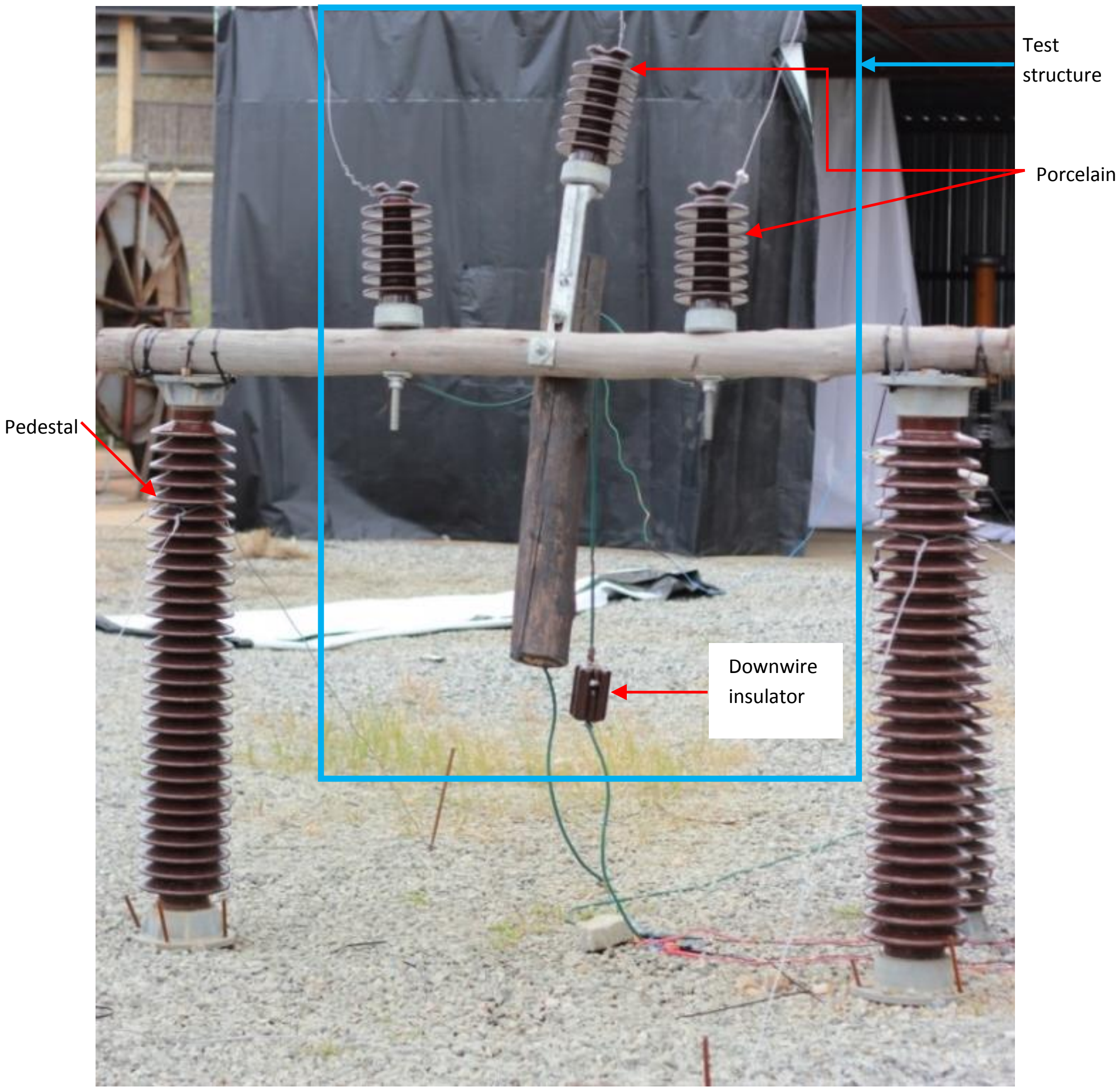
### 3.3.1 Test structures

Only one structure was erected. The purpose was to compare the performance of glazed and unglazed downwire insulators effectively using the same woodpole. Modifications were made to the test structure when necessary. Figure 3.5 depicts the test structure with a glazed stay wire insulator. Two porcelain pedestals (bushings) were used to support and suspend the test structure above the ground, while providing adequate insulation from the ground. The pedestals were stayed to ground to secure the test structure for the duration of the tests. The porcelain bushings were washed with water and allowed to dry before and during testing to reduce the risk of leakage current from flowing through the stay wires to ground.

It is clear from Figure 3.5 that the key components of the test structures are woodpole, downwire insulators and the phase insulators. The wood cross-arm was effectively taken out of the circuit by correctly bonding all the phase insulators together. The key components are briefly described as follows:

i) The woodpole chosen in this work was a 1.2 m long woodpole. The pole was treated with creosote and was relatively new (i.e. was not used in the field or for other testing).
ii) Porcelain insulators were used due to their hydrophilic capability. This is because the tests were conducted outdoors with an air temperature up to 30 °C. Use of porcelain insulators rather than silicone rubber insulators used at KIPTS would result in greater and more sustained wetting of the insulators and subsequently higher levels of leakage currents (in mA), making test and measurement easier. The porcelain insulators used had a specific creepage of 38 mm/kV at 11 kV phase-to-ground. The large specific creepage was chosen to reduce the risk of flashover, which could damage the measurement equipment.
iii) The glazed and unglazed porcelain stay insulators chosen are similar to the ones used at KIPTS. The two insulators had similar dimensions (creepage, dry arc distance, profile, etc.) and were from the same manufacturer. These insulators are shown in Figure 3.5 b).

The phase insulators were directly bonded together and the bonding was connected to earth via a downwire insulator. The bonding wire used was insulated (up to 600 V AC) and u-nails were used to secure the earthed bonding wire to the woodpole – refer to Figure 3.5 c).




a)

b)

c)

**Figure 3.5: Test structure and components: a) Test structure with associated support, b) the glazed and unglazed downwire (stay wire) insulators used on the test structure, c) connection of earthed bonding wire to the woodpole**

#### 3.3.2 Test structure evaluation methodology

The test structure(s) were evaluated as follows:

##### 3.3.2.1 Simultaneous measurement of current flowing on the woodpole, current flowing on the downwire insulator (both glazed and unglazed) and insulator voltage waveforms.

This test is similar to the tests conducted at KIPTS, except that the current flowing on the woodpole was measured. Furthermore, 10 kΩ shunt resistors were used to measure the current flowing along the woodpole and downwire insulator instead of the 120 Ω used at KIPTS. This was because lower levels of leakage currents were expected due to environmental conditions at the Corona Cage. The two 10 k Ω resistors were connected below the downwire insulator and woodpole as shown in Figure 3.6. The measurement method for the insulator voltage was similar to the method used at KIPTS. The oscilloscope was battery operated during testing and its earth terminal was connected to the test station earth point to ensure that the measurement channels were referenced to a common earth point.

The measurements of current flowing on the woodpole and downwire insulator were used to determine if the use of the downwire insulator is effective in diverting the leakage current away from the woodpole and the conditions thereof, and to evaluate the effect of the downwire insulator surface material on the ability of the downwire insulator to divert leakage current away from the woodpole.

The results for simultaneous measurement of insulator voltage, current flowing along the downwire and along the woodpole were used to estimate the impedance of the downwire insulator and to determine the insulation levels provided by the downwire insulators.

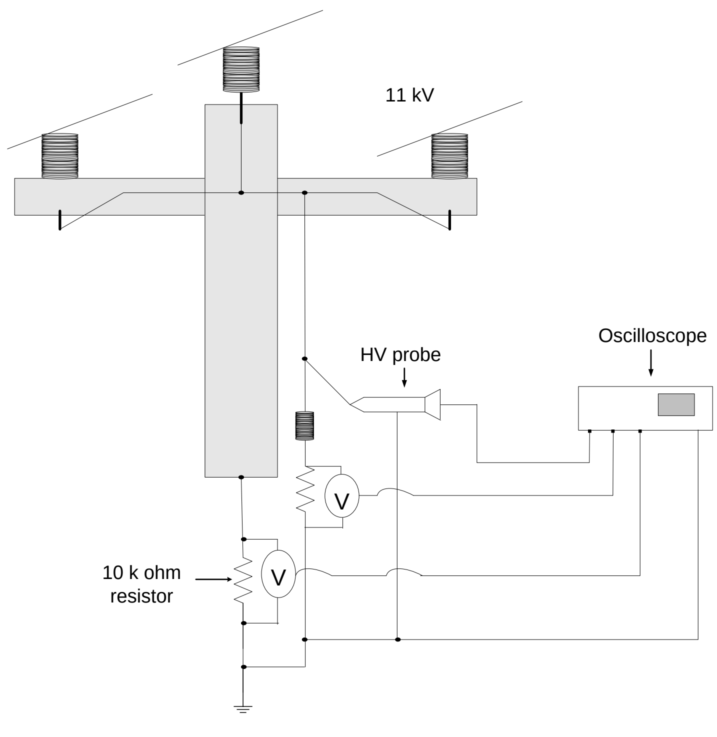



**Figure 3.6: Downwire insulator voltage, downwire current and woodpole current measurement method**

#### 3.3.2.2 Visual observations of the test structures

Visual observations of the test structures were performed daily, before the test, during testing and at the end of the tests to trace any changes of the visual state of the woodpole. Photographs were taken during visual observations to track the changes on the surface of the woodpole of the structure. Ultra-violet (UV) recordings were also performed at times to detect any signs of internal heating of the wood.

### 3.3.3 Tests conditions

The tests were conducted under the following conditions:

- **Dry conditions**:

All the phase insulators, downwire insulators and woodpole were cleaned with pure water and allowed to dry before the structures were energized. Thereafter, the structures were energised and measurements taken.

- **Polluted and wet conditions**

All the insulators and wood were sprayed with a salt solution. Due to limitation of power supply, the polluted tests were conducted under the following conditions

  - 5 g of table salt (sodium chloride - NaCl) solution added to 1 litre of pure water. This is equivalent to 0.005 $g/m^3$.
  - 10 g of table salt solution added to 1 litre of pure water. This is equivalent to 0.01 $g/m^3$
  - 15 g of table salt solution added to 1 litre of pure water. This is equivalent to 0.015 $g/m^3$.
  - 20 g of table salt solution added to 1 litre of pure water. This is equivalent to 0.02 $g/m^3$

According to SANS 60815, the four conditions are classified as light pollution severity (ranges between 10 $kg/m^3$ to 15 $kg/m^3$) [7]. However, the salt pollution was increased during the test when necessary.

## 3.4 Summary

This chapter covered the research methodology and test setup undertaken in this work, which included erecting and energisation of the test structures in a heavily polluted natural environment at KIPTS and laboratory tests and the rationale therefore. The following chapter details the results of the experiment conducted at KIPTS.

# 4. RESULTS OF TESTS AT KIPTS

## 4.1 Introduction

This chapter details the results of the experiments conducted at KIPTS. This included the measurement of insulator voltage and downwire current, visual observation of the test structures and analysis of logged leakage currents.

## 4.2 Measurements of the insulator voltage and the downwire current waveforms

The tests were performed only on the two structures (i.e. the one structure with glazed downwire and the other with unglazed downwire insulator) and not on the fully bonded and earthed structure. The tests were performed in September and November 2012. For practical reasons, only the current flowing along the downwire insulator was measured (the current flowing along the woodpole was not measured due to unavailability of current sensor with large enough diameter to cover the circumference of the woodpole and have a low sensitivity (in order of mA) to measure the desired current accurately.

### 4.2.1 September 2012

The tests were conducted on the 18th of September, at night, under the conditions listed in Table 4.1. Leakage current activity (or sparking) was visually observed on the phase insulators of the structure with a glazed downwire insulator. The structure with an unglazed insulator showed the least activity of all the structures. High activity was observed on the other components under test at KIPTS. Refer to Sections 4.4.1 for UV and IR imaging for some examples of activity observed on the test structures.

**Table 4.1: Weather conditions during the tests**

| Parameter | Before the test | After the test |
|---|---|---|
| Humidity | 77 % | 79 % |
| Temperature | 12 ºC | 11 ºC |
| Dew point temperature | 9 ºC | 9.5 ºC |
| Wind speed and direction | 6 km/hr, South West | 4 km/hr South West |

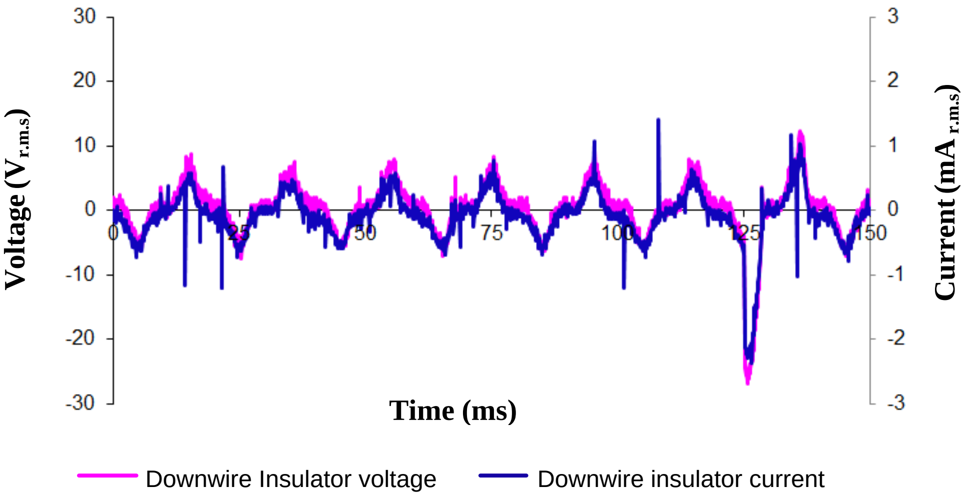
#### 4.2.1.1 Structure with unglazed insulator

Figures 4.1 and 4.2 depict the two sets of measurement results obtained on the structure with an unglazed downwire insulator. Figures 4.1 a) and 4.2 a) show the relationship between the insulator voltage and the downwire current with time. Figures 4.1 b) and 4.2 b) show the relationship between the downwire insulator voltage and current.

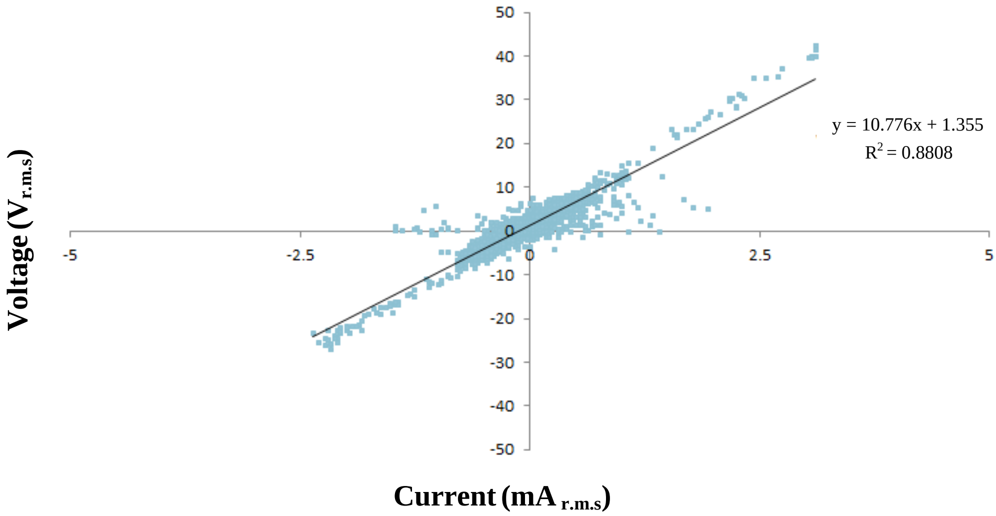
Significant currents (in order of 1 to 2.5 mA) were recorded on the downwire of the structure. This is attributed to the phenomenon covered in [26], where it is indicated that in certain circumstances, the pollution layer and wetting deposited on the phase insulators of the structure are non-uniform and as such resultant current (summed current) flow on earthed downwire. The downwire current measured in this case is at a frequency of 50 Hz.

The measured insulator/woodpole (also at 50 Hz) was low (in the order of 10 Vr.m.s and 30 Vr.m.s). The insulator voltage and the current are in-phase and linearly related. The degree of linearity between the downwire insulator voltage and downwire current is better illustrated in Figure 4.1 b) and 4.2 b), with the $R^2$ (or goodness-of-fit of linear curves) value close to 1. This is an indication that the impedance of the downwire insulator $(z = R + jC)$ was predominantly resistive rather than capacitive. This is expected under the pollution severity (refer to Figure 4.14) and high relative humidity recorded during the test.

The insulator impedance was approximated as the gradient of the voltage vs. current graph and was approximately 10.8 kΩ as shown in Figures 4.1 b and 4.2 b). However, it must be noted that the resistance estimated above is the equivalent impedance of the downwire insulator in parallel with the woodpole.

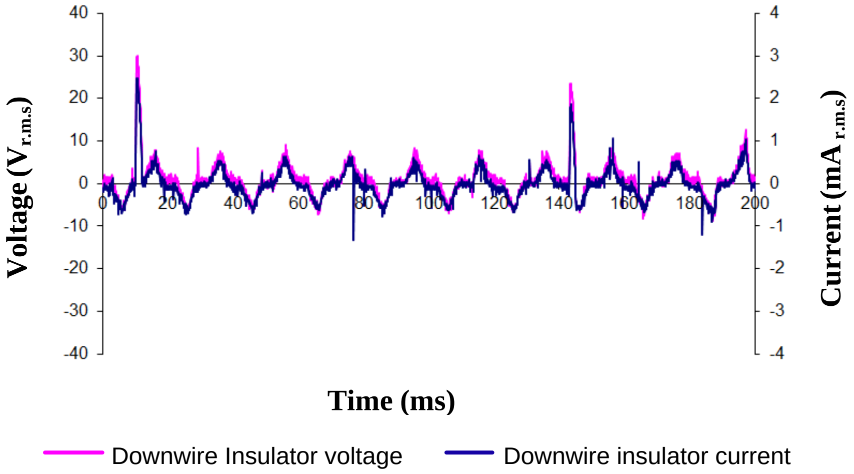



a)

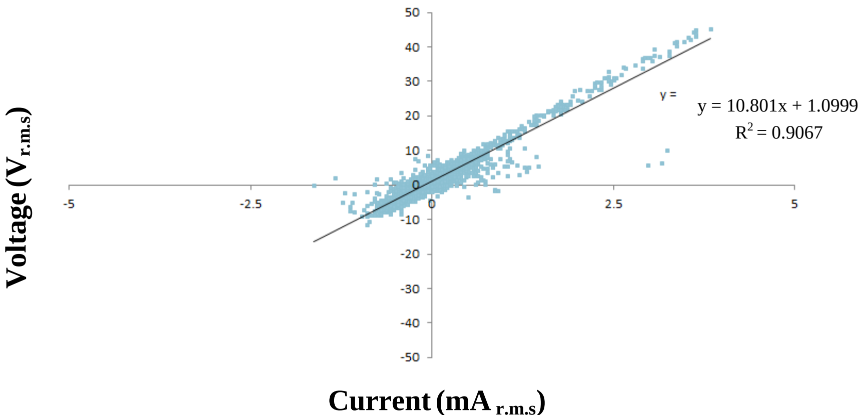



b)

**Figure 4.1 Example of measurements obtained on the structure with unglazed downwire insulator: a) voltage and current waveforms, b) relationship between insulator voltage and downwire current**




a)



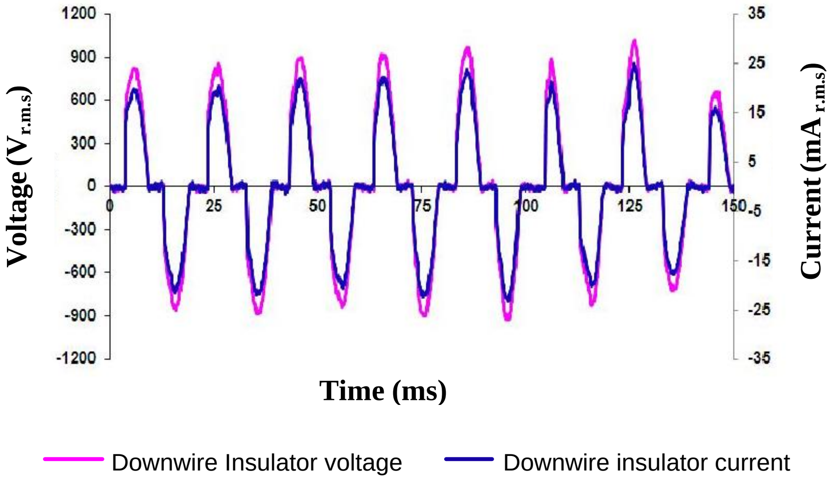

b)

**Figure 4.2: Another example of measurements obtained on the structure with unglazed downwire insulator**

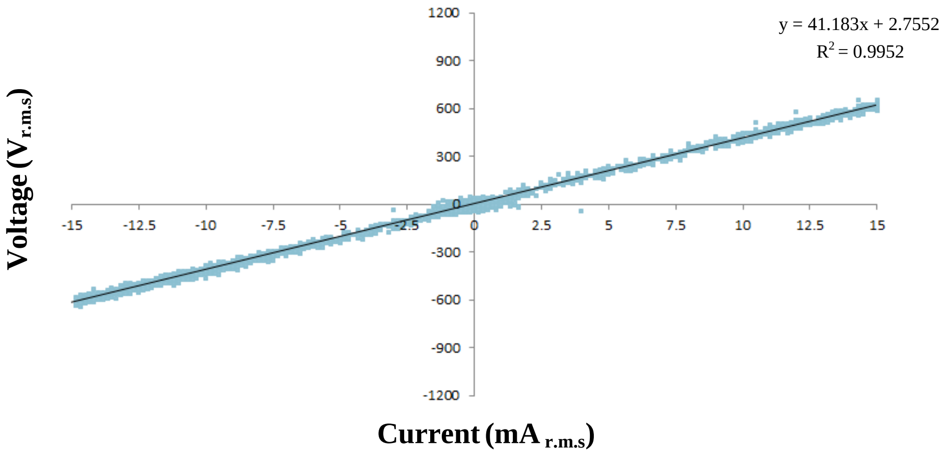
#### 4.2.1.2 Structure with glazed insulator

Figures 4.3 and 4.4 depict two sets of measurement results obtained on the structure with glazed downwire insulator. Similar findings were observed as with the structure with unglazed downwire insulator, where the downwire current and insulator voltage were in-phase and at a frequency of 50 Hz and the insulator impedance was purely resistive. However, higher magnitudes of insulator voltages (in order of $kV_{r.m.s}$) and current flowing on the downwire (up to 25 mA) were measured on this structure. The higher magnitude of downwire current could be attributed to the structure position from the sea (this structure is closest to the sea), and the prevailing wind direction from the South West direction that delivered relatively higher levels of sea salt and moisture to the phase insulators on this structure when compared with the other structures. Refer to Figure 3.3 for orientation of the structures at KIPTS. This is also supported by the pollution severity discussed in Section 4.5, where it is observed that in certain conditions, the measured pollution severity of West discs (closest to the sea) is higher than the East discs (inland).

Such high voltages would cause a significant effect on the neutral shift voltage (i.e. rise of neutral voltage relative to pole earth). The high voltages may cause high electric fields to exist between the insulator spindle and inside of the wood or between the bonding wire and wood, causing sparking and fire to initiate inside of the wood, a phenomenon discussed in [2]. Thus the effectiveness of the modified structure also requires proper bonding of the structure and using insulators with conductive end-fittings to eliminate fires on the cross-arm or at the junction of the main pole and cross-arm. The insulator was predominantly resistive and approximately 41 kΩ. The insulator resistance was higher than the resistance of the unglazed downwire insulator estimated in Section 4.2.1.1.

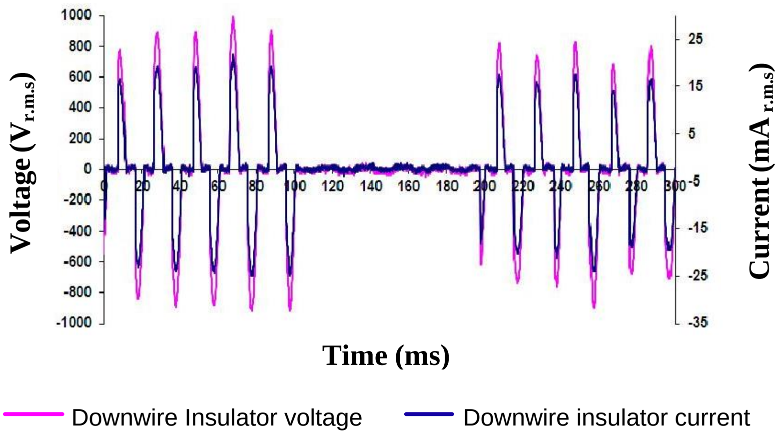



a)

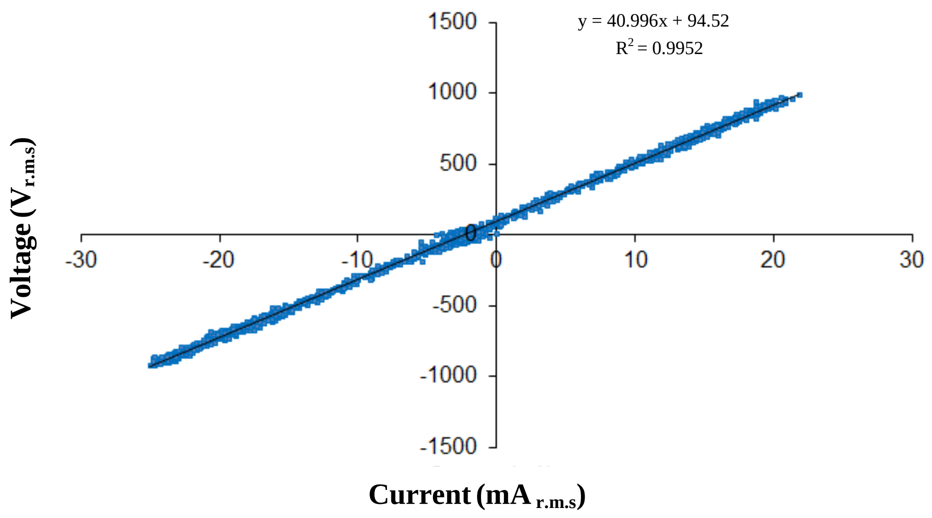



b)

**Figure 4.3: Example of measurements obtained on the structure with glazed downwire insulator**




a)




b)

**Figure 4.4: Another example of measurements obtained on the structure with a glazed downwire insulator**

### 4.2.2 November 2012 measurements

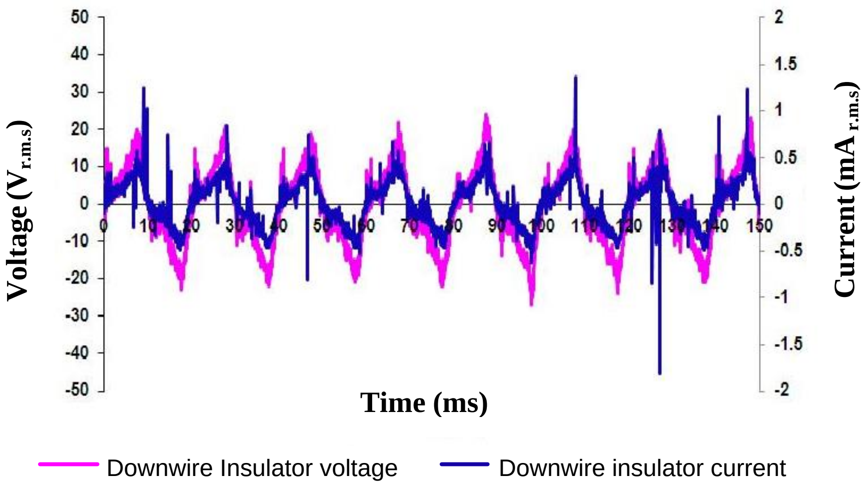
The measurements were repeated on the 6th of November 2012 under the weather conditions listed in Table 4.2. Severe leakage current activity was observed on all three phases of the structure with a glazed downwire insulator. The activity on the other test structures was less noticeable.

**Table 4.2: Weather conditions during the tests conducted on 6th November 2012**

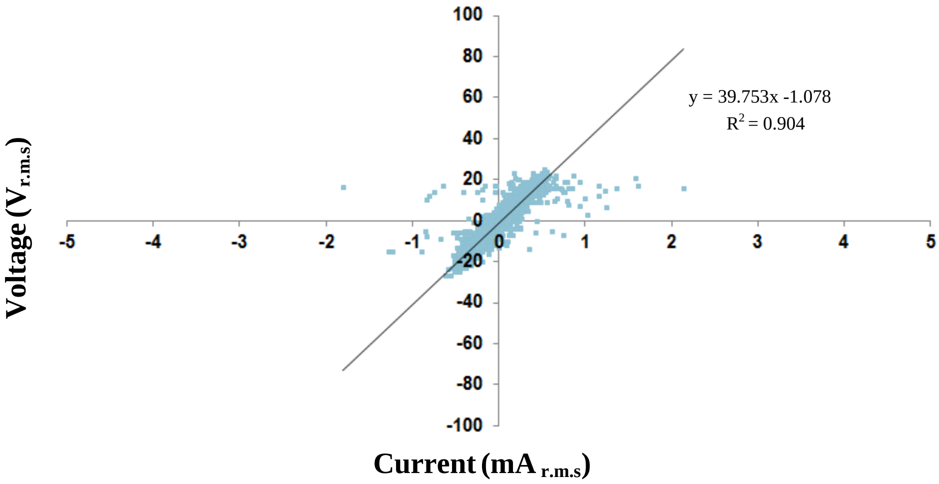
| Parameter | Before the test | After the after |
|---|---|---|
| Humidity | 76 % | 71% |
| Temperature | 17 ºC | 15 ºC |
| Dew point temperature | 12 ºC | 10 ºC |
| Wind speed and direction | 16 km/hr, South South West | 20 km/hr South |

#### 4.2.2.1 Structure with unglazed insulator

Figure 4.5 depicts a set of measurement results obtained. Similar results were obtained as in September, where the magnitude of the downwire insulator current and the downwire insulator voltage varied little with time and at a frequency of 50 Hz. The maximum measured insulator voltage was approximately 25 V, which is comparable to the 30 V measured in September. The magnitude of the downwire insulator current was also similar to the magnitude measured in September (approximately 1 mA). The insulator voltage and downwire current were linearly related as before. The insulator resistance was approximately 40 kΩ and is slightly higher than the 10 kΩ estimated in September.




a)



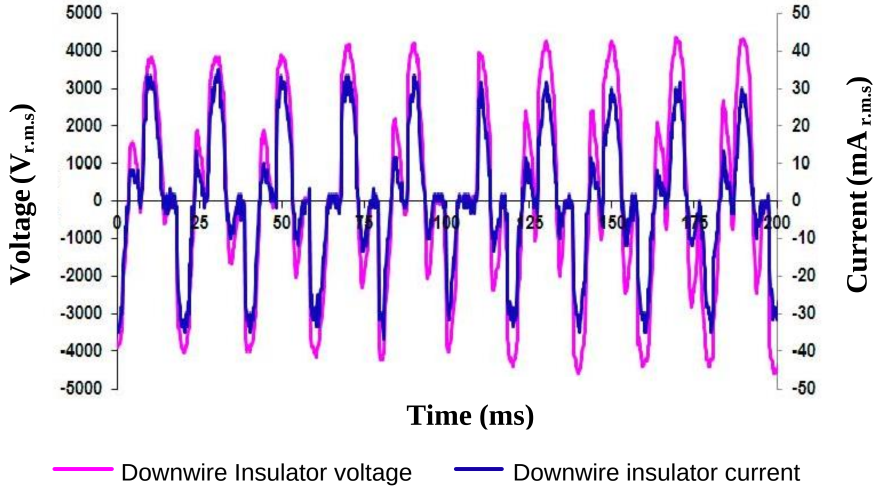

b)

**Figure 4.5: Example of measurements obtained on the structure with an unglazed downwire insulator**

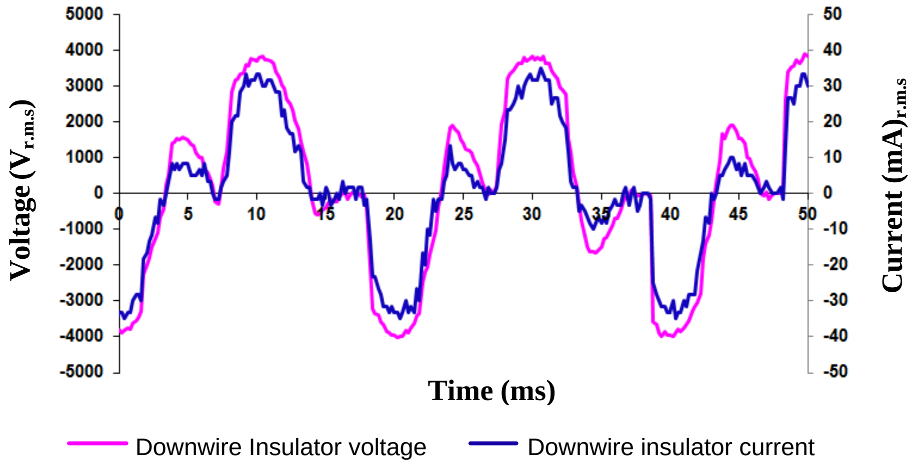
#### 4.2.2.2 Structure with glazed insulator

Figure 4.6 depicts an example of measurements obtained on the structure with a glazed downwire insulator. In this case, the downwire insulator voltage and downwire insulator current were at a frequency of 150 Hz. Figure 4.6 b) shows a close-up of the insulator voltage and current waveforms. The 150 Hz phenomenon is covered in [26] and is a result of all three phases conducting significant amount of leakage current trough the downwire to earth. This occurs during high polluted and high humidity conditions and agrees with the visual observations conducted before the tests, where severe leakage current activity was observed on all the phases of the structure.

The magnitude of the insulator voltage varied considerably with time (maximum measured insulator voltage was approximately 4 kVr.m.s). This voltage would cause higher electric field to be developed on the insulator spindle and wood to possibly initiate sparking from inside the wood. However, no evidence of activity was observed on the insulator spindle and kingbolts – refer to Section 4.4.2. The measured current along the downwire insulator was in the order of 35 mA. The insulator voltage and downwire current were linearly related, although the $R^2$ value is lower than in the previous cases. The downwire insulator impedance was resistive and approximately 132 kΩ. This was higher than the 40 kΩ calculated in September.




a)

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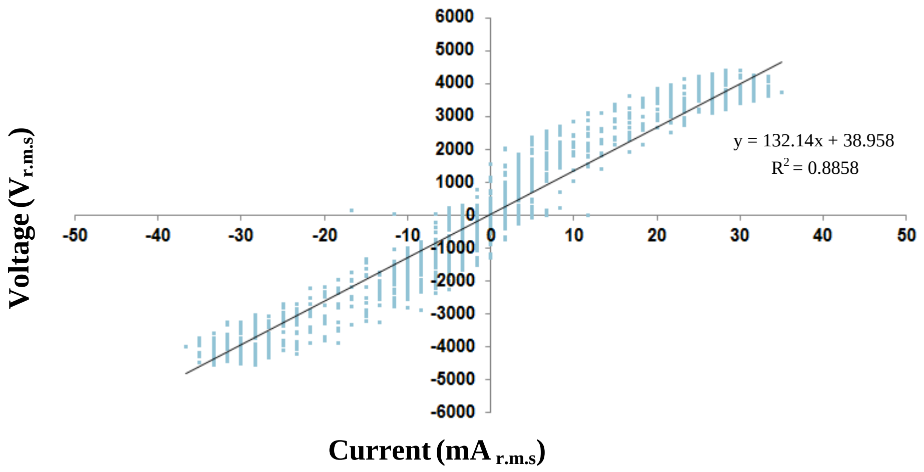



c)

**Figure 4.6: Example of measurements obtained on the structure with glazed downwire insulator: a) downwire insulator voltage and downwire current waveforms, b) close-up of current and voltage waveforms, c) relationship between insulator voltage and downwire current**

The results presented in this section indicated that under certain conditions, considerable levels of leakage current flows on the surface of the insulators, and through the downwire insulator path. The impedance of the glazed downwire insulator (in order of hundreds of kΩ) was higher than that of an unglazed insulator (consistently in tens of kΩ). Higher levels of insulator voltages were developed on the structure with a glazed downwire insulator (in the order of 4 kV) than on the structure with an unglazed downwire insulator (in order of tens of V).

## 4.3 Logged leakage currents

The analysis was performed over a month to improve the readability of the results.

#### 4.3.1.1 24 July to 31 August 2012 period

Figure 4.7 shows the r.m.s current recordings of the three structures for the period 24 July to 31 August 2012. Figure 4.7 a) shows the r.m.s current time trend and Figure 4.7 b) shows the r.m.s current time-of-day trends. The time of day trends give an indication of leakage current behaviour over this period, averaged to 24 hours. In July, the fully bonded and earthed structure recorded slightly higher magnitudes of current than the other two structures with downwire insulators. This is clearly demonstrated by the time-of-day trends (Figure 4.7 b)) and is expected since fully bonding and earthing (continuous earth wire) provides a low resistance for current to flow to ground.

The magnitude of the leakage current recorded at night is higher than the values recorded during the day. This behaviour is consistent with the findings of Vosloo et al and is attributed to high relative humidity at night and early mornings of the day [11].

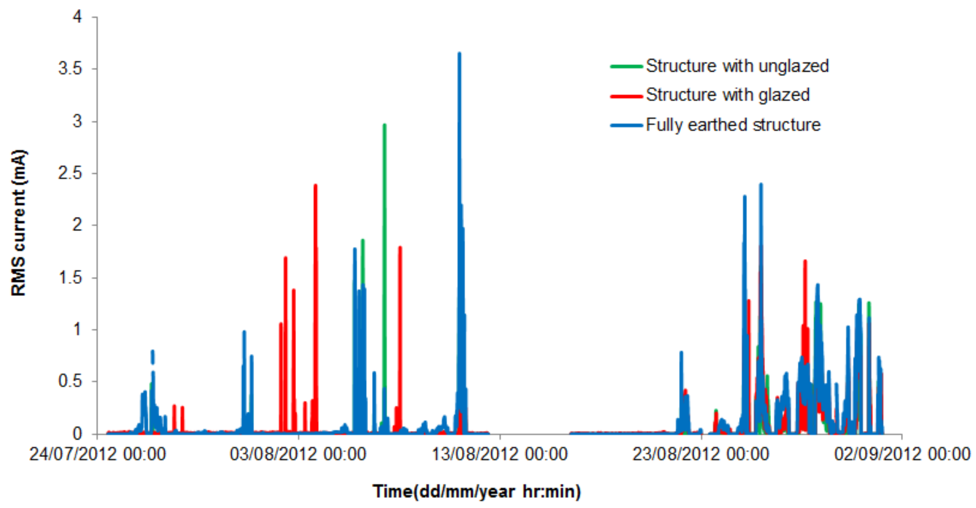
#### 4.3.1.2 01 September to 30 September 2012

Figure 4.8 depicts the r.m.s current recordings of the three structures for the above-mentioned period. Higher levels of leakage current were recorded on the three structures than in the July-August period. This may be due to the pollution building up on the phase insulators and downwire insulators throughout the time of energisation, and possibly weather conditions. Of importance is that the three structures recorded similar magnitudes of current, as shown in Figure 4.8 b). It is suspected that the high pollution and high humidity caused the impedance of the glazed and unglazed downwire to become resistive and low, thus providing low resistance paths for current to flow to earth – much similar to a fully earthed structure. These results are encouraging for pole-top fires.

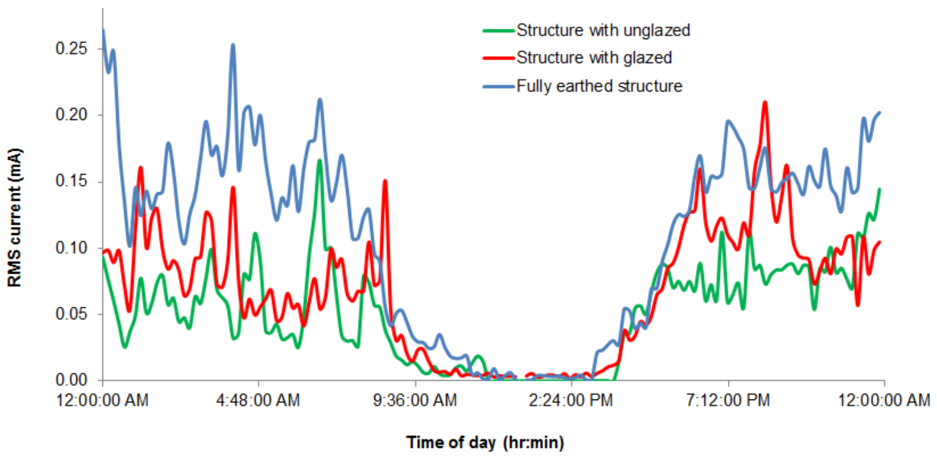
#### 4.3.1.3 01 November to 05 December 2012

There was no data recorded in October since the site was un-energised for several days and the OLCA system was malfunctioning. The problem was resolved and the currents were logged from 1 November to 5 December. Figure 4.9 shows the r.m.s. currents of the three structures. The structure with glazed downwire insulator recorded higher levels of currents than the other two structures. Again, this is attributed to the structure position from the sea. This is consistence with the measurement of current waveforms discussed in Section 4.2, where higher levels of leakage current were recorded on this structure during the measurement performed in September and November than on the structure with unglazed downwire insulator.

The fully bonded and earth structure and the structure with unglazed downwire insulator recorded similar levels of currents. Again, the results are promising and indicate that under certain conditions, the downwire insulators conducts significant levels of leakage current to earth – similar to a fully bonded and earthed structure.

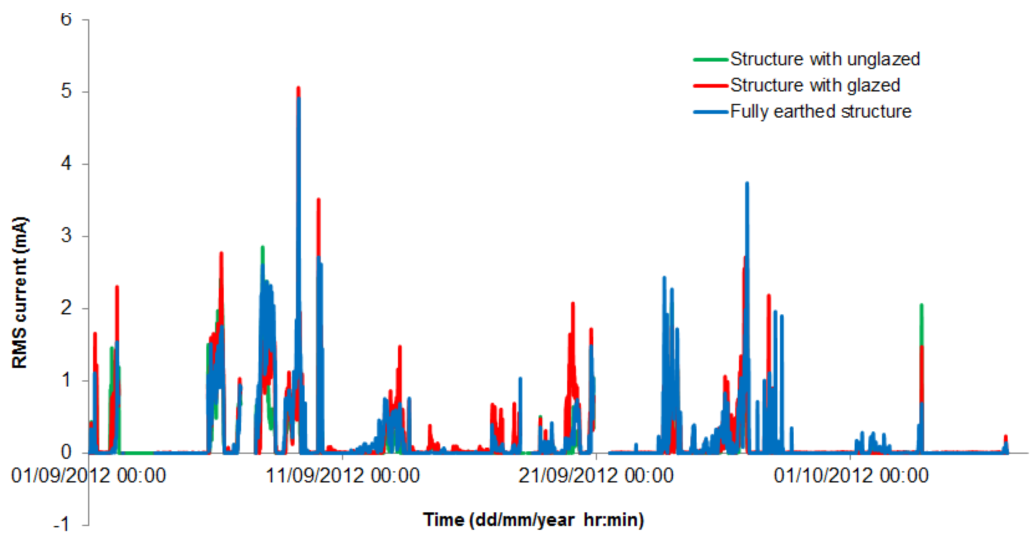



a)

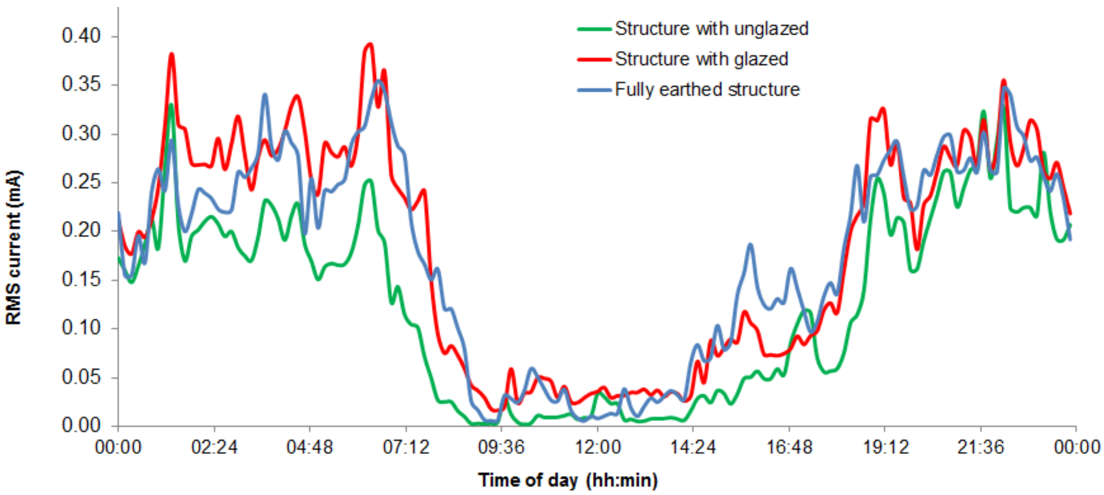



b)

**Figure 4.7: Comparison of current time trends for the three structures for the period 25 July to 31 August 2012: a) r.m.s current time trends, b) r.m.s time-of-day**

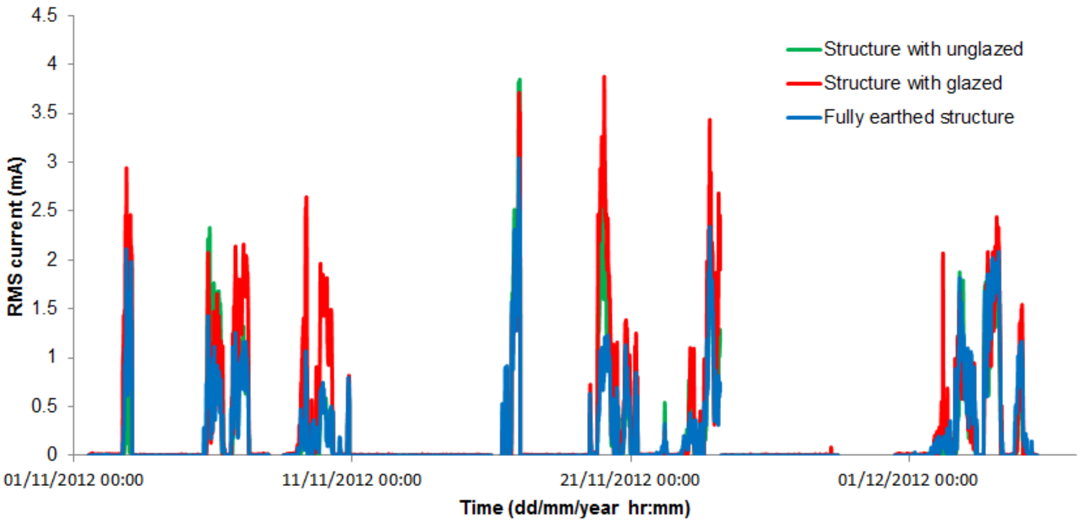



a)

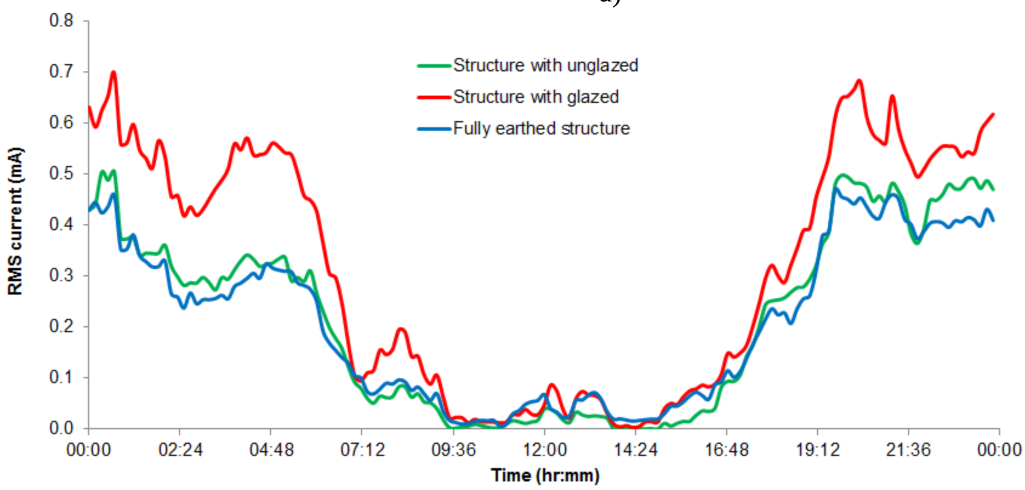



b)

**Figure 4.8: Comparison of r.m.s currents for the three structures for 4 Sep to 7 Oct 2012**




a)




b)

**Figure 4.9: Comparison of r.m.s currents for the period 1 November to 5 December 2012**

It has therefore been shown that under certain conditions the structures with downwire insulators behave like a fully bonded and earthed structure, i.e. provide a low resistance path for current to flow to earth. While the portion of the current flowing in or on the pole was not measured (this would be extremely difficult practically), this is in agreement with the laboratory tests performed at the Corona Cage, where under polluted and wet conditions, significant current was diverted away from the woodpole using an unglazed downwire insulator – refer to Section 5.2. This result is encouraging from the perspective of mitigating against pole-top fires and indicates that under wet and polluted conditions, the downwire insulators provides a low resistance path for current to flow to earth without flowing through the wood.

Under certain conditions, the fully bonded and earthed structure recorded slightly higher currents than the two structures with downwire insulators. This was observed in July, when the pollution severity was low. It is also deduced (based on the results of the Corona Cage tests presented in Section 5) that the low pollution and low humidity caused the impedance of the downwire insulator to remain capacitive and very high – thus resisting the flow of leakage current to earth.

## 4.4 State of the test structures

### 4.4.1 Infra-red (IR) and ultra-violet (UV) imaging

UV and IR measurements were conducted in September, November and December 2012, while the structures were energised. Leakage current activity and heating were observed on the phase insulators of all three structures. Figures 4.10 and 4.11 shows typical examples of the heating and leakage current activity observed on the phase insulators respectively. The IR recordings indicate that heating was detected on the phase insulators. No similar heating was detected on the woodpole and downwire insulators as shown in Figure 4.12.

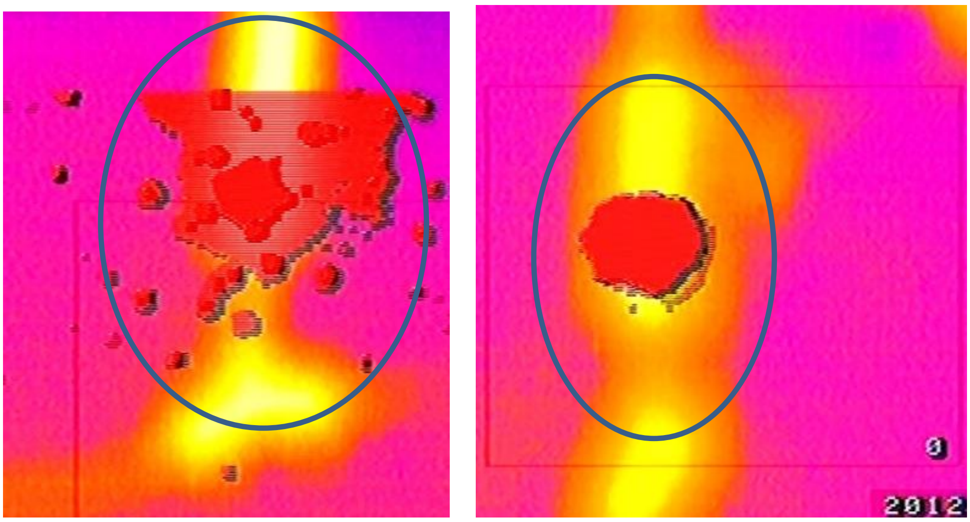



**Figure 4.10: Typical examples of IR recordings: heating and activity observed on phase insulator of the structure with glazed downwire insulator (left), heating and activity observed on phase insulator of the structure with unglazed downwire insulator (right)**

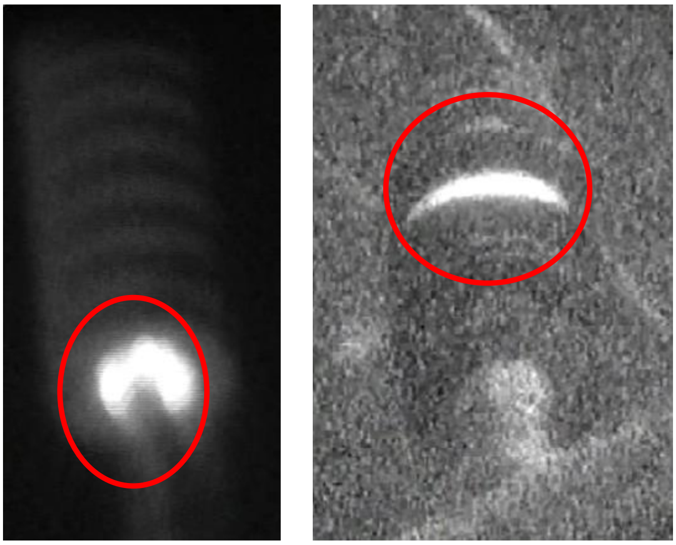
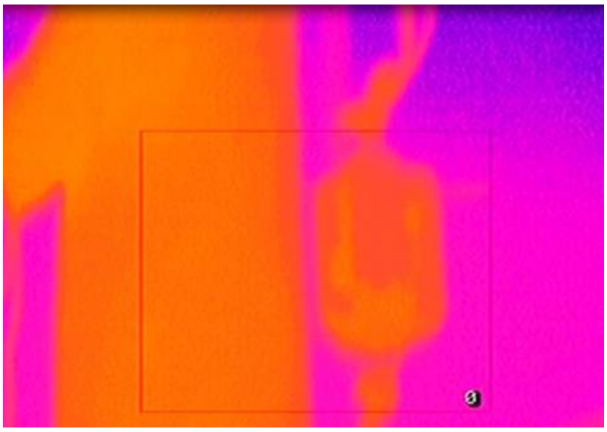
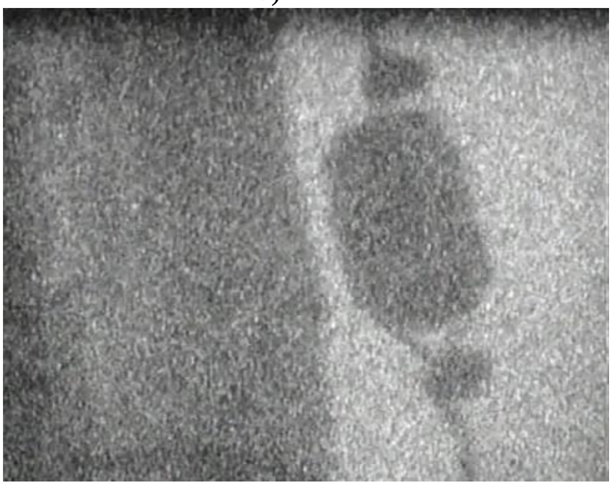


**Figure 4.11: Typical examples of UV recordings showing activity on the phase insulators of the structures, a) activity observed on the structure with glazed downwire insulator, b) activity observed on fully bonded and earthed structure**



a)



b)

**Figure 4.12: No surface discharges observed on the woodpole and downwire**

### 4.4.2 Visual observation of the structure

No tracking was observed on the woodpole (surface, top and bottom), insulator spindle, wood cross-arm (surface and inside of the cross-arm) and at the woodpole – cross-arm interface. Figure 4.13 shows some the photographs taken during visual observation of the test structure with glazed downwire insulator. The results indicates that the downwire insulators were effective in diverting leakage current to earth, with very little current flowing on the pole. Furthermore, the neutral shift and the possible high gradients discussed in Section 4.2 did not appear to have caused noticeable burning on the surface of the wood cross, inside of the wood cross-arm, insulator spindle and junction between the cross-arm and main woodpole.

Similar observations were noted on the other two structures.

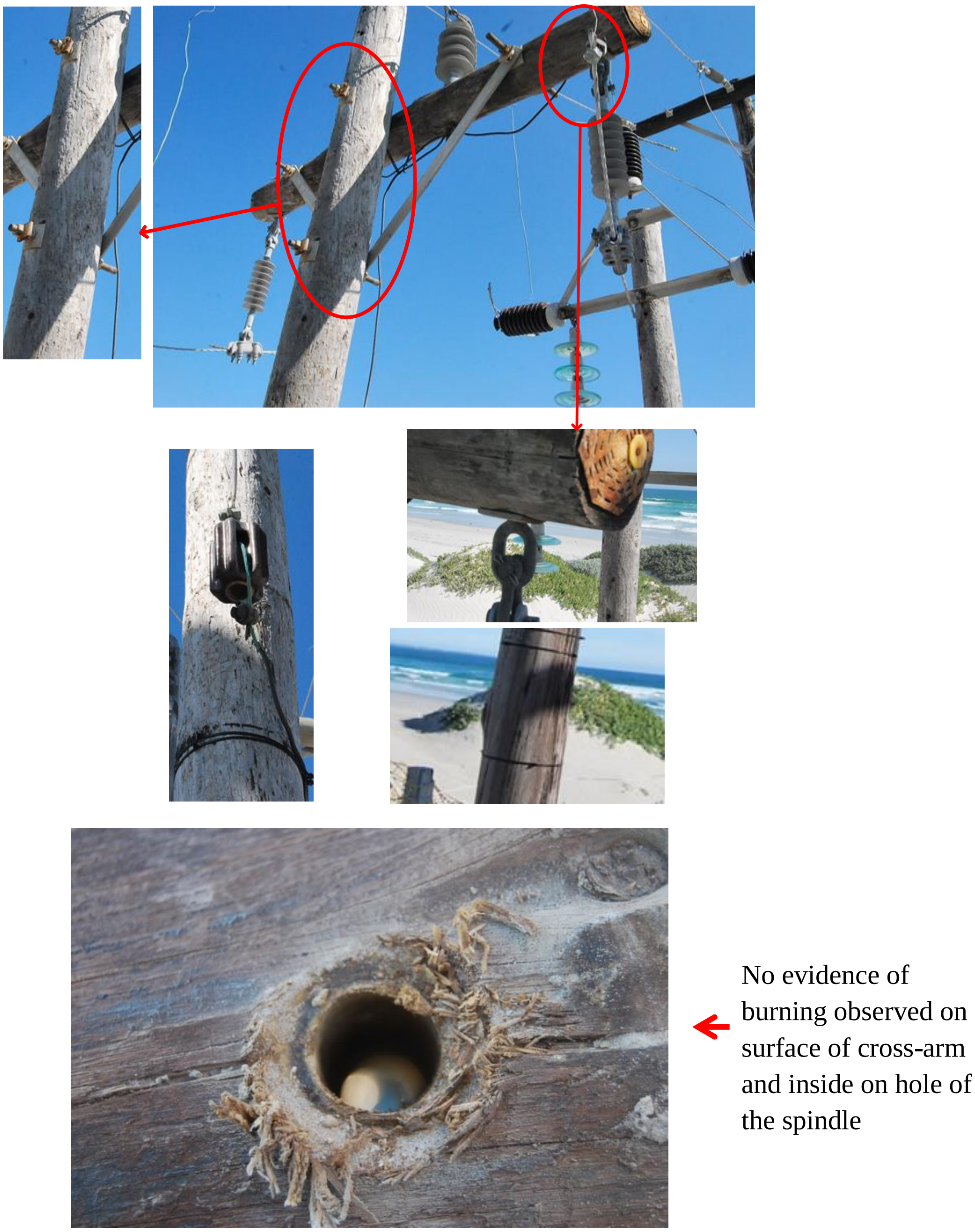



**Figure 4.13: Photographs taken on a structure with glazed downwire insulator**

## 4.5 Pollution severity and weather conditions

Figure 4.14 depicts the pollution severity recorded at KIPTS during the test period. The West disc was attached on the structure closest to the sea and the East disc was attached on the structure furthest from the sea (some 8 m away from the structure closest to the sea). The equivalent salt deposit density (ESDD) was performed in accrodarnce with IEC 60815-1:2008 [25]. The results indicated that there was significant difference on the ESDD measured between the West and East discs in certain cases. Throughout the test, the pollution severity on the West discs was higher than that recorded on the East discs, except for July and November, where the converse was true.

The results demonstrate the effect of structure position from the sea and the possible effect on the pollution and wetting accumulated on the test structures. This may be at least part of the reason why the structure with glazed downwire insulator (closest to sea) recorded higher levels of leakage current than structure with unglazed downwire insulator (from current waveforms and logged leakage currents as discussed in section 4.2 and 4.3 respectively) and fully bonded and earthed structure. The pollution severity recorded in July was light, and therefore lower levels of logged leakage currents recorded on the three structures – as discussed in Section 4.3.

It is also clear from Figure 4.14 that the tests were conducted in heavy and very pollution severity for most times. The fact that the was no tracking or burning observed on the tests structures is therefore encouraging.

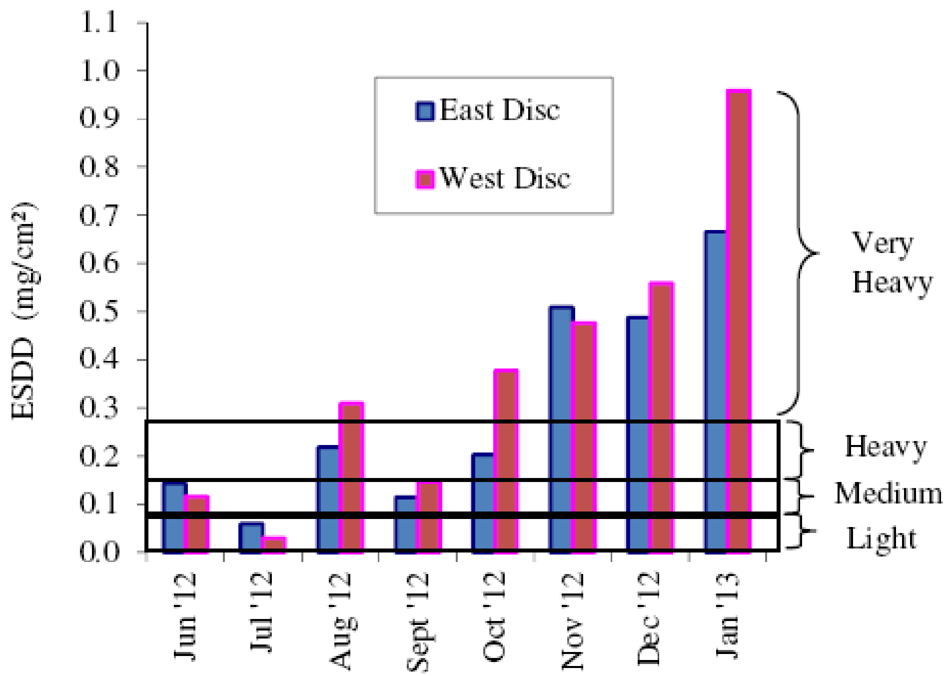



**Figure 4.14: Pollution severity recorded at KIPTS**

## 4.6 Summary

This chapter may be summarized as follows:

- The measurement of the downwire insulator voltage and the downwire insulator current waveforms indicated that under wet and polluted conditions, the downwire insulators (glazed and unglazed surface) were able to conduct the leakage current of the phase insulators to earth. However, the current flowing along the woodpole was not measured.
- When the downwire insulator conducts leakage current, the downwire insulator voltage is in phase with the downwire current. The degree of linearity between the insulator voltage and downwire current is close to unity, indicating that the impedance of the downwire insulator was significantly more resistive than capacitive.
- Higher levels of downwire insulator voltages (in order of 4 $kV_{r.m.s}$) were recorded on the structure with a glazed insulator. The high voltages may have caused considerable neutral shift (rise in neutral voltage relative to pole earth) and high electric fields on the metal-to-wood interfaces. However, no signs of tracking or burning were observed on the wood surfaces and inside of the wood (only at the wood –to- metal interface).
- The magnitude of the unglazed downwire insulator voltage was very low (tens of volts) when compared to the glazed downwire insulator (hundreds of volts to tens of kilovolts).
- The approximated impedance of the unglazed downwire insulator is lower (consistently in order of tens of kΩ) when compared to that of the glazed downwire insulator (in order of hundreds of kΩ) under polluted and wetting conditions.
- The logged current over time indicates that under certain conditions, a structure with a downwire insulator (glazed or unglazed porcelain) behaves like a fully bonded and earthed structure by offering a low resistance path for current to flow to earth – this is consistent with the measurement of the downwire current waveforms. The conditions under which this is possible could not be verified because the weather sensor was not operational.
- In some cases, the structure with a glazed a downwire insulator recorded higher currents that the fully bonded and earthed structure. This may be attributed to the structure position from the sea, where this structure is closest to the sea.
- However, under certain conditions, the fully bonded and earthed structure recorded slightly higher magnitudes of current than the two structures with downwire insulators. This occurred in July when the pollution severity recorded at KIPTS was at a low level. This was expected since the impedance of downwire insulators are capacitive and very high in very light polluted and wet conditions.
- No tracking was observed on the surface of all the test structures. This is encouraging and indicate that the downwire insulators were able to divert leakage current, similar to fully bonded and earthed structures, thereby reducing burning of the woodpole.

The following chapter details the results of the experiment conducted at Corona Cage.

# 5. RESULTS OF TESTS AT THE ESKOM CORONA CAGE

## 5.1 Introduction

This chapter details the results of the experiments conducted at the Eskom Corona Cage, which includes among others simultaneous measurements of the current flowing along the woodpole and on the downwire insulator and the insulator voltage and visual observation of the test structures. The tests were conducted in accordance with the procedure detailed in Appendix C.

## 5.2 Downwire and wood current waveforms

The objectives of the tests were to investigate the feasibility of diverting the leakage current into the downwire, and the effect of the downwire insulator surface material.

### 5.2.1 Structure with unglazed downwire insulator

#### 5.2.1.1 Dry test

The structure was energised without spraying water or pollution on any key component of the test structure. The downwire insulator and woodpole were visually observed to be completely dry. Figure 5.1 shows the measurement results. The resultant current was calculated as the sum of the current flowing via the woodpole path and current flowing via the downwire insulator path. Significantly more leakage current flowed via the wood than via the downwire insulator. This was not expected since the impedance of woodpole and insulator are predominately capacitive and high under dry and clean conditions. It is suspected that the rain that occurred in the area a few days before the tests may have caused the woodpole, especially the inside of the wood, to remain wet and conductive. This is consistence with the findings of Darveniza [3], where wet wood was found to be more conductive than dry wood.

The current flowing along the woodpole was substantially in phase with the resultant current and of similar magnitude. The magnitude of the current did not vary significantly with time and was at a frequency of 50 Hz. No significant current was recorded on the downwire insulator. This was expected since the impedance of the insulator under dry and clean conditions is high and tends to resist the flow of current.

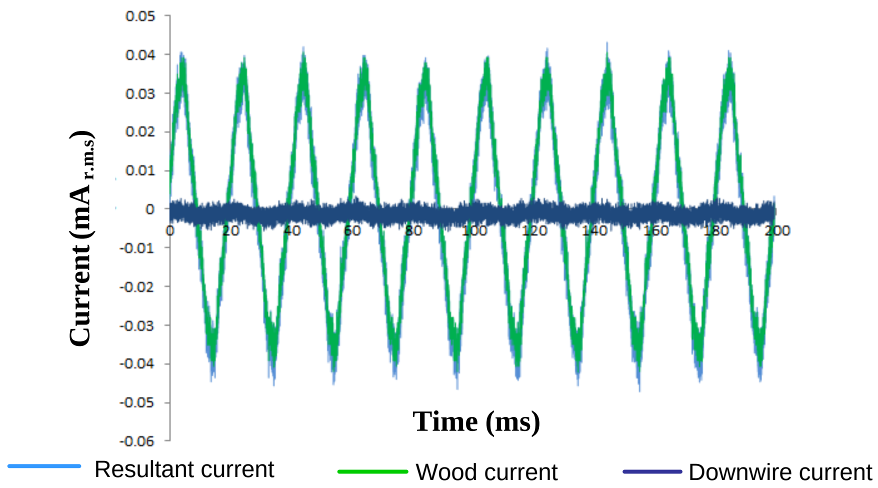



**Figure 5.1: Measured currents and calculated resultant current with unglazed insulator under dry conditions**

#### 5.2.1.2 Wet and polluted test

5.2.1.2.1 Downwire insulator sprayed with a salt solution

After above the test, the downwire insulator was sprayed with a 5 g/l salt solution, while the phase insulators and woodpole were not sprayed. The idea was to investigate the possibility of diverting leakage current that was previously recorded on the woodpole path (the current measured in Section 5.2.1.1) through the downwire insulator path, while keeping the source of leakage current (i.e. the phase insulators) constant. Figure 5.2 shows the measurement results obtained. In this instance, significantly more leakage current was recorded along the downwire insulator than along the woodpole. The resultant current was similar in magnitude to the current reported in Section 5.2.1.1 (since the source of leakage current was kept constant). The downwire insulator current was in phase with the resultant current, at a frequency of 50 Hz as before.

This result shows that under wet and polluted conditions, an unglazed downwire insulator conducts significant current, with relatively very low current flowing through the wood of a structure.

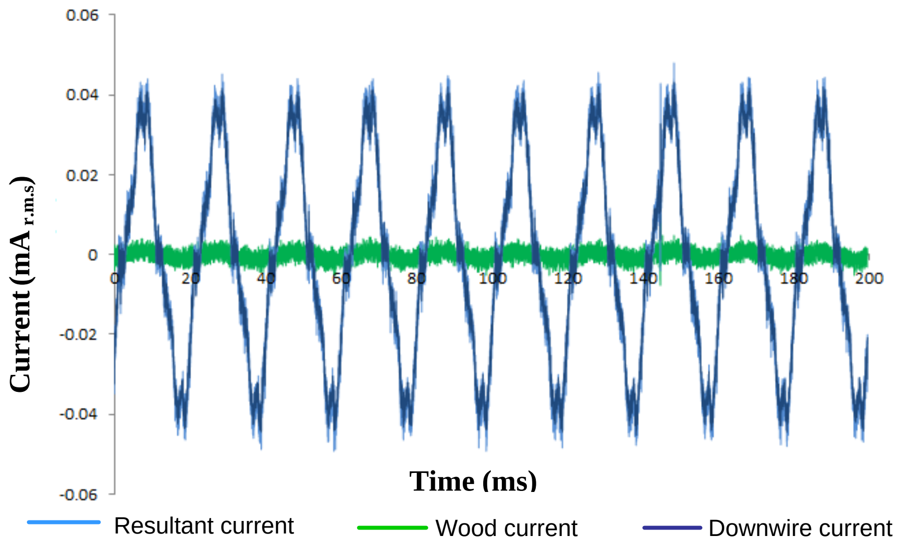



**Figure 5.2: Measured currents and calculated resultant current with polluted and wet unglazed insulator**

5.2.1.2.2 All components of the structure sprayed with a salt solution

This test was performed in three stages. In Stage 1, the measurement was performed immediately after all the key components of the test structure were sprayed with a salt solution and test structure energised. The test structure remained energised after the first set of measurement was recorded. A second set of measurement was recorded when the downwire insulator was observed to have partially dried out. This is referred to as Stage 2 in this report. The third measurement was recorded when the downwire insulator was observed to have completely dried out (Stage 3). The purpose of the exercise was to determine the performance of the downwire insulators (i.e. ability to conduct leakage current) under different wetting conditions (i.e. when downwire insulator was completely wet, partially wet and dry).

*Stage 1: Downwire insulator (visually) completely wet*

Figure 5.3 shows a typical example of the results obtained for Stage 1. All the key structure components (woodpole, downwire insulator and phase insulators) were sprayed with a 10 g/l salt solution in this case. Significantly more leakage current flowed via the downwire insulator than via the woodpole, consistence with the findings of Section 5.2.1.2.1 above. The downwire current was substantially in phase with the resultant current. The magnitude of the resultant current (and downwire current) is slightly higher than the current recorded in Section 5.2.1.2.1, as expected (i.e. the wet pollution led to increased levels of surface leakage current flowing on the phase insulators).

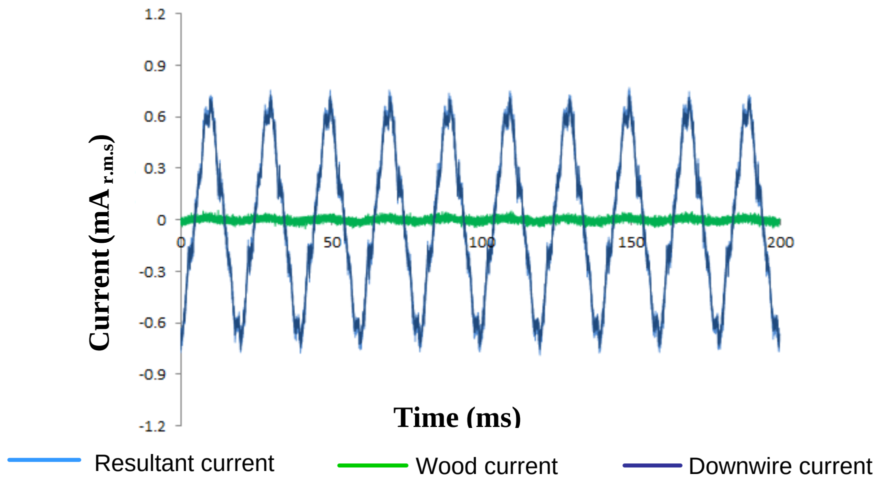



**Figure 5.3: Measurements obtained using unglazed insulator for Stage 1**

*Stage 2: Downwire insulator observed to be partially dry*

Figure 5.4 shows a typical example of the results obtained for Stage 2. In this case, the leakage current started to distribute between the woodpole and the downwire insulator. The downwire insulator, woodpole and resultant currents were substantially in phase. The magnitude of the resultant current is lower than the magnitude recorded in Stage 1, as expected (since leakage current flowing on phase insulators causes the phase insulators to dry out; resulting in reduced levels of leakage current). This results show that as the downwire insulator dries out, leakage current distributes between the woodpole and the downwire insulator.

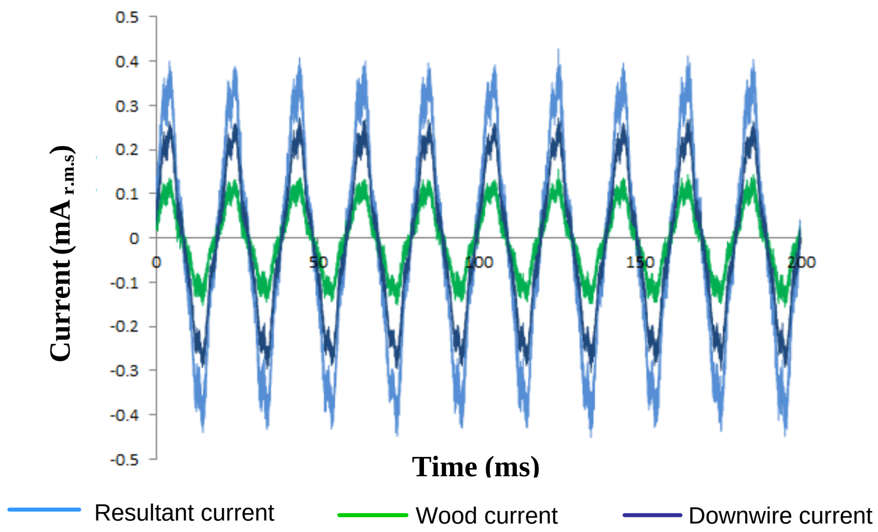



**Figure 5.4: Measurements obtained using unglazed insulator for Stage 2**

*Stage 3: Downwire insulator observed to have completely dried out*

Figure 5.5 shows a typical example of the results obtained for Stage 3. The results are similar to the results obtained under dry conditions, with most of the current recorded on the woodpole path than on the downwire insulator; and this current was substantially in phase with the resultant current.

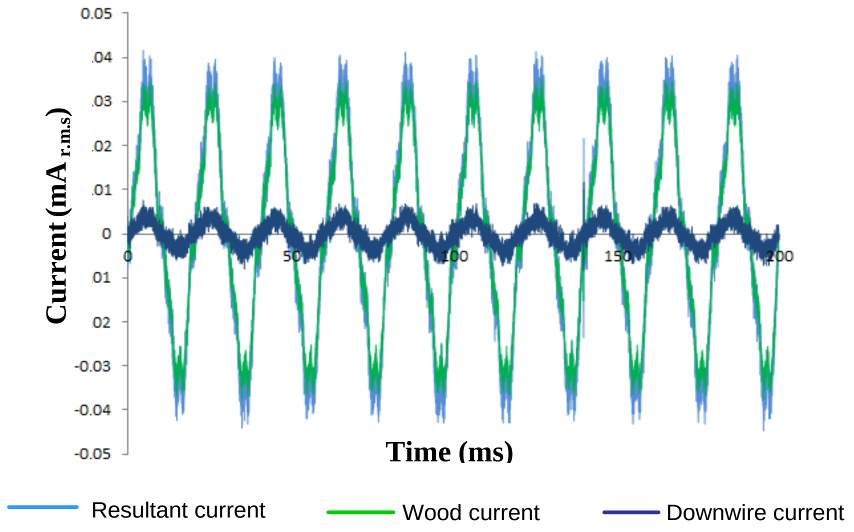



**Figure 5.5: Measurements obtained using unglazed insulator for Stage 3**

The results presented above indicates that under polluted and wetting conditions, an unglazed downwire insulator is capable of conducting significant current to earth, without current flowing through the wood. However, continuous wetting of a downwire insulator is essential to continuously divert leakage current away from the woodpole

### 5.2.2 Structure with glazed downwire insulator

#### 5.2.2.1 Dry test

Figure 5.6 shows a typical example of the results obtained under dry conditions. Similar results were observed as with the structure with unglazed insulator, as leakage current flow was predominantly in the woodpole path. This shows that under dry conditions, the behaviour of the two downwire insulators (glazed and unglazed) was similar.

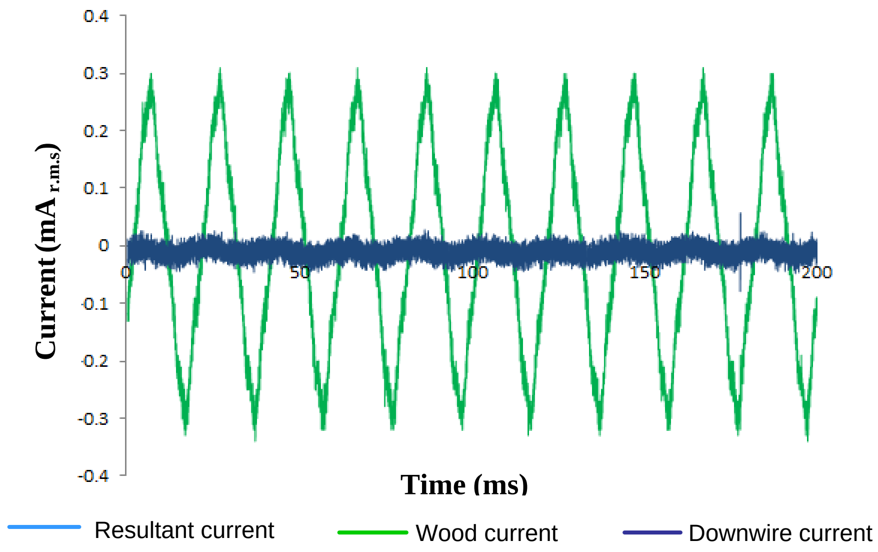
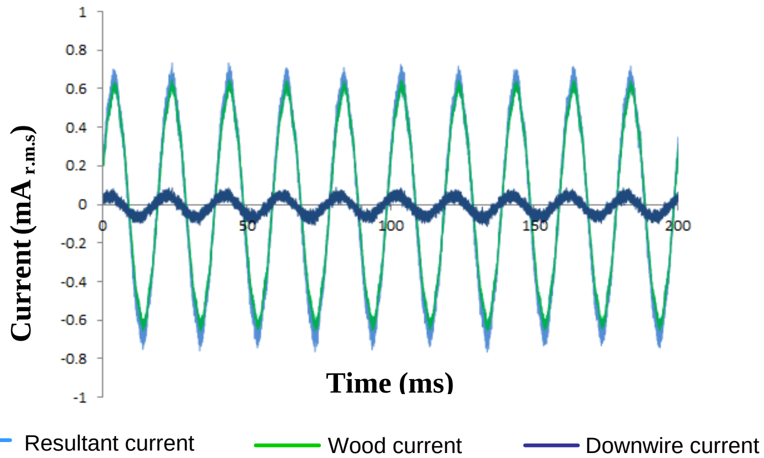



**Figure 5.6: Measurements using a glazed downwire insulator under dry conditions**

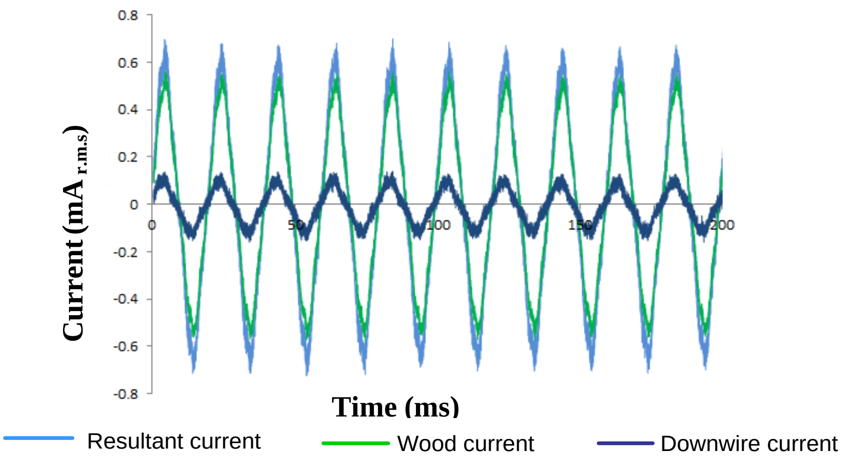
#### 5.2.2.2 Wet and polluted test

The downwire insulator was sprayed with several salt solutions before significant current was recorded on the downwire insulator. The problem was that the solutions were dripping off from the downwire insulator (glazed material). It is suspected that this led to the loss of wetting, causing the impedance of the downwire insulator to remain capacitive and very high. Several such tests were performed using higher salt concentration (such as10 g/l, 15 g/l and 20 g/l), with little effect. Figure 5.7 shows typical examples of measurement obtained. Relatively low levels currents were recorded on the glazed downwire insulator when compared to the unglazed insulator, for the same pollution. Furthermore, the downwire current is slightly out of phase with the resultant current, while the current flowing through the wood is in phase with the resultant current. This is indicating that the glazed downwire insulator had high capacitive component.

The results show that while the glazed downwire insulator is capable of conducting leakage current (as observed at KIPTS in Section 4), its ability is reduced under low relative humidity (i.e. where continuous wetting is not possible). This test demonstrates the effect the insulator surface material plays on the ability of the downwire insulator to conduct current to earth and supports the hypothesis made in this work.




a)




b)

**Figure 5.7: Examples of measurements obtained using glazed downwire insulator under wet and polluted conditions: 15 g/l sprayed, b) 20 g/l sprayed**

### 5.2.3 Fully bonded and earthed structure

The downwire insulators were removed and the bonding wire was connected directly to the station earth. The current flowing on the earthed downwire and current flowing on the wood were measured simultaneously, as before. Figure 5.8 show a typical example of measurements obtained. The current flow is only limited to the earthed downwire and no significant current was measured on the woodpole path. This was expected since fully bonding and earthing a structure provides a low resistance for current to flow to earth.

The results of Figure 5.8 compares well with the results obtained on the structure with an unglazed downwire insulator.

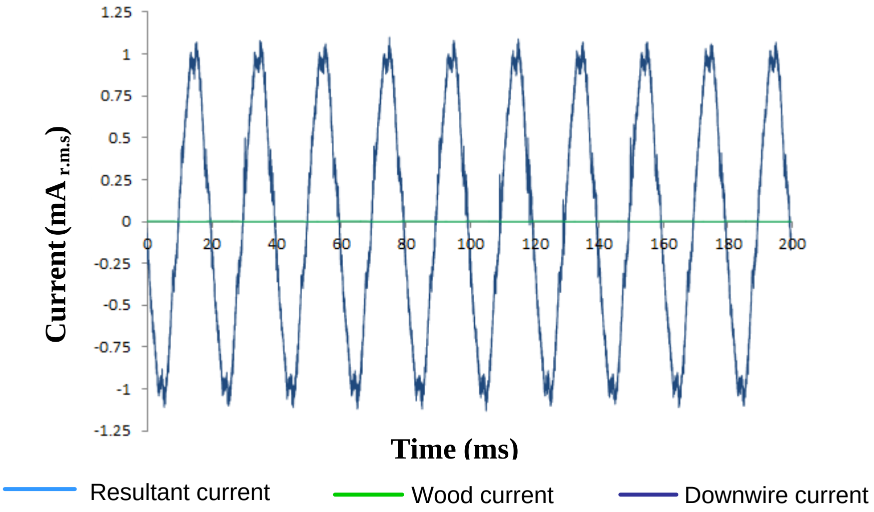



**Figure 5.8: Measurement obtained on the fully earthed test structure**

## 5.3 Downwire insulator voltage, downwire current and wood current waveforms

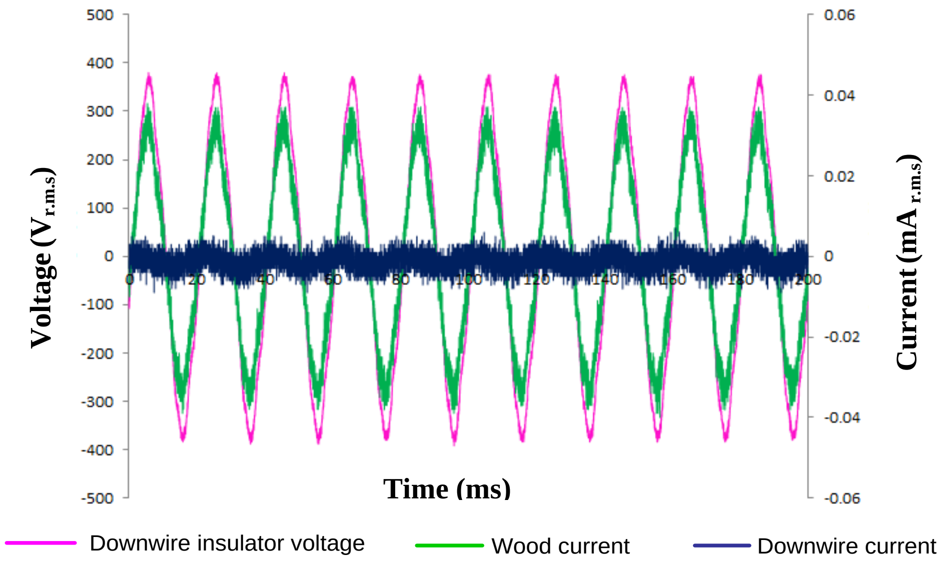
The objective of the tests was to determine the insulator voltage and to approximate the impedance of the downwire insulators and woodpole.

### 5.3.1 Structure with unglazed downwire insulator

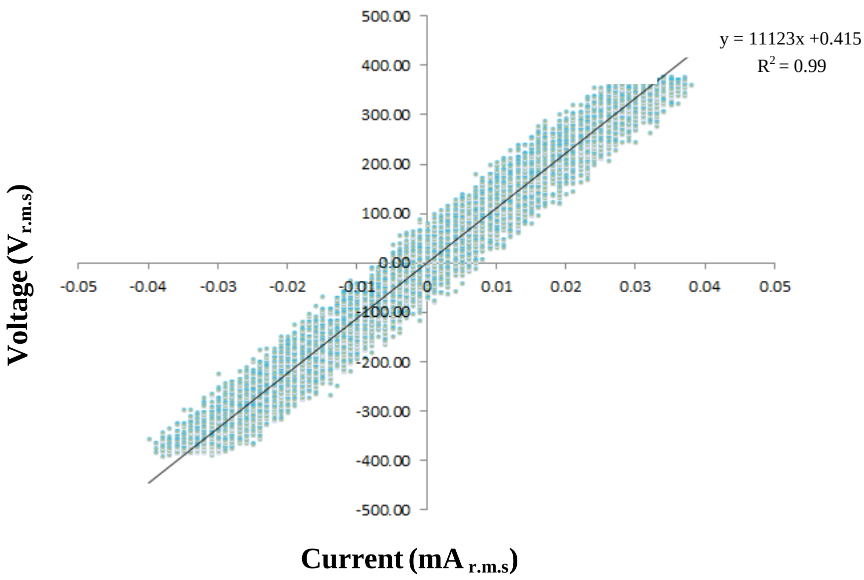
#### 5.3.1.1 Dry test

Figure 5.9 shows a set of measurements obtained. Figure 5.9 a) shows the relationship between the insulator voltage, downwire current and woodpole current with time. Figure 5.9 b) shows the relationship between the downwire insulator voltage and woodpole current. Most of the current continued to flow via the woodpole than on the downwire insulator, as in Sections 5.2.1.1 and 5.2.2.1. This current is in phase with the downwire insulator voltage (of magnitude 380 $V_{r.m.s}$). This and the fact that the $R^2$ is close to 1 indicate that the impedance of the wood was predominantly resistive rather than capacitive. The wood impedance was approximated as the gradient of the voltage versus current graph and was approximately 11 MΩ as shown in Figure 5.9 b). Again, it is suspected that the rain that occurred in the area a few days before the tests caused the wood to become conductive.

The impedance of the downwire insulator was not estimated since there was no significant current measured on the downwire insulator.




a)




b)

**Figure 5.9: Measurements obtained under dry conditions: a) voltage and current waveforms, b) relationship between downwire insulator voltage and woodpole current**

### 5.3.1.2 Wet and polluted test

The measurements were also performed in three stages as in 5.2.2.

*Stage 1: All the components (particularly downwire insulator) visually wet and polluted*

Figure 5.10 shows a typical example of measurement results obtained with the downwire insulator completely wet and polluted with a 5 g/l salt solution. The flow of current was dominantly on the path with the downwire insulator than on the woodpole – as before (Section 5.2.1). The magnitude of the downwire insulator voltage was 16 $V_{r.m.s}$ and is in comparable to the results obtained at KIPTS. The 50 Hz current through the downwire insulator was substantially in phase with insulator voltage. This and that the $R^2$ is 0.978, indicates that the downwire insulator impedance was predominantly resistive, similar to the results obtained at KIPTS. The downwire insulator impedance was approximately 38 kΩ. This was slightly higher than the magnitude estimated at KIPTS (in order of 10 kΩ).

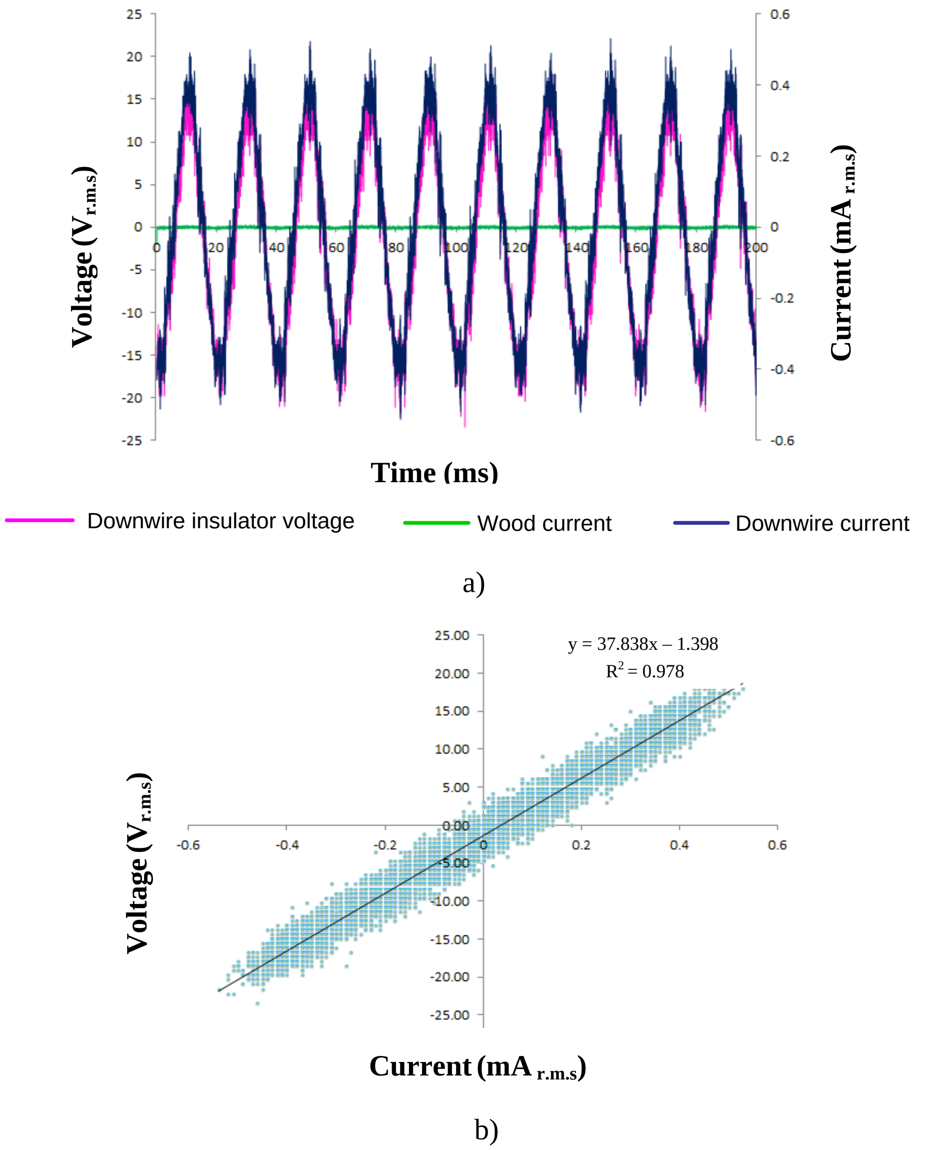
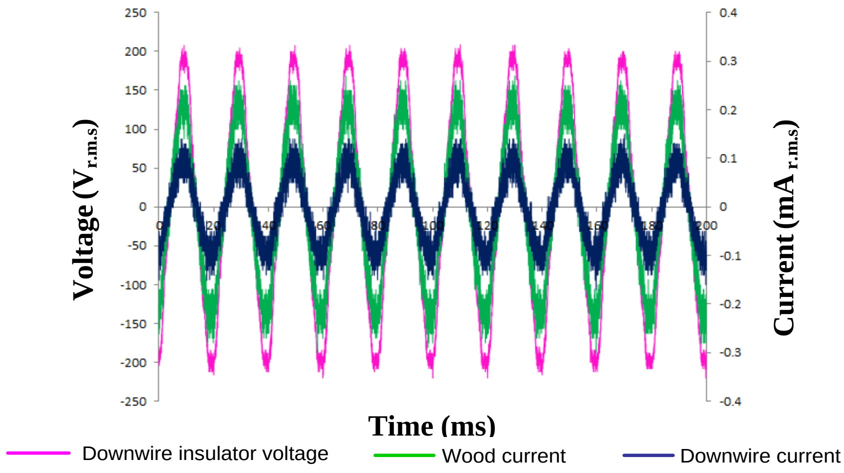


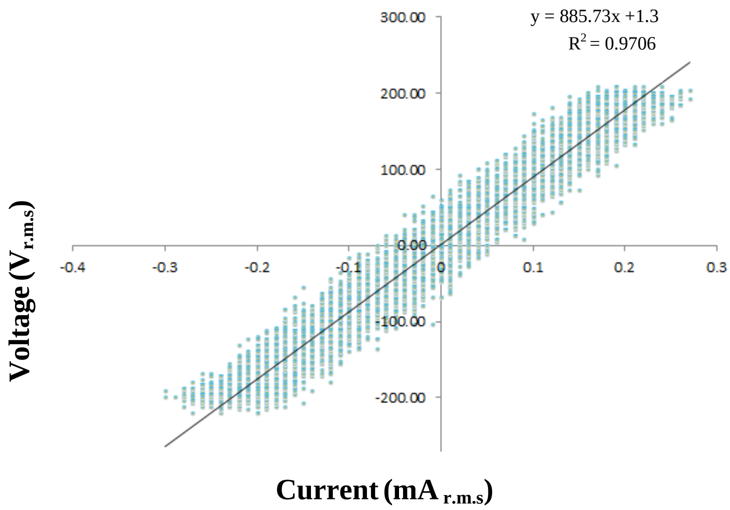

**Figure 5.10: Measurements obtained with a glazed downwire insulator under wet and polluted conditions – Stage 1: a) voltage and current waveforms, b) relationship between downwire insulator voltage and downwire current**

*Stage 2: Downwire insulator observed to have partially dried out*

Figure 5.11 shows a set of measurements obtained for Stage 2. In this case, the leakage current distributed between the woodpole path and the downwire insulator path – as before (Section 5.2.1). The measured insulator voltage was significantly higher (approximately 200 $V_{r.m.s}$) than the value recorded in Stage 1 (approximately 16 $V_{r.m.s}$). However, the voltage and currents were still in-phase. The downwire insulator and woodpole impedance were both highly resistive as shown in Figures 5.11 b) and c). The impedance of the downwire insulator increased from 38 kΩ (Stage 1) to 1.8 MΩ. This was expected since the flow of leakage current caused the downwire insulator to dry out (heating effect). The wood impedance was approximately 885 MΩ.




a)

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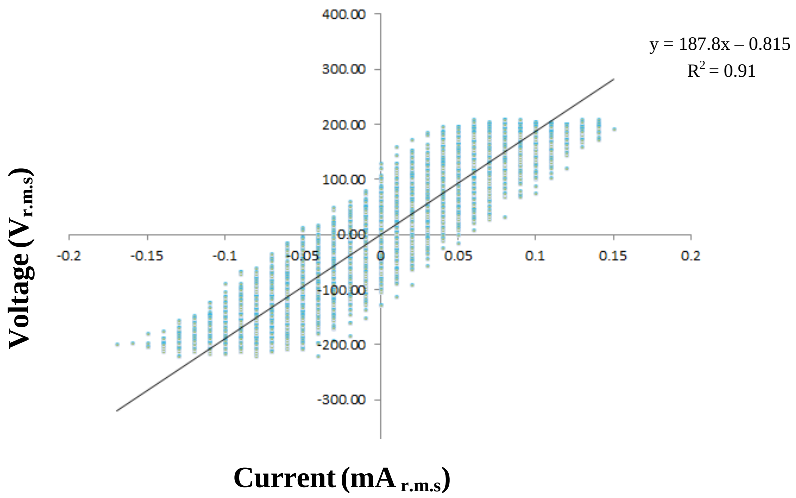
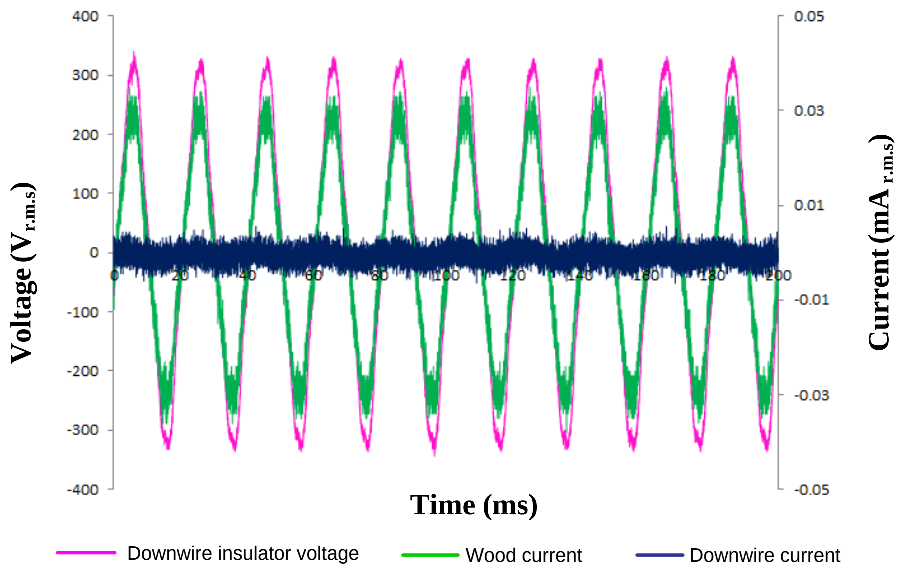



c)

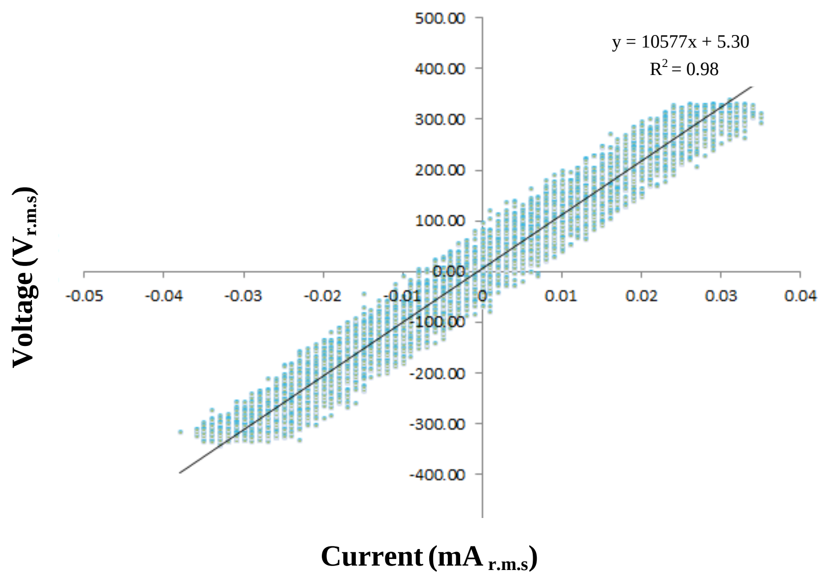
**Figure 5.11: Measurements obtained with an unglazed downwire insulator for Stage 2: a) waveforms, b) relationship between voltage and woodpole current, c) relationship between the downwire insulator voltage and downwire insulator current**

*Stage 3: downwire insulator observed to be completely dried out*

Figure 5.12 shows a set of measurements obtained for Stage 3. At this stage, the magnitude of the downwire insulator voltage increased to 350 $V_{r.m.s}$. Furthermore, the impedance of the wood also increased to approximately 10.5 MΩ. This value is comparable to the value estimated under dry conditions, which was approximately 11 MΩ. The difference may be attributed to that the downwire insulator may not have completely dried out and a certain amount of current (although very low to be measured accurately) continued to flow along the downwire insulator path. However, the impedance of the downwire insulator was not estimated since the current through the downwire insulator (if any) was very low and could not be measured accurately. This is evidence since the $R^2$ = 0.28.




a)

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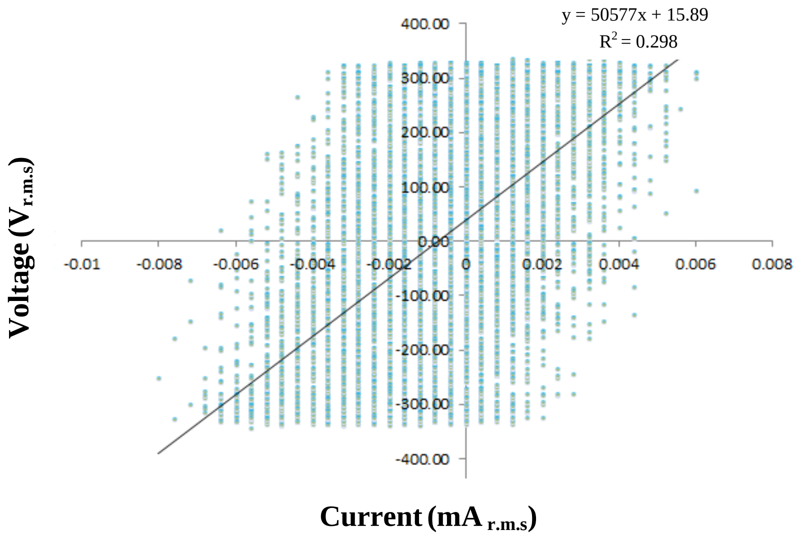
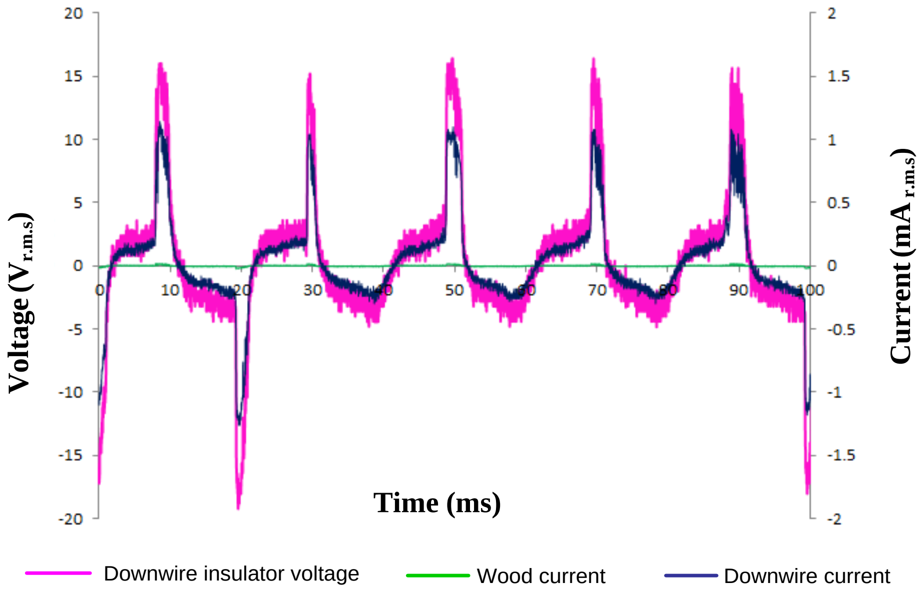


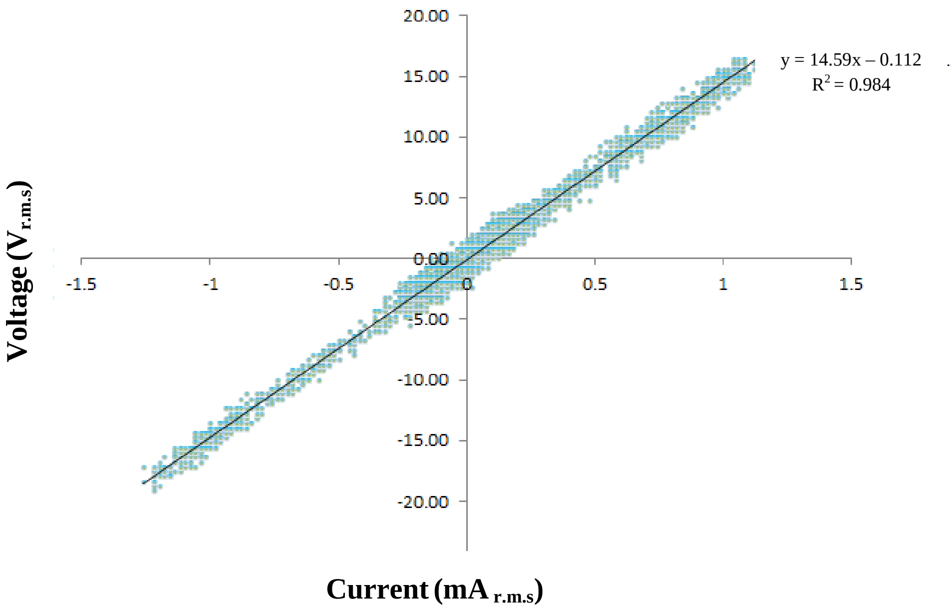

c)

**Figure 5.12: Measurements obtained with an unglazed downwire insulator for stage 3: a) waveforms, b) relationship between voltage and woodpole current, c) relationship between the downwire insulator voltage and the downwire insulator current**

Figure 5.13 shows another set of measurement obtained for Stage 1. In this case, the phase insulators, downwire insulator and woodpole were sprayed with 20 g/l of salt solution. Leakage current activity was visually observed on one of the phase insulators during this test. It is clear from Figure 5.13 a) that one phase contributed more significantly to the leakage current flowing on the downwire insulator than the other phases. The magnitude of the 50 Hz downwire currents and the downwire insulator voltage varied continuously with time. The measured insulator voltage is 15 $V_{r.m.s}$ and is comparable to previous result. The measured insulator current reached a maximum of 1 $mA_{rms}$. The downwire current and downwire insulator voltage are in phase as before. The impedance of the downwire insulator was therefore predominantly resistive and approximately 14.5 kΩ.




a)




b)

**Figure 5.13: Measurements obtained for stage 1: a) downwire insulator voltage and current waveforms, b) downwire insulator voltage and downwire current**

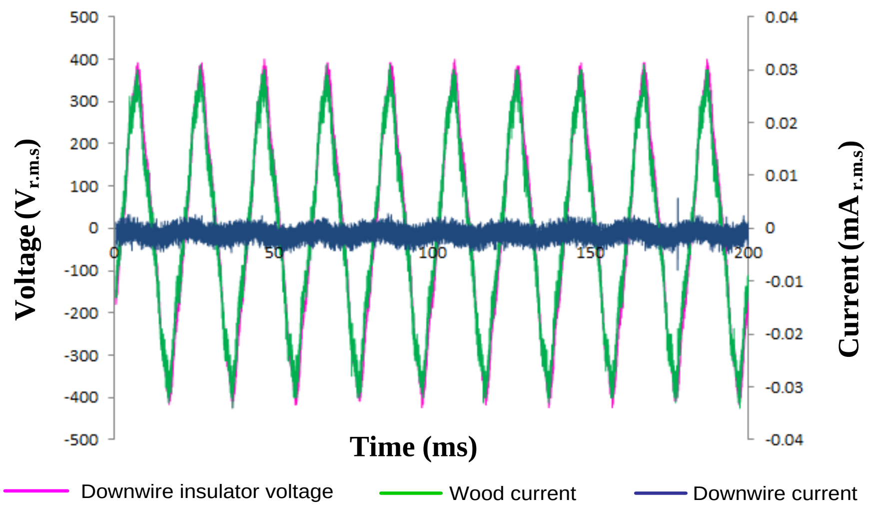
The results presented in this section show that under polluted and wet conditions, the impedance of the unglazed downwire insulator was resistive and lower than the impedance under dry conditions. This results in significantly more current flowing along the downwire insulator than along the woodpole. The downside to that this impedance (resistance) of the downwire insulator may not be adequate to adequately reduce the risk of bird electrocution.

Furthermore, the insulator voltages measured on structure with unglazed downwire insulator under polluted and wet conditions is consistently in order of tens of volts. A bird perching on the cross-arm and making contact with the live phase conductor may be subjected to a voltage close to the phase-to-earth voltage, which may exceed the 5 kV recommended in [10] for 11 kV and 22 kV systems. Thus the insulation provided by the downwire insulator may not be adequate to acceptably limit the risk of bird electrocution.

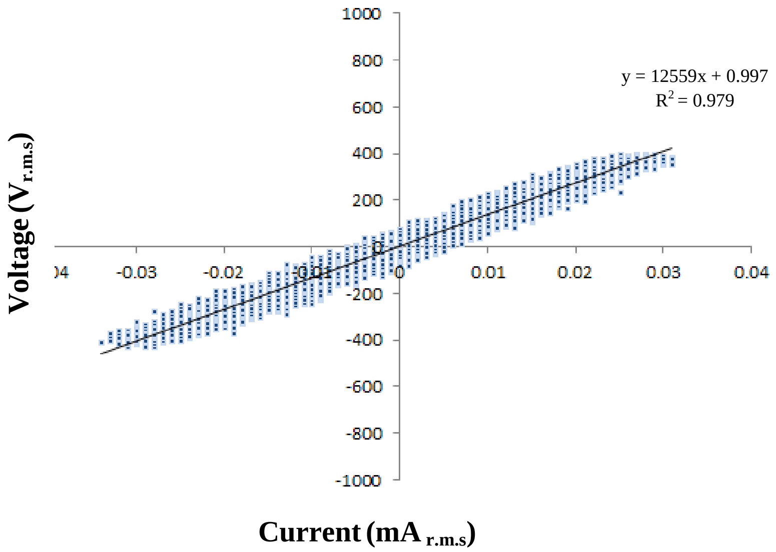
### 5.3.2 Structure with glazed downwire insulator

#### 5.3.2.1 Dry test

Figure 5.14 shows the measurements obtained when the downwire insulator and wood were dry. Similar results were observed as with the unglazed downwire insulator, where most of the current flowed through the woodpole. The woodpole current was in phase with the voltage. The wood impedance approximated 12.5 MΩ, which is higher than the value approximated in Section 5.3.1. This could attributed to that the woodpole was had dried out more as this test was conducted by midday.




a)



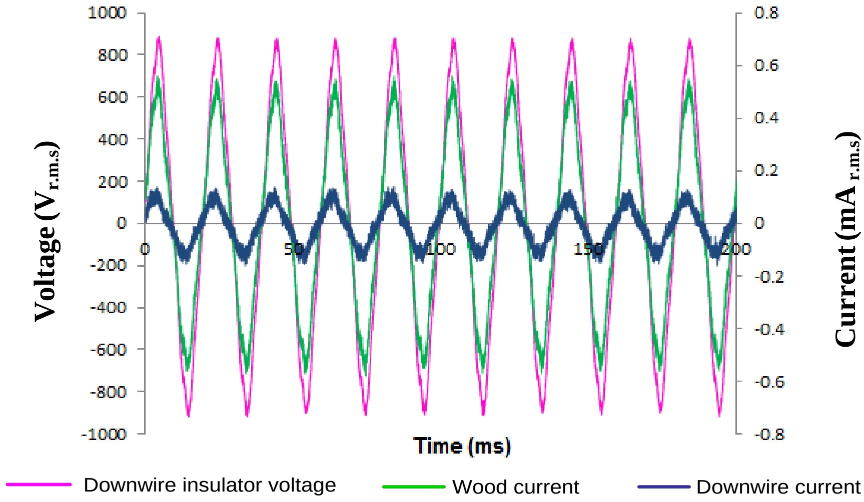

b)

**Figure 5.14: Measurements obtained under wet and polluted conditions: a) downwire insulator voltage and woodpole current waveforms, b) downwire insulator voltage and woodpole current**

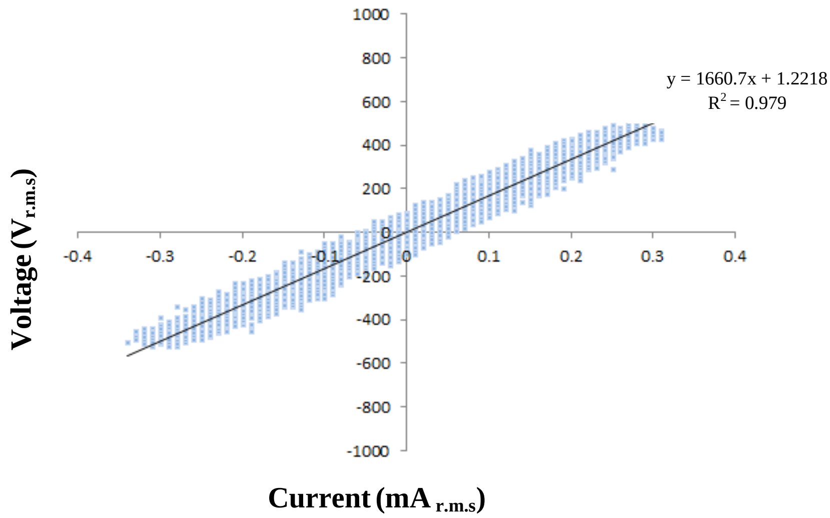
### 5.3.2.2 Wet and polluted tests

Wetting of the glazed downwire insulator remained a serious problem even with this test. Figures 5.15 and 5.16 show two sets of measurement results, where all the components were sprayed with 15 g/l and 20 g/l solution respectively. Significant current continued to flow along the woodpole path, with very little current flowing along the downwire insulator, when compared to the equivalent structure with unglazed surface material. This is attributed to the phenomenon discussed in Section 5.2.2, where the pollution dripped off the insulator easily and the insulator remained dry. The impedance of the downwire insulator was predominantly high and capacitive (current flowing along the downwire insulator is out of phase with insulator voltage and $R^2$ is 0.002) and therefore could not be estimated accurately. The impedance of the woodpole was predominantly resistive and of magnitude 1.7 MΩ.

The insulator voltage (in order of hundreds of volts to kVrms) is higher than the voltages measured on the structure with unglazed insulator (in order of tens of volts).




a)

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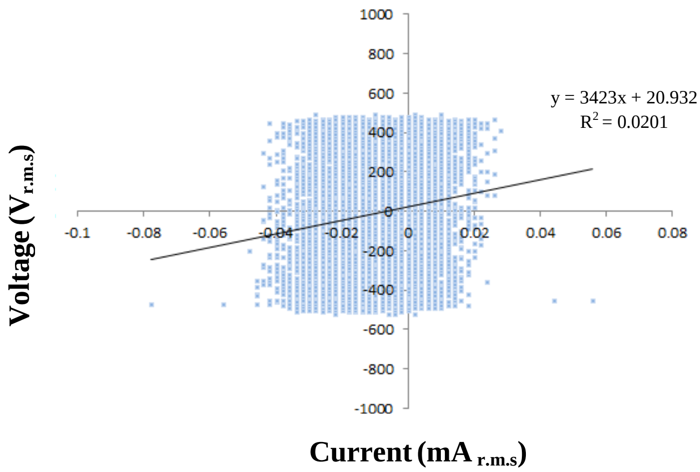
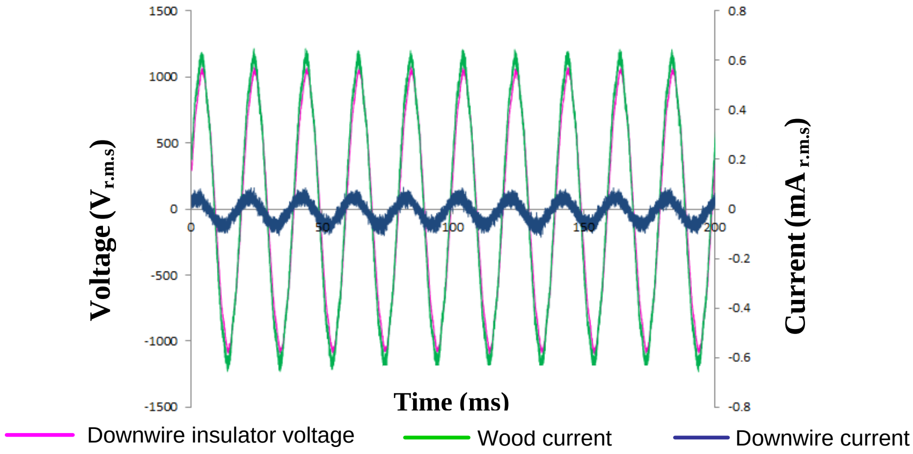
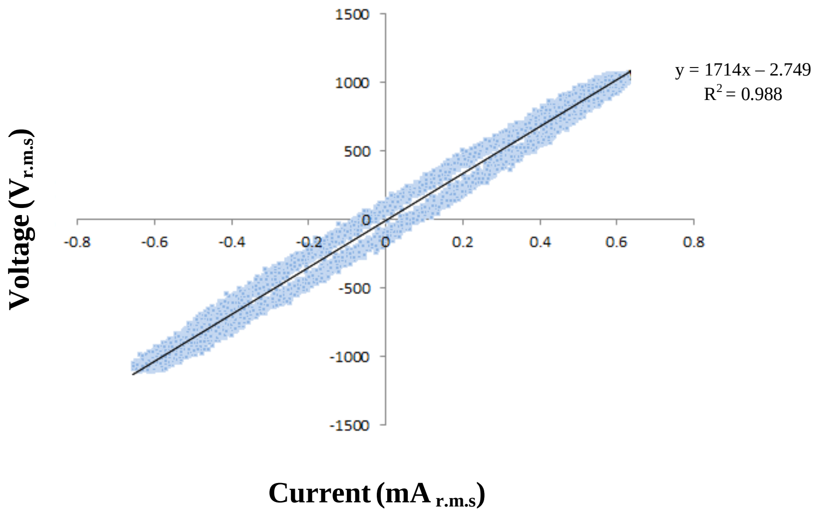



c)

**Figure 5.15: Measurements obtained under wet and polluted conditions**




a)

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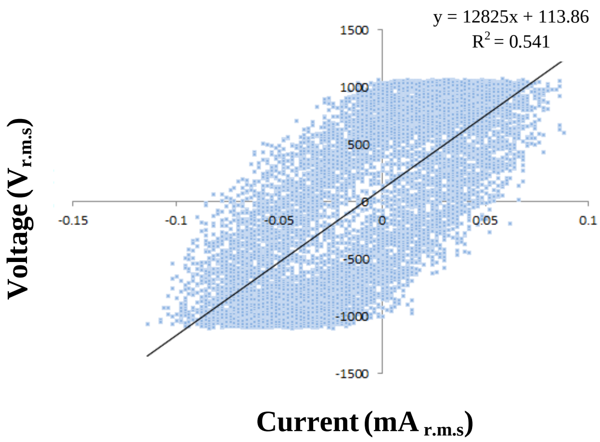



c)

**Figure 5.16: Another measurement obtained with a glazed downwire insulator under wet and polluted conditions**

The results indicate that under dry conditions, the behaviour of the glazed and unglazed downwire insulators are similar (i.e. their impedances are high and possibly purely capacitive). However, under polluted and wet conditions, the effect of the downwire insulator surface material may be noticeable. This occurs when the wetting of the downwire is not maintained. In such conditions, the glazed downwire insulator surface remains dry and provide high impedance to resist the flow of leakage current to earth. This result indicates the importance of wetting of the downwire insulator and agrees with Loxton's findings that humidity (which essentially provides wetting of the insulators) is the most critical factor necessary for leakage current to flow on the insulator.

### 5.3.3 Fully earthed structure

Figure 5.17 shows the measured earth downwire current, woodpole current and the voltage. Significantly more current was measured along the earthed downwire than along the woodpole path. This was also observed in section 5.2.3 and is attributed to the fact that the fully earthed downwire provides a low resistance path for current to flow to ground. No significant voltage was measured on the earthed downwire, as expected (since $V = IR$ and $R$ is very low). This result may prove that the low voltages measured across the unglazed downwire insulator were due to the low impedance of the downwire insulator.

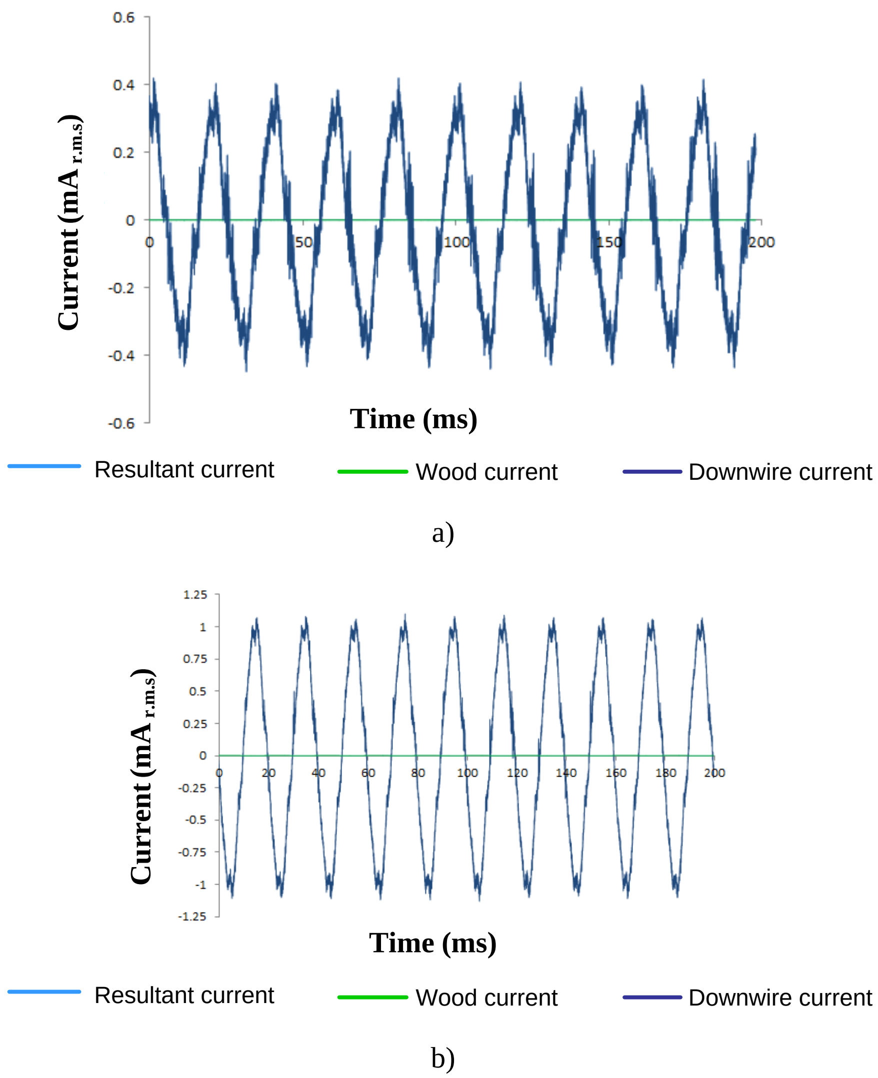



**Figure 5.17: Measurements obtained under dry conditions**

## 5.4 Measurement of downwire insulator and phase voltage waveforms

The objectives of the tests were merely to determine the relationship between the downwire insulator voltage and the phase voltage and the effect (if any) the downwire insulator voltage have on the on the floating neutral voltage with respect to pole earth.

The test was conducted by simultaneously measurement of downwire insulator voltage and phase voltage. Only one phase was measured since only two HV probes were available for the experiment; the voltages of the other phases were simulated by shifting the measured voltage in time accordingly.

The effect of the downwire insulator voltage on the neutral shift was investigated using the phasor diagram shown in Figure 5.18 [2]. It is clear that the insulator voltage may cause considerable neutral shift to occur, where the voltage across the phase insulators $E_{RN}$, $E_{BN}$ and $E_{WN}$ are not equal (R, W and B are the red, white and blue phases of three phase system respectively). In this work, the voltages across the phase insulators were calculated as the difference between each phase supply voltage and the downwire insulator voltage.

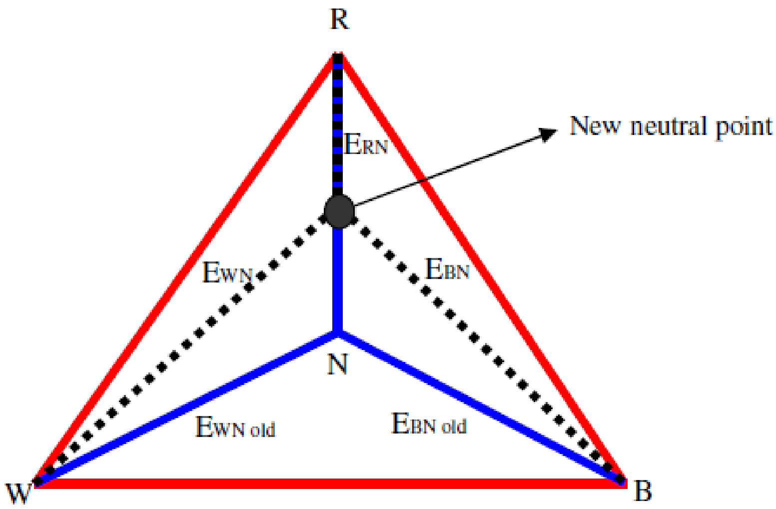
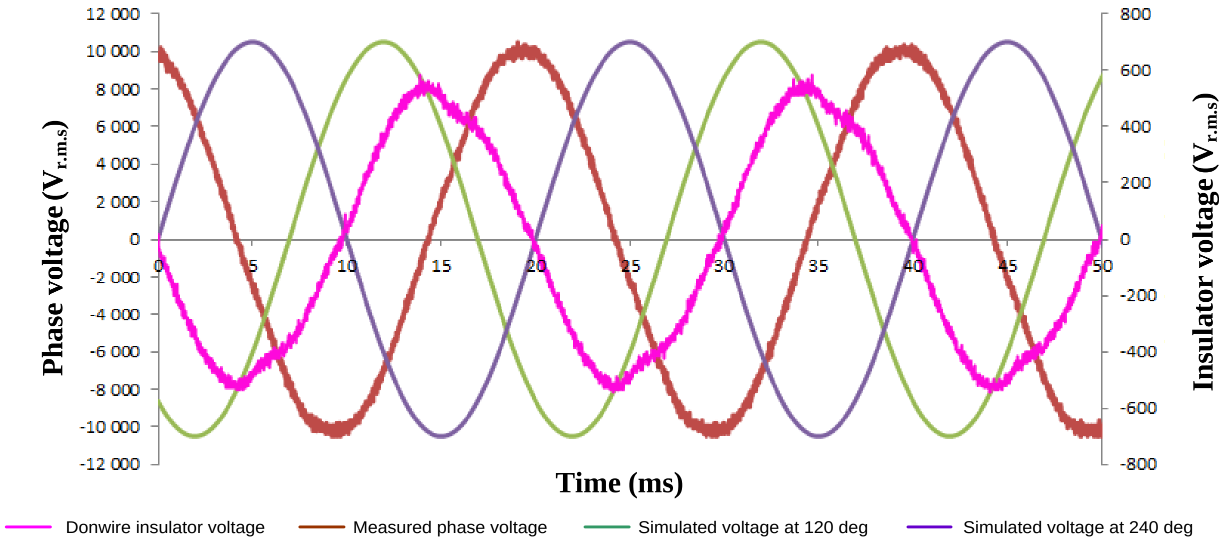



**Figure 5.18: Phasor diagram illustrating neutral shift [2]**

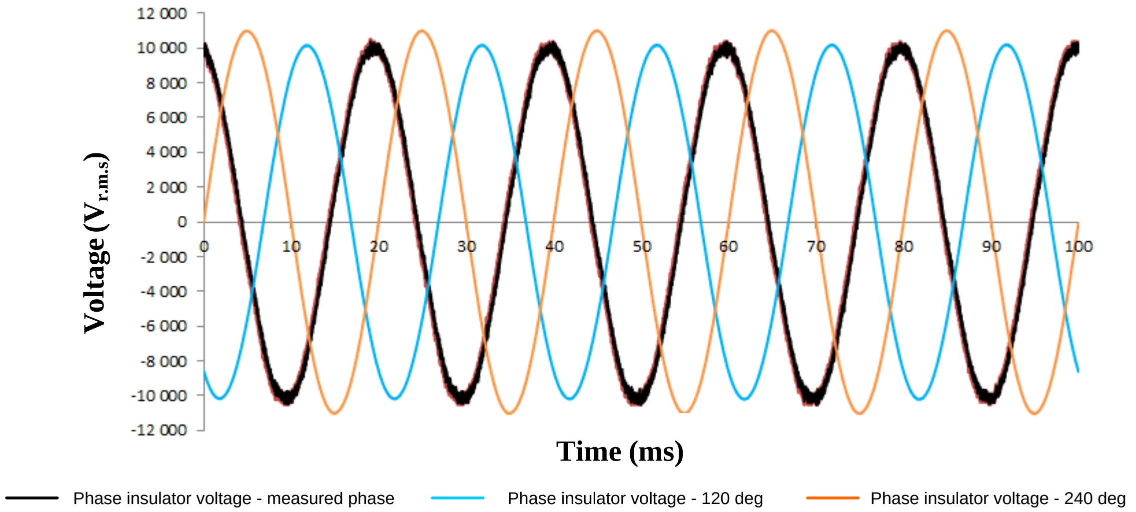
### 5.4.1 Dry test

Figure 5.19 shows the results obtained on the structure with unglazed downwire insulator. Figure 5.19 a) shows the relationship between the measured downwire insulator voltage, measured phase voltage and the two simulated phase voltages. Figure 5.19 b) shows the effect the neutral shift have on the voltage across the phase voltages. The magnitude of the measured phase voltage approximately 10.5 $kV_{r.m.s.}$. This is slightly lower than the expected value of 11 $kV_{r.m.s}$, but sufficient for the work performed. The downwire insulator voltage was also sinusoidal at a frequency of 50 Hz as in Section 5.3.1. The magnitude of the downwire insulator voltage was approximately 600 $V_{r.m.s}$. This voltage was 90° (5 ms) out of phase with the measured phase voltage. This is indicative that the downwire insulator voltage is a result of capacitive effect (downwire insulator voltage is a result of capacitive current, which leads voltage by 90 °) as expected.

The effect of the downwire insulator voltage (neutral shift) on the voltage across the phase insulators is minimal, specifically because the insulator voltage is low when compared to the phase voltage. Furthermore, the downwire insulator voltage has no noticeable effect on the phase angles of the phase insulator voltages as shown in Figure 5.19 b). This is better illustrated by that the three voltages seen by the phase insulators continue to be 120 ° out of phase with each other, similar to the phase voltages.




a)



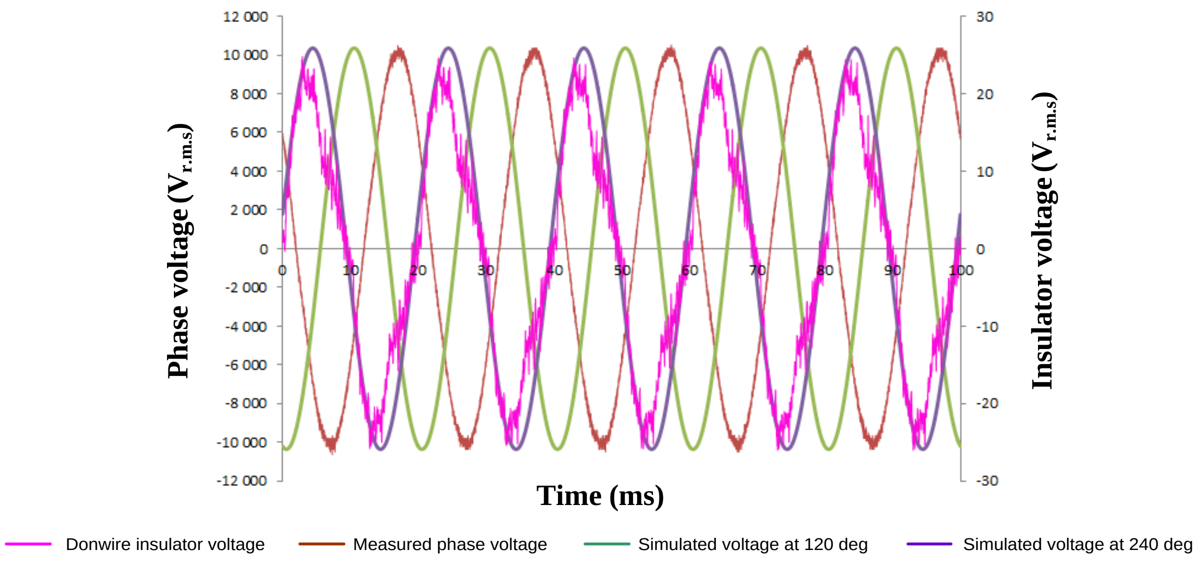

b)

**Figure 5.19: Measured and simulated voltages der dry conditions: a) downwire insulator voltage and phase voltage waveforms, b) phase insulator and voltage across phase insulators**

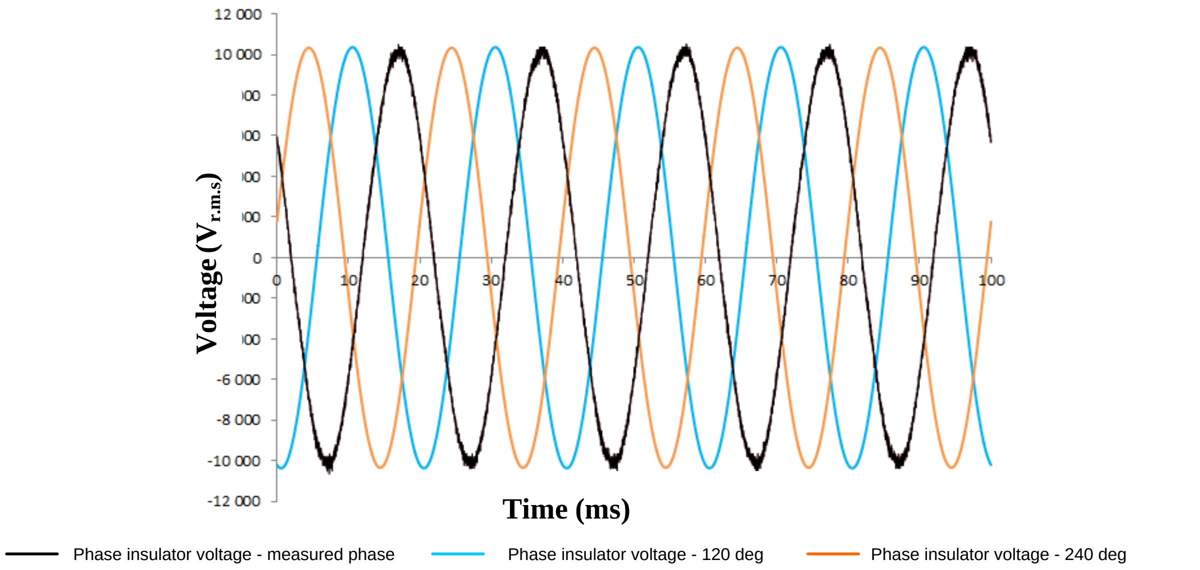
### 5.4.2 Wet and polluted conditions

*Stage 1: All the components (particularly downwire insulator) visually wet and polluted*

All the key components of the structure were sprayed with a 10 g/l salt solution and the measurement taken immediately after energisation (Stage 1). The results are shown in Figure 5.20. In this case, the insulator voltage (≈ 25 $V_{r.m.s}$) was significantly lower than the magnitude recorded under dry conditions (≈ 200 $V_{r.m.s}$). The downwire insulator voltage was 120° out of phase with the measured phase voltage and was therefore in phase with the simulated voltage at 240°. This shows that the downwire insulator voltage was due to the leakage current flowing along the phase insulator and not due to any capacitive effect. This is expected under the polluted and wet conditions sprayed on the test structures. The downwire insulator voltage has no noticeable effect on the phase angles of the insulator voltages and the voltage across the phase insulators as shown in Figure 5.20 b).




a)

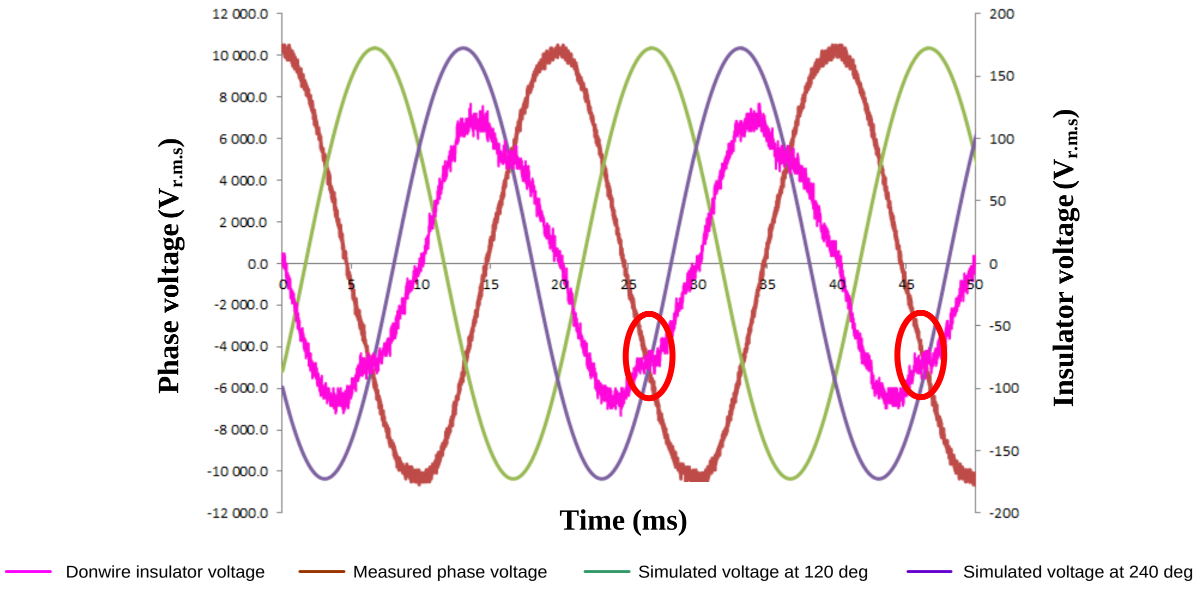



b)

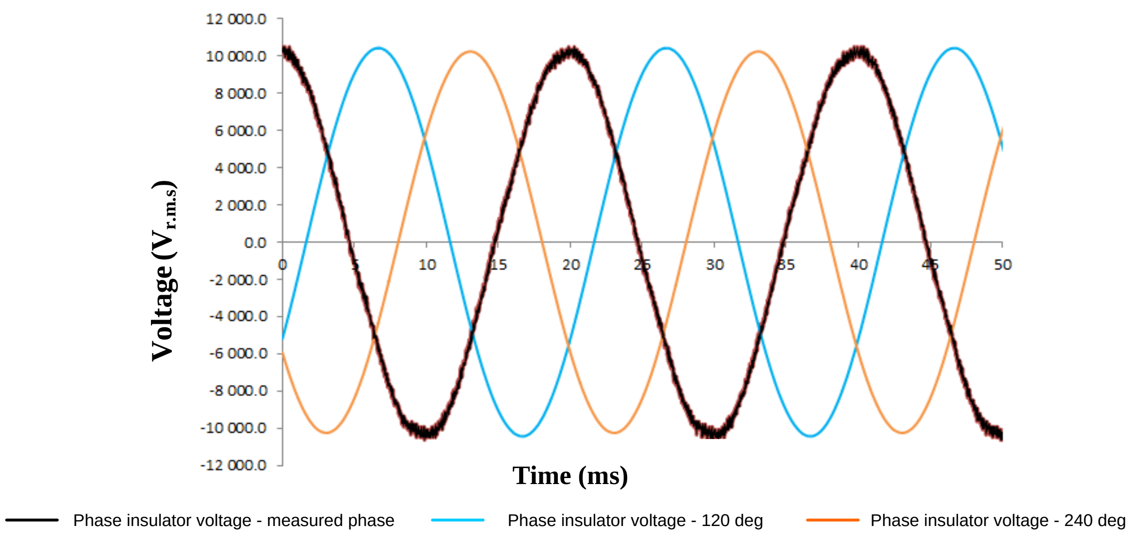
**Figure 5.20: Measured and simulated voltages with unglazed insulator under wet conditions – Stage 1**

*Stage 2: Downwire insulator partially wet*

Figure 5.21 shows results for Stage 2 (when the downwire insulator was observed to have partially dried out). The same was observed as under dry conditions, where the insulator voltage was sinusoidal and led the phase voltage by 90 °. However, it appears as if one of the phases was conducting some leakage current; this is shown by the distortion in downwire insulator voltage (circled in Figure 5.21). However, the downwire insulator voltage has no noticeable effect on the phase angles of the insulator voltages and the voltages across the phase insulators.




a)




b)

**Figure 5.21: Measured and simulated voltages with unglazed insulator under wet conditions – stage 2**

*Stage 3: Downwire insulator completely dried out*

The results for Stage 3 (i.e. when the downwire insulator was observed to have completely dried out) were similar to those obtained under dry conditions.

## 5.5 Visual state of the test structure

No tracking was observed on the surface, top and bottom of the woodpole. This was true for the cases where both downwire insulators (glazed and unglazed) were used. This is consistence with the findings at KIPTS. However, the woodpole was not dissected to inspect for internal tracking as the structure will likely be used for further testing.

## 5.6 Summary

The results presented in this chapter may be summarised as follows:

- Under dry conditions, the impedance of the glazed and unglazed insulators is high and capacitive and therefore resists the flow of leakage current through to earth. This is not a concern for pole-top fires since most of the pole-top fires are reported to occur under polluted and wet conditions.
- However, under polluted and wet conditions, the impedance of an unglazed downwire insulator is predominantly resistive and very low (in order of tens of kΩ). As such, the downwire conducts significant amount of leakage current to earth without substantial current flowing through the wood.
- The impedance of the glazed downwire insulator remained predominantly capacitive and high throughout this testing. This was caused by the salt solution dripped off easily on the glazed downwire insulator, making the insulator dry faster than the unglazed insulator under the same conditions. This highlights the effect of the downwire insulator material to conduct leakage current in cases where continuous wetting is not achievable (i.e. in low humidity areas).
- Under dry conditions, the downwire insulator voltage is caused by capacitance of the phase insulators and the downwire insulator voltage leads the phase voltage by 90°. However, under polluted and wet conditions, the insulator voltage is caused by the leakage current flowing on the phase insulators.
- The insulator voltages measured in this work do not appear to have noticeable effect on magnitude of the voltage seen by the phase insulators and their phase angles.
- Fully bonding and earthing a structure effectively provides a low resistance path for current to flow to earth without current flowing through the woodpole.

# 6. DISCUSSIONS

## 6.1 Summary of results

Tables 6.1 and 6.2 provide a summary and comparison of the KIPTS and the Corona Cage results. The following may be deduced from these tables:

- The impedance of the (unglazed or glazed) porcelain downwire insulator is purely resistive and of relatively low magnitude (tens of kΩ), provided that the downwire insulator is polluted and completely wet. Under such conditions, a significant level of leakage current can flow along the downwire insulator, with relatively little current flowing in or on the woodpole.
- Under certain conditions, the magnitude of total leakage current flowing to earth can be similar to that flowing on a fully earthed structure. This may be attributed to the low impedance of the glazed and unglazed downwire insulator (under wet and polluted conditions) that provides a low resistance path for leakage current to flow along the downwire insulator. This is a positive finding from a pole-top fire mitigation perspective, as under these conditions, which are conducive to pole-top fires occurring, leakage current is diverted away from the woodpole.
- When very lightly wetted, the downwire insulator surface material plays a role on the ability of the downwire insulator to conduct significant amounts of leakage current. In such cases, an unglazed insulator appears to perform better (conduct higher current) than the glazed insulator in conducting leakage current to earth.
- As the downwire insulator dries out, or if it is not completely wet, leakage current distributes between the woodpole and downwire insulator in a manner determined by the relative impedance of the wood and insulator surface. This demonstrates the effect that the woodpole properties play in determining the effectiveness of the modified structure in preventing pole-top fires. However, the present and previous results indicate that the impedance of the woodpole (hundreds of kΩ) is higher than the impedance of the downwire insulator (tens of kΩ) under polluted and wet conditions. Further investigation is required to effectively investigate the role of wood, while taking into account practical aspects such as age of the woodpole, typical length of the pole used in MV lines and other factors.
- No tracking or burning was observed on all the test structures. The high insulator voltages measured on the structure with a glazed downwire insulator and possible neutral shift did not appear to have caused noticeable burning on the wood surface or inside of the wood.

**Table 6.1: Summary of results for test at KIPTS**

| | Structure with unglazed downwire insulator | Structure with glazed insulator |
|---|---|---|
| 1. Ability of the downwire insulator to conduct significant levels of leakage current to earth | Waveforms:<br><br>- Under wet and polluted conditions, the downwire insulator conducts significant levels of leakage current to earth. | - Under wet and polluted conditions, the downwire insulator conducts significant levels of leakage current to earth. |
| | Logged currents:<br><br>- The downwire insulator conducts a significant level of leakage current to earth. The levels of leakage current were at times comparable to the levels measured on the structure with glazed insulator and fully bonded and earthed structure. The conditions were not verified due to the weather sensor not working. | - The downwire insulator conducts a significant level of leakage current to earth. At times, higher levels were recorded on this structure, than on the fully bonded and earthed structure and structure with unglazed insulator (suspect effect of structure position to the coast). |
| 2. Downwire insulator voltage | - Under wet and polluted conditions insulator voltage is in tens of volts. | - Under wet and polluted conditions insulator voltage is in hundreds of volts to tens of kV. |
| 3. Downwire insulator impedance | - Under wet and polluted conditions, the impedance of the downwire insulator is in tens of kΩ (typically 10 to 40 kΩ). | - Under wet conditions, the impedance of the downwire insulator is in the range of 39 kΩ to 150 kΩ, consistently higher than that of unglazed insulator. |
| 4. Visual state of the structure | - No tracking observed on wood surface. | - No tracking observed on wood surface. |

**Table 6.2: Summary of results for test at Corona cage**

| | Structure with unglazed insulator | Structure with glazed insulator |
|---|---|---|
| 1. Ability of the downwire insulator to conduct leakage current | <u>Ease of wetting:</u><br>- Pollution and moisture attach relatively easily to the downwire insulator. | - Pollution and moisture attach with relative difficulty to the downwire insulator. |
| | <u>Ability to conduct current when wet and polluted:</u><br>- The downwire insulator allows relatively high levels of leakage current to flow to earth, with very little current flowing through the wood. | - The downwire insulator allows relatively low levels of leakage current to flow to earth, when compared to current flowing along wood path, even at extremely high pollution level. |
| | <u>Ability to conduct current when dry:</u><br>- The downwire insulator resists current flow through the insulator to earth, leakage current (if any), may flow through the wood. | - The downwire insulator resists current flow through the insulator to earth, leakage current (if any), may flow through the wood. |
| 2. Downwire insulator voltage | - Under wet and polluted conditions, the insulator voltage is in tens of volts – similar to magnitudes recorded at KIPTS. | - Under wet and polluted conditions, the insulator voltage is in hundreds of volts to tens of kV – similar to magnitudes recorded at KIPTS. |
| | - Under dry conditions, insulator voltage is high (hundreds of volts). | - Under dry conditions, insulator voltage is high (hundreds of volts). |
| 3. Downwire insulator impedance | - Under wet conditions, impedance of the downwire insulator is in order of tens of kΩ (typically 10 to 40 kΩ). | - Insulator impedance could not be estimated due to difficulty in keeping the downwire insulator continuously wet. |
| | - Under dry conditions, the impedance of unglazed downwire insulator is high (MΩ). | - Under dry conditions, the impedance of unglazed downwire insulator is high (MΩ). |
| 4. Visual state | - No tracking observed on the wood. | - No tracking observed on the wood. |

## 6.2 Mitigation against pole-top fires

The results indicate that the downwire insulators are capable of conducting leakage current from the pole-top to earth, without significant current flowing though the wood. This occurs under polluted and wet conditions, where the downwire insulator provides a lower resistance path for current to flow to earth than the wood tested. The results also indicate that the effect of the downwire insulator material has an effect on the surface impedance and ultimately on the ability of the downwire insulator to allow current to flow to earth. This was found to be applicable in cases where continuous wetting was not possible. An unglazed downwire insulator material conducted significantly more current than the equivalent insulator with a glazed surface. However, the glazed surface material is capable of conducting significant current to earth if continuous wetting is ensured.

The high insulator voltages measured on the structure with a glazed downwire insulator and possible neutral shift did not appear to seem to have caused noticeable burning on the wood surface or inside of the wood. This could be attributed to the fact that the test structures were correctly bonded and the insulators had conductive end-fittings.

Thus from a pole-top fire point of view, both downwire insulators (glazed or unglazed) are feasible in limiting the risk of pole-top fires in woodpole structures. However, the unglazed surface material allows for pollution and wetting of the insulator material to occur for prolonged periods, even in light wetting conditions. This allows the downwire insulator with unglazed surface to conduct significant leakage current to earth, with relatively low current flowing through the wood. Thus the choice insulator material is important in cases where light wetting may dominate.

## 6.3 Bird safety

No published information related to the impedance or resistance of the birds was located. Therefore SANS 60479-3 was used to evaluate the risk of bird electrocution on powerlines. The challenge is that the impedances specified in SANS 60479-3 are for human beings and livestock and for voltages up to 230 V [27]. In such cases, the total impedance of the livestock with four limbs ranges from 600 Ω to 1.2 kΩ [27]. It is suspected that the impedance of the bird may be lower that the values specified in [27]. However, for analysis of bird electrocution a value of 600 Ω was chosen as a worst case scenario.

In the absence of literature available on the minimum current required for bird electrocution, the electrical stunning of poultry water bath systems was used in this work. Literature indicates that at 50 Hz, birds and chickens are stunned effectively by currents between 100 mA to 120 mA under wet conditions [28, 29]. However, under dry conditions, the stunning current ranges between 240mA to 400 mA [28]. Thus in order to reduce the risk of bird electrocution in wet conditions (conditions under which pole-top fires occurs), the current through the bird must be less than 100 mA. A current of 80 mA was chosen in this work to provide acceptable safety margin.

Thus for a 22 kV system (with normal phase-to-earth voltage of 12.7 kV r.m.s), the equivalent impedance of the bird, wood and downwire insulator necessary to limit the current through the bird below 80 mA should be 160 kΩ or higher – refer to equivalent circuit shown in Figure 6.1. Since the impedance of the bird was chosen as 600 Ω, it follows that the downwire insulator and wood should provide an additional 159.4 kΩ in order to limit the risk of bird electrocution. In [2] and [3], the impedance of wood was in order of hundreds of kΩ to MΩ.

It follows that the impedance of typical woodpoles used on MV lines that are 8 m long may be even higher. Therefore under wet and polluted conditions, the impedance of the glazed and unglazed insulators may be lower than the impedance of the wood. As such, the equivalent resistance of wood in parallel with the downwire insulator (Refer to Figure 1.5) will always be lower than the impedance of the downwire insulator, which may be as low as 10 kΩ to 39 kΩ, depending on whether an unglazed or glazed surface material is used. It is clear that the impedance or resistance of the glazed and unglazed downwire insulators will not be adequate to limit the current to 80 mA or lower under polluted and wet conditions. However, the glazed downwire insulator (with resistance in order of 132 kΩ under polluted and wet conditions) may limit the risk of bird electrocution to a certain extent when compared to the unglazed downwire insulator (consistently in tens of kΩ). The problem is that the glazed downwire insulator requires continuous wetting to keep the impedance low, a drawback for pole-top fires.

Furthermore, higher insulator voltages (several kV) were recorded on the structure with a glazed downwire insulator than on the structure with unglazed insulator (consistently in tens of volts). According to [10], a bird with wet feathers may be electrocuted by voltages 5 kV or higher. Thus, a bird perching on the cross-arm and making contact with a live phase conductor on the structure with an unglazed downwire insulator may be subjected to voltage close to the phase-to-ground voltage of the line. For the structure with a glazed downwire insulator, the voltage applied to the bird in such cases may be lower (e.g. measured insulator voltage on 12.7 kV is 4 kV, thus bird may be subjected to 8.7 kV, assuming that the voltages are in phase). This is still likely too high to prevent electrocution of a bird (> 5 kV). Furthermore, the insulation offered by the insulated bonding wire (typically less than 1 kV) may not reduce the risk of bird electrocution to acceptable levels if an unglazed downwire insulator is used.

Under dry conditions, the downwire insulator will provide higher impedances to limit the current to below 240mA to 400 mA.

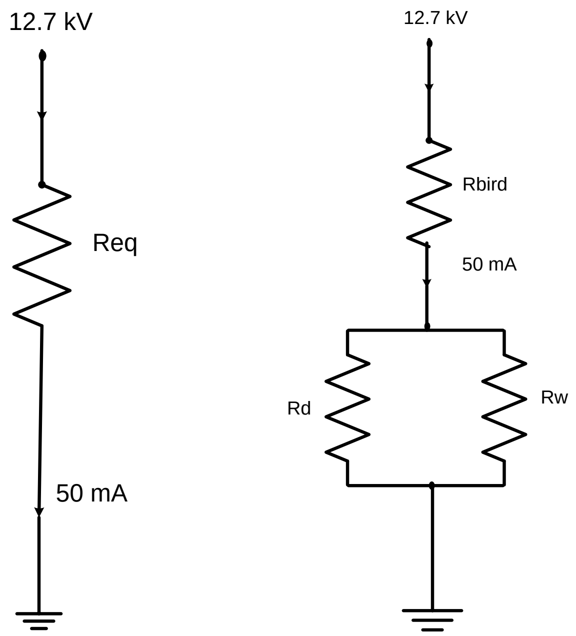



**Figure 6.1: Equivalent circuit illustrating the impedance required to limit risk of bird electrocution: a) $R_{eq}$ is the approximate equivalent resistance of bird in series with the downwire insulator and wood, b) approximate resistance of bird, wood and downwire insulator**

## 6.4 Specifications of downwire insulator

The glazed downwire insulator has been proven to substantially reduce the risk of pole-top fires while resulting in less of a bird safety risk than an unglazed insulator. Thus the glazed downwire insulator may be used as is. Most of the pole-top fires are reported to occur after prolonged periods where pollution accumulates on the insulators over time. The disadvantage of the glazed surface is that the pollution may be easily washed by rain or wind, making it to not conduct current when the structure is lightly wetted by fog or light rain.

The unglazed surface has been proven to retain pollution and wetting better than the glazed surface, and thus is preferable from the pole-top fires point of view. This is because an unglazed downwire insulator continues to conduct significant current to earth, with very little flowing through the wood, even when lightly polluted and wet. The disadvantage is that the impedances of the downwire insulator under polluted and wet conditions are very low (in order of tens of kΩ) and may provide significant risk of bird electrocution.

A guide in the design of this insulator is now provided. The design is based on equation 1.1.

It follows that in order to increase the resistance of an unglazed insulator under wet and polluted conditions, one need to increase the length and reduce the width of the insulator, for the same area, as shown in Figure 6.2. The downwire insulators tested in this work are 140 mm long and 85 mm wide and deep [30], with area 47,600 $mm^2$ (this is a rough guide using the total dimensions of the insulator on all four sides). Reducing the width of the insulator from 85 mm to 20 mm (relatively close to the diameter of fiberglass stay wire insulators used in South Africa), the length of the insulator becomes 595 mm (for the same area).

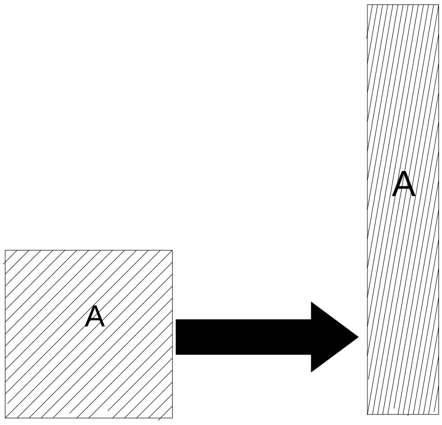



**Figure 6.2: Proposed changes in dimensions of an unglazed downwire insulator to increase resistance for bird safety**

A new insulator should therefore be designed, using the above criterion with the following specifications:

- Material: unglazed porcelain – to give acceptable performance under light and heavy pollution conditions.
- Dimensions: 20 mm wide and deep and 600 mm long – similar dimensions to the fiberglass stay wire insulator currently used (700 mm long) [30].
- Basic insulation level (BIL) comparable to the same fiberglass stay wire insulator (150 kV).

However, these specifications of the insulators should be checked with relevant experts before it is designed and tested.

## 7. CONCLUSION AND RECOMMENDATIONS

The following conclusions were reached from the results presented in this report:

- The feasibility of using a downwire insulator instead of a 500 mm wood gap to limit the risk of pole-top fires, while offering adequate bird safety, was investigated.
- The results indicate that the downwire insulator is effective in diverting leakage current away from the woodpole, indicating that the downwire may be effective in reducing the risk of pole-top fires.
- However, use of such an insulator to conduct sufficient leakage current to earth to prevent pole-top fires while simultaneously preventing bird electrocutions is not feasible.
- It may be feasible to design such an insulator that only conducts leakage current when necessary to prevent pole-top fires, while maintaining sufficiently high impedance to prevent bird electrocution.
- Cognizance of the large variation in the impedance of woodpoles, and typical bird impedances (yet to be determined for wild birds) would need to be taken into account in performing this design.
- Based on the results to date, an appropriate downwire insulator would be an unglazed porcelain insulator, with dimensions of 20x20x600 mm and a basic insulation level (BIL) comparable to the fiberglass stay wire insulator that is currently used.
- The above notwithstanding, a thorough risk assessment would be required for areas with both risk of pole-top fires and prevalence of large (endangered) birds.

The recommendations for future work are:

- The effect of wood properties on the effectiveness of modified structure, especially taking into account practical aspects such as age of the woodpole, typical length of the pole used in MV lines and other factors should be investigated further.
- The typical impedances of wild birds should be estimated before a conclusion is reached.
- A downwire insulator should then be designed with respect to the required characteristics and dimensions presented in this report as a guide. The insulator should be designed using appropriate means such as a salt fog test chamber, for acceptable leakage current performance under polluted and wet conditions.
- The insulation level of this insulator should then be evaluated to determine whether this is adequate for bird safety. This may include geographic evaluation of the risk with respect to the frequency of polluted and wet conditions occurring and the abundance of large birds.

# 8. REFERENCES


[1] A.E. Loxton, A.C Britten, I.A. Fergusson, 'Recent experience in Eskom with pole-top fires on 22 kV woodpole lines, IEEE 4th AFRICON, Volume 2, 1996.

[2] A. K. Persadh, "A study of pole top fires on 22 kV woodpole power lines in KwaZulu – Natal", Dissertation for Master of Science in Electrical Engineering, University of KwaZulu-Natal, October 2007.

[3] M. Darveniza, "Electrical properties of wood and line design", University of Quensland Press, 1980.

[4] K.V. Thejane, A.A. Beutel, M.D. Ntshani, H.J. Geldenhuys, A.C. Britten, W. Vosloo, T.D. Mvayo, R. Watson, R. Swinny, C.R. Evert, A. Khatri, 'Pole Top Fires: Review of work to Date and case for Further Research', IEEE PES Power Africa 2012 Conference and exposition, pp 7B-1.

[5] A. Beutel, H. Geldenhuys, B. McLaren, M. Ntshani, K. Thejane, A. Khatri, 'Pole-top fires risk assessment: A South African perspective', 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), pages 1-4.

[6] C.T. Gaunt, A.C. Britten ,H.J. Geldenhuys, "Insulation Coordination of unshielded distribution lines from 1 kV to 36 kV", Report prepared for the High Voltage Co-ordinating Committee Task Force on Lightning Protection of Distribution Lines of the CSIR, 1989.

[7] H. J. Geldenhuys, R.B. Lagesse, A.C. Britten, K. Sadurski, W.C. van der Merwe, "Practical insulation Co-Ordination Of Woodpole Distribution Lines In High-Lightning Areas", Proceedings 3rd AFRICON Conference, 1992.

[8] M.D. Ntshani, A.A. Beutel, K.V. Thejane, H.J. Geldenhuys, A.C. Britten, T.D. Mvayo, R. Watson, R. Swinny, A. Khatri, "Leakage current performance of woodpole line distribution structures: experiences from Koeberg Insulator Pollution Test Station, '7th Cigre Southern Africa Regional Conference 2013, paper CN202.

[9] M. D. Ntshani, K. V. Thejane, H. J. Geldenhuys, T. D. Mvayo, R. Watson, W. L. Vosloo, A. Khatri, B. W. McLaren and A. A. Beutel, J M Van Coller, 'Investigation into the feasibility of modified woodpole distribution structures to reduce their pole-top fire risk, 18th International Symposium on High Voltage Engineering (ISH), pages 2230-2235.

[10] R.E. Harness, 'Steel distribution poles-environmental implications', Paper presented at 42nd Annual conference on Rural Electric Power Conference, 1998.

[11] W. L. Vosloo, "A comparison of the performance of high-voltage insulator materials in a severely polluted coastal environment", PhD dissertation, University of Stellenbosch, South Africa, 2002.

[12] P. M. Ross, 1947, "Wood structure burning by leakage currents," *Elect. Eng.*, Vol. 66, pp. 472–4.

[13] M. Darveniza, G.J. Limbourn, S.A. Prentice, 'Line Design and Electrical Properties of Wood' IEEE Transactions on Power Apparatus and Systems, Volume PAS-86, Issue: 11, 1967.

[14] S. Pathak, P.J. Sokolowsk, A Dwiyedi, F. Buratto, X. Yu, K.L. Wong. "Investigation of pole fire on 22 kV wooden power structure", Symposium on Electrical Energy Evolution in China and Australia, Palm Cove, July 2008.

[15] K. L. Wong, M. F. Rahmat, 'Feasibility study of leakage current shunting method based on the ladder network model' , *IEEE Trans. Power Delivery*, Vol. 25, Issue 2, pp. 1133–1137, 2010.

[16] K.L Wong, S. Pathak, X. Yu, "Aging effect on leakage current flow in wooden poles", IEEE Transactions on Dielectric and Electrical Insulation, Vol. 16, No. 1, Feb 2009, pp. 133-138.

[17] M. F. Rahmat, K. L. Wong, 2009, "Thermographic study of stainless steel cross-arm on overhead distribution system", *Proceedings AUPEC*, pp. 1-6, 2009.

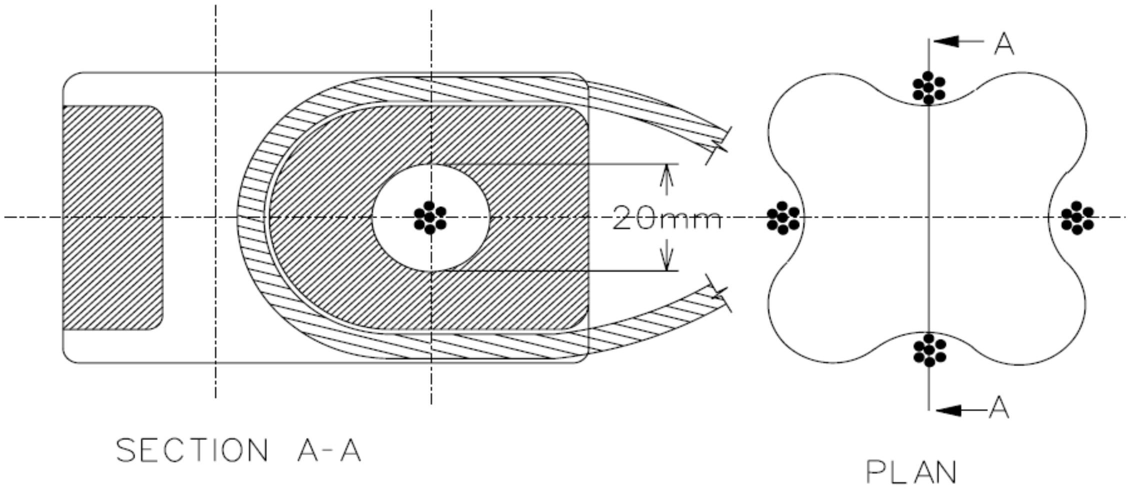
[18] K. L. Wong, M. F. Rahmat, "Feasibility study of leakage current shunting method on wooden pole", Paper C-56, International Symposium on High Voltage Engineering (ISH 2009), August 2009.

[19] Safety Performance Report on Victorian Electricity Distribution and Transmission Businesses for 2012, published June 2013.

[20] A.R. Hileman, "Insulation co-ordination for Power Systems", 1999.

[21] A. Piantini, 'Lightning protection of overhead power distribution lines, Invited lecture at 29th international conference on Lightning protection, 2008.
[22] F.J. Jooste, W.J.D. van Schalkwyk and A.C. Britten, 'The influence of lightning on 11 & 22 kV lines with varying BIL' Proceedings of the 16th International Symposium on High Voltage Engineering, 2009.
[23] R.E Harness, 'Effectively retrofitting power lines to reduce raptor mortality', Rural Electric Power Conference, 2000.
[24] E-mail communication with Winston Davids, CT Lab (Pty) Ltd, 16 Sep 2011.
[25] IEC 60815-1, 'Selection and dimensioning of high voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles', Edition 1, 2008.
[26] SANS 60479-3, 'Effects of current on human beings and livestock – part 3: effects of currents flowing through the body of livestock', Edition 1, 1998.
[27] A. A. Beutel, M. D. Ntshani, K. V. Thejane, H. J. Geldenhuys, T. D. Mvayo, R. F. Watson, W. L. Vosloo, A. Khatri, 'Natural pollution test for investigating leakage current effects on medium voltage woodpole distribution line structures', Southern African University Power Engineering Conference (SAUPEC) 2015, paper SAU014
[28] J. Fernandez-Lopez, E. Sendra-Nadal, E. Sayas-Barbera, "Handbook of Poultry Science and Technology, Primary processing", John Wiley and Sons Inc, New Jersey, 2010.
[29] J. Wilkins, S.B Wotton, I.D Parkaman, P.J. Kettlewell, P. Griffiths, "Constant Current Stunning Effects on Bird Welfare and Carcass Quality", The Journal of Applied Poultry Research, pages 465-471, 1999.
[30] Eskom Drawing No. D-DT-3144.

# 9. APPENDIX A: CONFIGURATION OF STAY INSULATOR AND ELECTRICAL CHARACTERISTICS

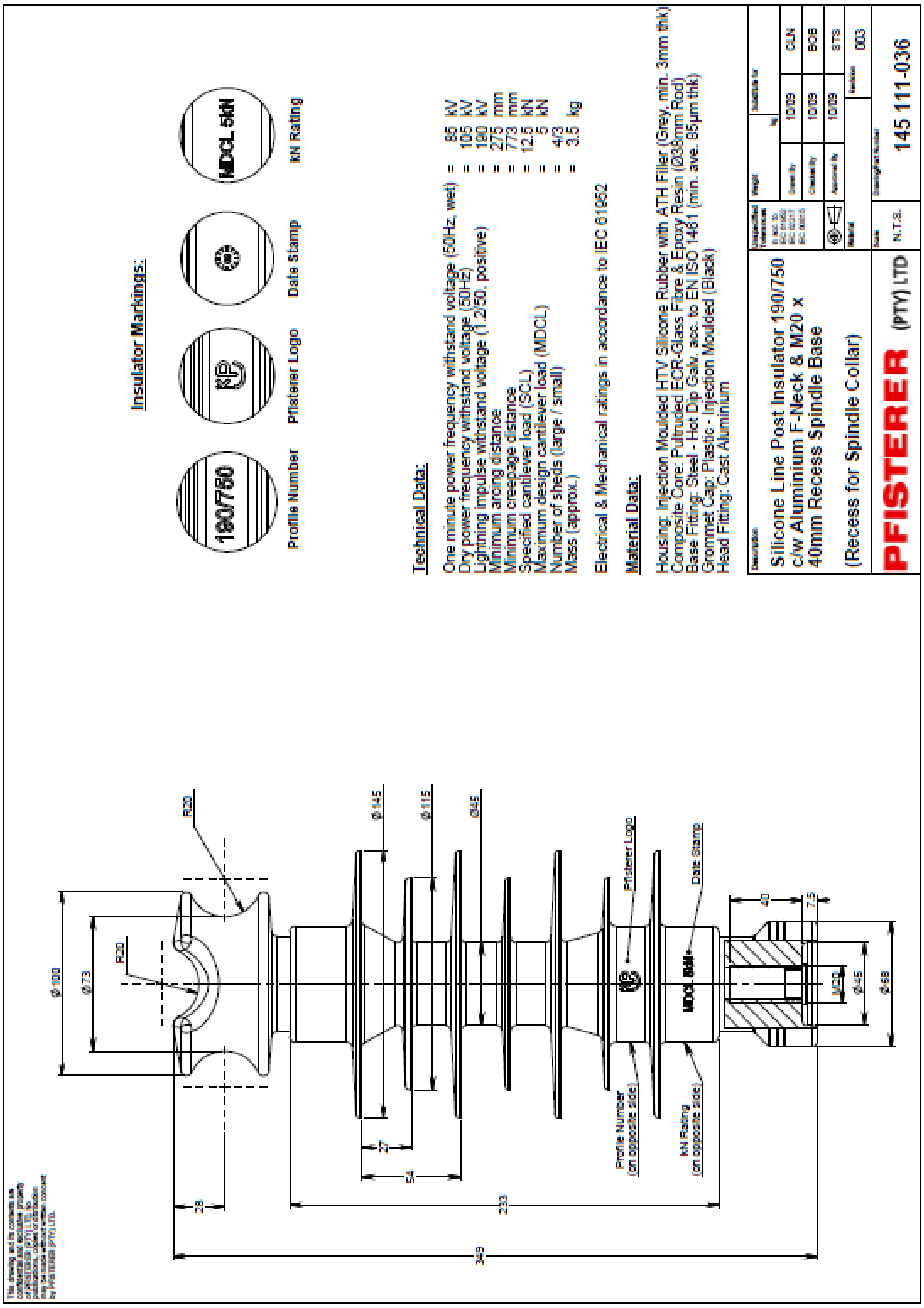



| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| **Stay insulator (Material type)** | **Dry withstand voltage<br>kV** | **Wet withstand voltage<br>kV** | **Creepage distance<br>mm** | **Breaking load of stay insulator<br>kN** |
| Porcelain<br>(for LV) | 25 | 11 | 60 | 34 |
| Porcelain<br>(for MV) | 38 | 22 | 76 | 96 |

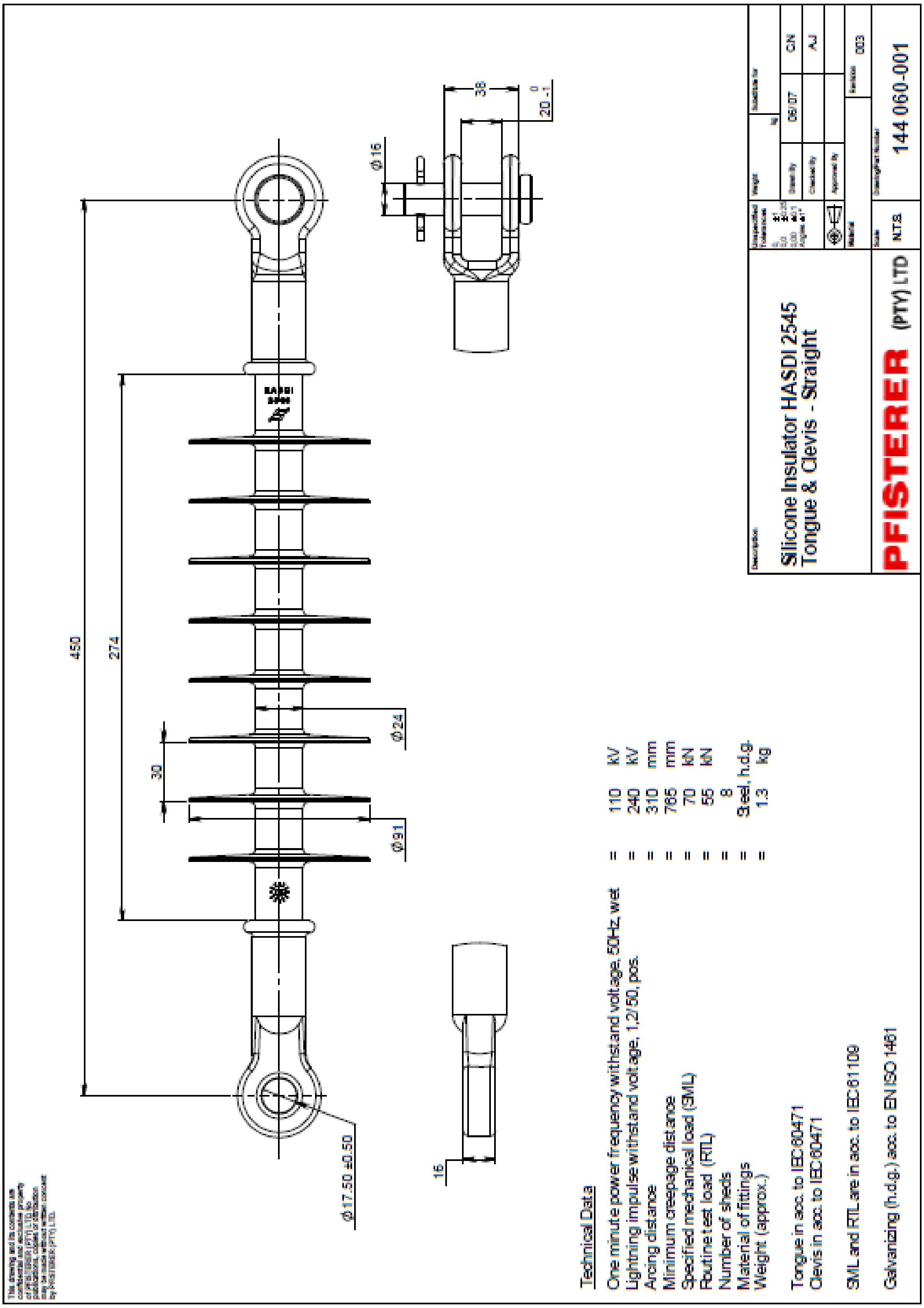
**Above information was taken off Eskom Standard – 34-1800, "Specifications for stay insulators porcelain or equivalent used for medium and low voltage overhead lines"**

# 10. APPENDIX B: SPECIFICATION OF INSULATORS USED DURING TESTING

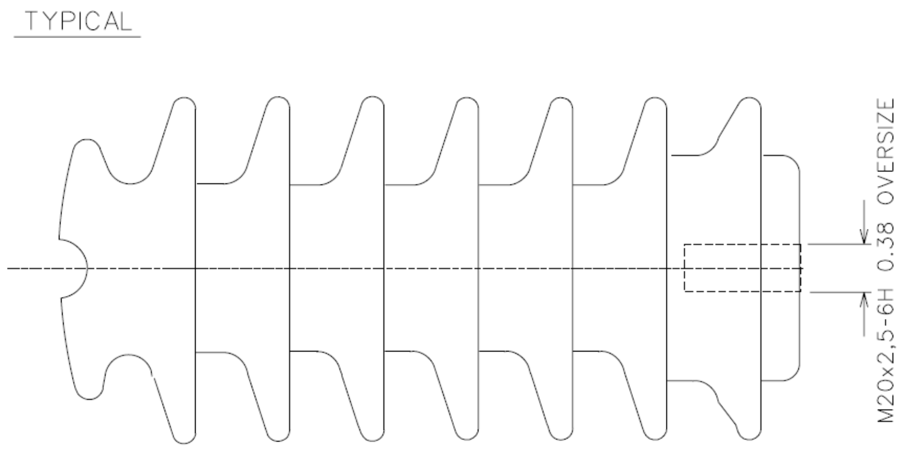
**B-1: Silicone rubber post insulators as phase insulators at KIPTS**



**B-2: Silicone rubber long rods used at KIPTS**



## B-2: Porcelain post insulators used at Corona Cage




NOTE :

- 4kN POST INSULATORS ARE TO BE USED ON ALL LINES UP TO OAK/HARE CONDUCTORS.
- 10kN POST INSULATORS TO BE USED WITH ALL CONDUCTORS AT ROAD CROSSINGS AND ON LINES WITH CONDUCTORS LARGER THAN OAK/HARE UP TO KINGBIRD CONDUCTOR.

| | | |
|---|---|---|
| ITEM | :- | INSUL,POST 33kV |
| MATERIAL SPECIFICATION | :- | PORCELAIN, CYCLO ALAPHATIC, COMPOSITE |
| FAILING LOAD (kN) | :- | 4kN AND 10kN MINIMUM |
| CREEPAGE DISTANCE (mm) | :- | 720mm (20mm/kV) & 1116mm (31mm/kV) |
| STANDARD SPECIFICATION | :- | F-NECK |
| ESKOM SPECIFICATION | :- | DSP_34-1677 |
| LAP MATERIAL GROUP | :- | LINE POST INSULATORS |
| TEST & CERTIFICATION REQUIREMENTS | :- | TESTS AS PER DSP_34-1677 |

| | | | | | |
|---|---|---|---|---|---|
| INSPECTION | Yes | No | ESKOM RELEASE NOTE | Yes | No |

IDENTIFICATION:- INDELIBLE MANUFACTURES TRADEMARK & PART No. ON ALL ITEMS

| REV | REVISION DESCRIPTION | BY | CHKD | AUTH | DATE | REF. DWGS |
|---|---|---|---|---|---|---|
| 9 | TOTAL CREEPAGE ADDED IN ADDITION TO SPECIFIC CREEPAGE DISTANCE & SPEC REFERENCE UPDATED | JJJ | J J JORDAAN | J J JORDAAN | 07.08.2009 | |
| 8 | SHORT DESCRIPTIONS CORRECTED | N.M. | D. RAMJASS | D. RAMJASS | 21.03.2009 | |
| 7 | ESKOM SPEC. CHANGED FROM SCSSCAB18 TO DISSCAB18 AND 0216691 CHANGED TO COMPOSITE | P.A.V. | G.STANFORD | G.STANFORD | 07.06.2006 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| AUTH: | P. CROWDY | DATE: | 06.10.1997 | SCALE NTS | Eskom Distribution | SAP No: | | |
| CHKD: | D. PILLAY | DATE: | 06.10.1997 | CAD REF: | | | | |
| | | | | SERIES 3000 | | SET | SHEET | REV |
| DRAWN: | P.A. VERMAAK | DATE: | 04.10.1997 | FILE No: 3189 | D-DT-3189 | 3 | 1 | 9 |

# 11. APPENDIX C: PROCEDURE FOR MEASUREMENT OF DOWNWIRE INSULATOR (OR BASIC INSULATION LEVEL - BIL) VOLTAGE AND DOWNWIRE CURRENT WAVEFORMS ON ENERGISED 11 kV (PHASE-TO-EARTH) WOODPOLE STRUCTURES FOR REASEARCH PURPOSES AT THE CORONA CAGE

Compiled: Mikhuva Ntshani and Keneilwe Thejane

Date: 02 January 2014

Accepted By: Nishanth Parus

## 1. INTRODUCTION

The objectives of the measurements are to:

1. Measure the magnitude and waveform of the current flowing on the downwire insulators and current flowing on the woodpole.
   - Deduce whether the downwire insulator can effectively divert leakage current from flowing along the surface or inside the interior of the wood.
2. Determine the relationship between the measured insulator voltage and downwire current.
   - Approximate impedance of the woodpole at the BIL gap and the downwire insulators using the measured waveforms.
   - Determine the approximate ratio of current flowing on the downwire insulator and current flowing along the downwire insulator.
3. Record visuals state of the test structure.

## 2. MEASUREMENT SET-UP AND METHODOLOGY

The measurement of current flowing down the woodpole, on the downwire insulator and the voltage waveforms will be measured simultaneously (if possible and if safe to do so). Alternatively, the test may be broken down into two parts, i.e. measurement of downwire insulator voltage (or BIL gap) and downwire current simultaneously; and simultaneous measurement of current flowing on the woodpole and across the downwire insulator (or bonding wire).

Fig 1 depicts the measurement set-up for the measurement of downwire insulator voltage (or BIL gap voltage), current flowing down the woodpole and current flowing along the downwire insulator.
A 1000: 1 Tektronix high voltage (HV) probe is used to measure the voltage between the point above the downwire insulator (or BIL gap) and earth similar to previous tests at KIPTS.

CSLW Series miniature wired open-loop current sensors with power supply circuit were chosen for measuring current flowing along the woodpole and across the downwire insulator. This sensor was chosen since it offers galvanic isolation (approximately 500 V), provides low sensitivity (40 mA), low cost and available at the time of testing. Although the galvanic isolation of the sensor is significantly low compared to other sensors (e.g. 6.6 kV for the sensor used at KIPTS), the isolation was considered to be adequate. This is because the sensor will be connected between the downwire insulator or BIL gap and earth. The isolation was considered adequate provided the sensor is used with reliable earthing system. Two of these sensors will be used to measure current flowing down the woodpole and on the downwire insulator simultaneously.

The output of the current sensor(s) and the HV probe are connected to the oscilloscope. The oscilloscope used is powered by a battery. It has a common earth point that ties the reference (outer) connections of the measurement channels to it. This scope's earth point is connected to the station earth and therefore all measurements are referenced to the same point.

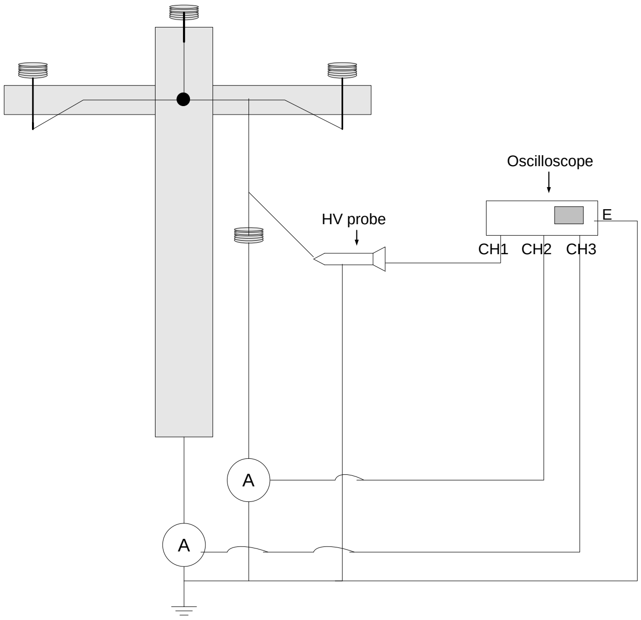



**Figure C-1: Downwire insulator voltage (or BIL gap voltage) and downwire current measurement method**

# 3. MEASUREMENT PROCEDURE

## 3.1 Before energisation

The following will be performed whilst the structures are un-energized:

- Before the project is started, a written risk assessment will be conducted. The risk assessment will identify all possible hazards and danger that may be encountered during the testing. Such hazards include the high voltage power, tripping hazards, etc. For subsequent days' work, a verbal assessment must be done prior to starting work, identifying any changes from the original assessment that may cause an impact on the work.
- The life saving rules will be observed.
  - o Ensure there is a permit to perform the work and that the workers register is signed and all potential risks are identified and recorded and appropriately mitigated against.
  - o Wear appropriated protective clothing including safety boots and appropriately rated rubber gloves.
  - o Check visually that the three phase supply socket plug is switched off and the three phase cable to the transformers is removed (isolated) from the socket plug.
- Visually confirm that the single earth point is in fact connected to the corona cage station earth (i.e. the central earth point is on the metallic transmission tower base at which point the station earth is connected).
- Visually confirm that all three high voltage phases of the independent three phase transformers are earthed to the central earth point.
  - o Use an earth stick to discharge the line and the structure.
  - o Test that the line and the transformers are dead using the voltage indicator probe.
- Test that the HV probes and channels of oscilloscope are working. This is accomplished by connecting the HV probe to the 220 V mains and measuring the voltage on all channels on the oscilloscope.

- If in working condition, the probe must be connected tightly to the bonding wire by using a line trap or similar.
- Test that the two current sensors are working. This is accomplished by using a 220 V supply and known resistors to give current in the mA range. The measurements should be recorded with an oscilloscope and confirmed with calculations using Ohms' law.
- If in working condition, the current sensors must be connected as in Fig 1 and in accordance with Appendix A. The bonding wire is connected between the Primary In and Primary out terminals, with the Primary out connected to earth side. The outputs of the sensors is connected between the Output terminal and ground.
    - Crocodile clipped probes or similar to be used for connections between the sensor and oscilloscope.
- Ensure that the oscilloscope is connected correctly.
- Ensure that all connections are making adequate contact; the earth connections are particularly important.
- Pollute the insulators (all phase insulators and, in some cases, also the downwire insulator) with brown sugar solution or kaolin until tacky and then spray with a salt solution. The brown sugar solution or kaolin solution may be applied using a brush.
- Inspect the set-up to ensure that all the connections are tight and in accordance with Fig 1.
- The oscilloscope must be setup to appropriately measure/record the currents and voltage including triggering levels.
- Ensure that appropriate barricades are in place and that safe clearances are understood by all present.
- Ensure that a fire extinguisher is on-hand near the test object.
- One person must be designated to supervise safety. This person should not directly be involved in conducting the testing.

## 3.2 Energisation

The following process will be followed when energizing the structure:

- Remove all the earths from the high voltage side of each single phase transformer.
- Connect the low voltage side of the transformers to the supply (i.e. connect the three phase cable plug to the mains and ensure that it is secured). Check that the breaker near the cage (behind the control room) has not tripped.
    - Switch the beaker on if it has tripped.
- Switch on the socket plug of the three phase supply cable.

Ensure that all the phases are energized by using a proximity sensor or similar and phasing stick. Please ensure that minimum safety clearances discussed in section 2.1.3 are maintained at all times.

## 3.3 After energisation, during testing

After energisation, the following will be performed:

- The scope must be at least 1 m away from the base of the test structure. It must also be at least 2 m away from the pole-top bonding (above BIL gap/down wire insulator) and at least 2 m away from all points that are energised at 11 kV., provided the scope, the voltage and current probes are connected to the earth point to create equipotential. If this is not possible, no operation of the oscilloscope will be allowed during energized conditions as during a fault situation, there is a possibility of currents flowing on the surface of the interconnected cable leads, thereby connecting dangerous voltages to the scope itself. No person shall encroach closer to the test setup than the clearances specified above for the oscilloscope.

- No person shall come into contact with the test structure or perform any connections to the structure or measurement system.
- The tests will be performed as follows:
  - Trigger the oscilloscope; stop and store results on the floppy disc.
  - Take several measurements (10 sets each).
- Perform visual state of test structures.
- A person shall be standing next to the 3-phase main supply switch at all times during tests. This is to ensure that if a problem such as an electrical fault or fire occurs, the person will be able to immediately open and isolate the mains power supply.

## 3.4 De-energisation

De-energisation will be performed at the end of each set of measurements and also when the insulators need to be polluted or wetted or any modifications or any other work needs to be performed on any part of the test setup, whether the test structure, measuring equipment or anything else. The following process will be adhered to:

- Switch off the 3-phase power supply (i.e. Open the power circuit)
- Remove the plug (i.e. isolate the test line)
- Test that the transformers and the line are dead, (i.e. there is no voltage on the line). This is done by first using a voltage proximity sensor and then a high voltage probe. If voltage is detected on the circuit then an earth stick must be used to discharge the line and the structure.
- Apply the three separate portable earths to the transformer high voltage output.

Re-test that the transformers and the line are dead, (i.e. there is no voltage on the line).

# 4. GENERAL SAFETY CONSIDERATIONS

- No persons shall be allowed to work at heights unless trained and certified to do so.
- No persons shall cross any barricade or enter into the corona cage live chamber area, unless authorised to do so.
- Work will only be done in clear fair weather conditions and not at night.
- At least three people will be required to perform the work (1 operating the mains supply and earthing, 1 conducting the tests measurements and 1 supervising safety during the tests).
- All injuries and near misses to be reported immediately to the Authorised person, or Responsible person or Transmission Solutions Manager.
- The high voltage proximity sensor and high voltage probe must be self-tested for correct operation prior to use.

Given that the test line is relatively short, inductive and electro-static charging thereof is not expected. However, if charge is measured on the line, then an equipotential zone must be created in addition to the earthing as described above. In this case all conductive parts must be bonded together. Additionally a worksite earth must be applied around the test object and bonded to the other conductive parts