

INVESTIGATION INTO THE
PERFORMANCE OF OUTDOOR
INSULATORS UNDER HIGH HUMIDITY
CONDITIONS

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I hereby declare that the work in this dissertation is my own and that it has
not previously been submitted as a Masters dissertation, or as an other
document, to this or any other University.

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Date: July 30, 2008

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr Derek Hoch for his support and guidance throughout my Masters research, his help was invaluable. Thank you for providing the means to perform the *Maxwell* simulations and the experimental work.

The University of Kwa-Zulu Natal needs to be acknowledged for allowing the use of the High Voltage Laboratory in which to perform my experimental work. Thanks go to Mr Bruce Burton for the loan of the refrigeration unit for the weather chamber tests. The technical staff must also be acknowledged for their help with the setting up of the weather chamber and provision of tools.

I would also like to thank The Department of Mechanical Engineering at the University of Kwa-Zulu Natal, in particular Mr Nirvan Sookay, for all his help with the heat analysis, and Mr Rob Bodger, for his sand blasting and boiling cylinder. Thanks also goes to the South African Weather Service for all the weather data they provided. Thanks to the Engineering administrative staff, in particular Marie Wayne and Fiona Higginson, for helping me with all the required paperwork.

Finally I would like to thank my family for their endless support during my masters research.

ABSTRACT

The performance of high voltage outdoor insulators can be greatly affected by weather conditions. The weather conditions under investigation are cold temperatures coupled with high humidity levels. Weather data from a number of coastal stations around South Africa was analyzed to determine whether surface condensation was likely on outdoor insulators under these weather conditions. A heat transfer equation was used to determine the response of the insulator surface temperature to the environmental temperature. It was found that surface condensation would occur on the insulator surfaces which would lead to sudden, heavy wetting of the surface. Outdoor insulators in coastal environments are often heavily polluted, due to salt spray, and when wet, a conductive layer can form on the insulator surface. This conductive layer can result in appreciable leakage currents flowing on the insulator surface, often leading to premature failure. The finite element method program, *Maxwell*, was used to simulate the outdoor insulators both under these polluted, wet conditions and under unpolluted conditions. Both cases were simulated for a silicone rubber, glass cap-and-pin and two EPDM outdoor insulators. The polluted insulators were simulated with varying pollution severities. The results of the simulations are analyzed and the surface resistances of the wet polluted insulators were calculated. An experiment was set up to mask the environmental weather conditions found which would lead to surface condensation. The insulators under test were placed in a chilled weather chamber which introduced a steam fog to simulate the humidity. The leakage current was measured and recorded for comparison with the simulation results. The results of the weather chamber test showed that surface condensation resulted in more severe wetting than manual wetting. The weather chamber surface resistances calculated were much lower than those calculated by the *Maxwell* simulations. This was due to the difference in humid particle temperature in the condensation rate equations used for the *Maxwell* simulations, and the humid particle temperature of the steam fog used in the weather chamber. Polluted coastal outdoor insulators exposed to the above weather conditions will experience larger than normal leakage currents which will lead to premature failure of the units.

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LIST OF SYMBOLS

| | |
|-----------------|---|
| ESDD | Equivalent salt deposit density |
| NSDD | non-soluble deposit density |
| h | Heat transfer coefficient |
| T | Temperature of the insulator |
| T_{sur} | Temperature of the surrounding environment |
| ϵ | Emissivity of the insulator |
| σ_b | Boltzmann's constant |
| A_s | Surface area of the insulator |
| ρ | Density of the insulator surface material |
| Vol_{ins} | Volume of the insulator |
| C_p | Specific heat of the insulator surface material |
| $\frac{dT}{dt}$ | Change in temperature with time |
| $Nu_{D,ave}$ | Nusselt Number |
| K | Thermal conductivity of the insulator |
| D | Diameter of the insulator |
| Re_D | Reynolds Number |
| Pr | Prandtl Number |
| V_∞ | Wind velocity |
| ν | Kinematic viscosity |
| α | Absorptivity of the insulator |
| x | Global radiation index |
| $\frac{dm}{dt}$ | Condensation rate |
| S_c | Condensing surface area |
| b | Mass transfer coefficient |

$p_{sat}(T_d)$ Saturation pressure at dew point temperature
 T_d Normal dew point temperature
 $p_c(T_c)$ Vapor pressure over the condensing surface
 T_c Temperature at which surface condensation takes place or the condensing surface
 H Humidity level
 T_a Ambient temperature
 $p_{sat}(T_c)$ Vapor pressure over the condensing surface at the temperature (T_c)
 (T_c) Condensation temperature
 g Correction factor for condensation equation
 p Atmospheric pressure
 C_a Specific heat of air
 a Correction factor for condensation equation
 k Correction factor for condensation equation
 f Empirical value for condensation equation
 D Apparent condensing surface area
 ε_c Emissivity of the condensing surface
 ε_s Emissivity of the sky
 ε_{so} Emissivity of the sky with no clouds present
 N Amount of cloud cover
 V Voltage
 J Current density
 σ Conductivity
 I Current
 A Cross-sectional area
 R Resistance
 L Length
 Vol Volume of deionized water
 S_a salinity
 A Surface area
 σ_{20} Conductivity at 20°C
 σ_t Conductivity at $t^\circ\text{C}$
 t Temperature

Chapter 1

INTRODUCTION

Past experience with outdoor insulators has shown that glass insulators perform poorly in coastal environments [1]. EPDM insulators do not fair much better in these environments as they lose their hydrophobicity quite quickly [1]. Research has shown that silicone rubber insulators perform better than glass and EPDM insulators in coastal sites due to their hydrophobic properties [1].

Certain environmental stresses can lead to the flashover of insulators. Insulators are particularly stressed in coastal environments due to excessive salt pollution [1]. This in combination with heavy wetting can also lead to failure. Insulators need to be subjected to these specific stresses to establish how they react under the given conditions.

The weather conditions which will be under investigation in this dissertation will be cold temperatures coupled with high humidity levels. It is thought that these conditions will result in surface condensation on the outdoor insulators. Surface condensation takes place when the insulator surface temperature is colder than the environmental temperature.

A mathematical equation was used to determine the response of the insulator surface temperature to the environmental conditions. Using this equation and weather data collected from coastal sites in South Africa, it was found that surface condensation would take place on insulator surfaces if the given weather conditions were to occur again, which is probable.

The amount of water that condenses onto the insulator surfaces as a result of surface condensation needs to be calculated so that the effect on the leakage currents can be determined. Practical experiments also need to be carried out so as to measure the effect of surface condensation on polluted insulator surfaces.

1.1 References

- [1] JT Burnham, DW Busch, JD Renowden. "*FPL's Christmas 1991 Transmission Outages*". IEEE Transactions on Power Delivery. Volume 8, Number 4. October 1993.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Outdoor insulators in coastal environments have been found to perform poorly [1]. This is particularly true for glass and EPDM type insulators [1]. This is due to the accumulation of a salt deposit on the insulator surface [1]. When these salt polluted insulators are wet, either by rain, mist or fog, intensive leakage currents may develop leading to dry band arcing which, if severe enough, can be followed by insulator flashover [2]. The specific weather conditions under investigation for this dissertation, which are cold temperatures along with high humidity levels, can lead to sudden severe wetting due to surface condensation. This is the main topic of investigation. The literature review gives more background to this topic.

The history of the development of outdoor insulators is presented, as well as the history of outdoor insulators in South Africa. A background is given to illustrate the need for a new test method to test the performance of outdoor insulators in a coastal environment under cold and humid weather conditions and the effect of a coastal environment on the insulators is shown.

A number of test methods currently in use are discussed. Hydrophobicity, and the recovery thereof, is investigated as it plays an important role in the performance of polymer insulators in polluted, wet environments. Some of the different types of discharge activities leading to degradation are covered as well as the effects of these discharges on the insulator surfaces. A new test method is then proposed which will simulate environmental stresses specific to the South African coastal environments.

2.2 History

The first glass pin type insulators appeared in 1858 and at the beginning of the 20th century suspension insulators came into being. By 1910 the cap-and-pin type insulators already had geometrical designs not dissimilar from those of today [3]. Glass and porcelain insulators still dominate the market today as they have an excellent service life of more than fifty years. However much research has been done in attempts to improve the contamination performance of insulators [3]. This was one of the reasons for the development of non-ceramic, or polymer, insulators.

The first non-ceramic insulators to be manufactured on a commercial bases were brought out in about 1964 and were composed of epoxy resin [4]. However these units failed after a short period of outdoor exposure. This initial design was followed by a composite insulator design having porcelain sheds supported by an epoxy resin coated fiberglass rod [4]. These non-ceramic insulators were mostly used on distribution lines in the 70's. However early installations failed due to inadequate sealing against the ingress of water into the interface between the glass fiber core and the covering sheath, resulting in acid attack on the core leading to brittle fracture [5]. After a few years the first generation of current polymer insulators were introduced by manufacturers in West Germany, the United States, France, England and Italy [4]. All these insulators were composed of a fiberglass core covered by polymer weathersheds.

However a number of problems arouse after a few years of operation in the field [4]. These problems were tracking and erosion of the shed material, chalking or crazing of the insulator surface, reduction of contamination flashover strength, deterioration of the mechanical strength, loosening of end fitting, bonding failures, breakdown along the rod-shed interface, and water penetration. As a result of these reported failures extensive research was conducted on the performance of polymer insulators under different electrical and environmental stresses [4].

An improved understanding of the failure mechanisms involved resulted in new, better performing insulator designs. An increase in quality control during production also resulted in more reliable insulators [4]. These improved units had better corona resistance, tracking free sheds and slip-free end fittings [4]. Polymer insulators are advantageous over traditional ceramic insulators as they are more light weight, resistant to vandalism, have a high strength to weight ratio, often better contamination performance and improved transmission line aesthetics [4].

These excellent qualities have lead to an increase in popularity of polymer insulators [6]. Experience with silicone rubber insulators is that flashovers are rare and failures are usually due to mechanical reasons like brittle fracture [5]. EPDM insulators, however, have been shown to perform more poorly than silicone rubber insulators under severely polluted conditions [1].

More research needs to be performed in order to determine the behavior of glass and polymer insulators under cold and humid conditions in coastal areas.

2.3 Previous Experience in Coastal Environments

In the Christmas of 1991 the Florida Power and Lighting Company, FPL, experienced a record number of contamination related outages [1]. After in-service investigations, which included reviews of weather data as well as results from accelerated aging tests on polymers, it was concluded that certain metrological conditions over the period of 21 to 29 December 1991, lead to transmission contamination outages[1]. A large number of the outages were attributed to specific insulator types and their reaction to the contamination events. Local pollutants in the Florida area included: salt, road dust, fly ash, construction dirt, and dust from cement plants, bird droppings and agricultural spray [1]. The transmission lines were situated near the coast, which is a source of sever salt pollution and abundant humidity.

The weather patterns prior to the outages are thought to be responsible for

the major part of the flashovers. There was very little rain in the beginning of the month of December and therefore the local contamination on the insulators accumulated as it could not be washed off as there was very little or no rain [1]. There were strong winds which deposited salt spray from the sea onto the insulator surfaces. These salt deposits occurred as far as 43 kilometers inland in some places [1].

A cold front then moved through Florida which brought cold weather accompanied by high humidity, which resulted in fog and surface dew formation. The heavily polluted insulators, wetted by humidity, fog and dew, then tended to flashover [1].

Many of the outages were attributed to contamination flashovers on EPDM polymer insulators and porcelain post and suspension insulators. Silicone rubber insulators had no contamination outages despite being in the heaviest salt contamination regions [1]. However the possibility of similar pollution flashovers on silicone rubber insulators should not be ruled out and should be investigated further. Particularly since silicone rubber is susceptible to surface erosion in severe coastal environments which often times has the effect of temporarily reducing the hydrophobicity of the insulator surface [7, 8]. It has also been shown that if a silicone rubber insulator is polluted suddenly, like from a salt storm, it will take a few hours for the hydrophobicity to recover. Should the silicone rubber insulator be wet before it has a chance to recover its hydrophobicity, flashover of the insulator will be more likely, as discussed in a later section. The cold front conditions mentioned above will be the conditions that will be used for the investigation into the performance of the outdoor insulators in cold and humid environments.

2.4 Insulators in South Africa

In South Africa the local power utility, Eskom, has found that the use of silicone rubber insulators has significantly improved the performance of transmission lines in highly polluted regions [9]. Previously glass cap-and-pin type insulators were in use in these areas which lead to a large number of contamination flashovers. Silicone rubber and other composite type insulators, like EPDM, are only really being used in areas of high pollution and vandalism [9].

Silicone rubber insulators have recently been used as the primary insulator in new installations in the Kwa-Zulu Natal province [9]. In Kwa-Zulu Natal the combination of marine pollution and industrial pollution, have lead to an unacceptable number of pollution flashovers in past years during late winter and early spring [9], this is a period of the year where the region experiences frequent cold fronts. The heavy pollution levels were exacerbated by local weather and atmospheric conditions. This was a problem which conventional glass cap-and-pin insulators are unable to withstand and the hydrophobic silicone rubber insulators are now being used to try and curb the problem [9].

In the Western Cape polymer insulators were first installed in 1978/79 [9]. Various 440kV lines in the Northern, Northwestern and Southern Cape have shown a great improvement in performance since the introduction of polymer insulators [9]. It was decided in 1990 to make a move towards progressively reinsulating the coastal 275 and 400kV lines with silicone rubber insulators with the aim to improve pollution performance with the aid of silicone rubber's

hydrophobic properties [9].

Very similar weather patterns are experienced in South Africa as to those which resulted in the large number of outages experienced in Florida in 1991. It could therefore be possible for South Africa to experience similar contamination related outages. It is important to be able to understand the processes which occur when heavily polluted insulators are exposed to sudden wetting due to these weather conditions. A thorough understanding will allow one to predict the insulators behavior and therefore prevent power outages.

2.5 Insulators in a Marine Environment

A marine environment is usually accompanied with a high relative humidity and salt pollution [10]. The salt from the sea is blown onto the insulator surfaces. Salt storms result in the rapid deposit of humid salt particles on the insulator surface, forming densely packed layers of salt on the surface [7]. A salt deposit density of more than $0.3\text{mg}/\text{cm}^2$ is classed as very heavy. Salt deposits due to marine pollution often exceed this limit [10]. It has been found that the salt deposit density depends on the wind velocity and duration, type of insulator, and whether or not it rains. Rain not only has a washing effect but can also prevent the salt from reaching the test site depending on the precipitation rate [11].

The high humidity levels may result in rapid wetting, where polluted insulators are then likely to flashover fairly readily [10]. It has been observed that intensive, long duration discharges occur in coastal or heavily contaminated areas; these too can result to rapid insulator failure [4].

Marine pollution results in a large number of flashover incidences on ceramic and EPDM insulators [9]. The hydrophobicity of the silicone rubber insulators makes the insulators more resistant to pollution flashovers.

2.6 Silicone Rubber and EPDM Insulators

Silicone rubber insulators are well known for their excellent performance in heavily polluted areas [9]. The hydrophobicity of the material is the major reason for its resistance to failures. EPDM insulators also display hydrophobic properties, but these tend to be lost quite quickly once the insulators are exposed to the environment [11].

Polymer insulators are good dielectrics, have a wide flexible temperature range and a mild resistance to UV radiation. They are resistant to thermal degradation and corona discharge. The most important attribute is their hydrophobicity and in the case of silicone rubber the migration of this hydrophobicity to aged or polluted layers [6].

2.6.1 Hydrophobicity

Hydrophobicity is not always fully effective as it can be diminished by weathering and surface electrical discharges or even temporarily lost [11, 12, 13]. When this occurs it results in a more easily wetted surface. The water on the surface may dissolve pollution particles and so become conductive, resulting in a change in electrical strength with a change in hydrophobicity [8]. Exposure to wetness

and contamination can also lead to a loss of hydrophobicity due to the reorientation of the methyl groups, but this can always be recovered in the case of silicone rubber [11, 14]. EPDM insulators get their hydrophobic properties from the silicone release agents used during their manufacturing process [15,16]. Once they are exposed to outdoor conditions they tend to lose their hydrophobicity fairly quickly and unlike silicone rubber insulators they are unable to recover their hydrophobicity.

Polymeric insulators, like silicone rubber and EPDM, are more prone to chemical changes which may adversely affect the performance of the insulators [11]. Polymers are weakly bonded on the molecular scale which gives them a low surface free energy value. This allows polymers to resist the formation of continuous water layers, thus making them hydrophobic [12]. The value of the surface free energy of the material indicates whether it is hydrophobic (low value) or hydrophilic (high value) [8]. Electrical discharges, which conduct pulses of current over the surface, can increase the value of the surface free energy, possibly due to photon action, thus reducing the surface hydrophobicity [8]. Insulators can be classed into different levels of hydrophobicity using the STRI hydrophobicity classification guide [17]. The hydrophobicity is divided into seven categories where 1 is completely hydrophobic and 7 is totally hydrophilic [6].

Silicone rubber has the ability to recover lost hydrophobicity if allowed to rest without subjecting it to electrical discharges [12]. It has been shown to exhibit a large improvement in electrical behavior after a rest period [12]. This recovery of hydrophobicity is due, in part, to the diffusion of low molecular weight, LMW, polymer chains from the bulk to the surface as well as the re-orientation of hydrophobic groups at the surface [11]. These LMW particles, which are transferred to some parts of the contamination layer, prevent a complete dissolution of the conductive pollution layer under wet conditions and can be seen as a reduction in the thickness of the contamination layer [12, 5].

Once the silicone rubber surface has been aged by electrical discharges the amount of polymer in the surface is depleted [5]. Here the electrical discharge breaks up the long polymer chains. The smallest chains then evaporate and the slightly longer chains diffuse to the surface. Therefore, after electrical degradation, there are quite a few of the slightly longer polymer chains (LMW) at the very surface (up to 10nm), their occurrence then reduces drastically due to the aging and then slowly builds up further into the bulk [5].

An increase in temperature increases the rate of the electrochemical process; however the same increase in temperature results in an increase in chain scission, hence resulting in the formation of new LMW components, giving rise to LMW renewal [5]. Long term electrical activity does not seem to destroy all the reserves of LMW particles [5].

When the electrical discharges cease, aging will stop and the recovery process can begin. If recovery is not complete aging will begin at more advanced stage in the next wet period [5]. When in a marine environment the insulator surfaces are occasionally coated with a dense layer of salt, this makes hydrophobicity transfer difficult. This is because the silicone fluid and LMW particles can not dissolve into the salt crystals on the surface, neither can they diffuse through them [7]. This further illustrates the need for investigations into the performance of silicone rubber insulators at the coast.

2.7 Glass Cap-and-Pin Insulators

Glass cap-and pin type insulators have been in use for many years. Over time experience has indicated that the flashover performance of glass insulators is poor in heavily polluted conditions [9]. This is mainly due to the glass's hydrophilic nature. It is easily wet and when the surface is severely polluted a continuous conduction layer is formed on the surface of the glass insulator, leading to high leakage currents and eventual flashover. For this reason glass insulators have to be washed periodically in order to improve service performance [9].

Glass insulators are not organic in nature and are therefore less prone to physical and chemical changes due to surface discharges, than polymer insulators [18]. This makes them more resistant to deterioration due to discharge activity. However they do experience other forms of damage through vandalism, cement growth, pin erosion and the corrosion of the metal flanges. This corrosion is especially prominent in coastal sites and can lead to flashover [1, 19, 20].

2.8 Tests and Contamination Methods

A range of different accelerated aging tests have been developed and consequently a range of different methods used to artificially contaminate the insulators under test have been introduced.

2.8.1 Current tests

One of the more common tests is the Salt-Fog test. The samples are mounted in the center of the test chamber and the fog is generated using *IEC 507* fog nozzles [2]. The fog flow rate most commonly used was approximately 1.6l/min. The water conductivities used tended to range from 300 to 2000 $\mu\text{S}/\text{m}$ [2]. The lower water conductivities are used to assess the leakage current suppression, while the higher conductivities are used to evaluate the tracking and erosion resistance of the insulators. The salt-fog chamber tests are usually run in cycles, with a period of applied wetting and voltage followed by a period of rest. Each cycle is several hours in duration. An electrical stress of approximately 50V/mm is most commonly used in these tests [2].

Another common test used to assess the behavior of insulators under contaminated conditions, is the clean fog or steam fog techniques. The steam or cold fog input rate recommended by *IEC 507* is 50m³/h [12]. The steam fog for the chamber is created by boiling water in basins. The cold fog is generated using *IEC 507* fog nozzles [6]. Voltage and wetting are applied simultaneously to the test object in the clean fog test, and is often cycled as mentioned above. A fog density of 13-15g/m³, is considered to be severe [13].

A multi-stress test has also been developed where different stresses, such as temperatures, UV radiation, contamination, rain and clear mist, can be applied in cycles [21]. UV radiation can be simulated using an array of fluorescent lights [22].

The dry-salt-layer (DSL) flashover test method has also been developed to test the insulators [23]. This test consists of separate pollution deposit and wetting phases. The test object is energized at a constant voltage during the pollution deposit phase; the voltage value is its maximum service voltage. The "progressive stress test" is used during the wetting phase [23]. During the

wetting phase steam fog is blown onto the test objects. Here the voltage is gradually stepped up until flashover occurs [23]. The duration of the steps is initially short. Over the expected range of the flashover the duration of each step is increased. After the predicted flashover range had been passed, the duration is shortened again to prevent pollution leaching [23].

A method that can be used to find the surface conductivity data is the insulator pollution monitoring apparatus (IPMA). For the IPMA test the insulator is placed in a closed controlled environment [24]. An air blower is then used to dry the insulator. The leakage current over the insulator is measured as a dry reference [24]. The wetting cycle then begins where a short pulse of steam is injected into the chamber and the voltage and leakage current are measured. This is repeated until an increase in the leakage current is recorded [24]. The surface conductivity can then be calculated using the current, voltage and a form factor [24].

The stepped tracking wheel test can also be used to evaluate the performance of insulators [2]. The wheel holds four samples and goes through four positions in the wheel cycle. In the first position the sample is dipped into a saline solution of a chosen conductivity. The second position allows excess solution to drip off the insulator. The third position is where the insulator is energized [2]. The last position allows the insulator to cool after possible dry band arcing. Each stage of the cycle has a very short duration of approximately 20 seconds [2].

As can be seen from the above test methods there is no official test used to evaluate the performance of outdoor high voltage insulators when exposed to both cold temperatures and high humidity levels. It is apparent that a new test method be introduced for this purpose. It is expected that the steam fog test will be the test setup that will be used to introduce the humid conditions for the purposes of this investigation.

2.8.2 Artificial Contamination Methods

The application of the contamination layer on composite insulators is difficult due to their hydrophobic properties. The traditional wet pollution application is difficult for EPDM and Silicone Rubber insulators due to the hydrophobicity of the materials [25]. Pre-treatment of the surface results in a fairly uniform contamination layer however this alters the original hydrophobicity of the insulator [25].

Insulators can be contaminated using a solid contaminant. The samples are precontaminated with a mixture made up of 240 mesh silicone dioxide, salt and paper pulp. The samples are dipped into a slurry of the above in order to contaminate them and then allowed to dry [2].

Another method of contamination is where minute water droplets are sprayed onto the surface of the insulator [20]. Powdered kaolin is then sprayed over the surface. After drying the kaolin is then washed off with tap water. The insulators are then immersed into the solution of kaolin with added salt, taken out and allowed to dry [20]. However this method, requiring drying time, does allow for hydrophobicity transfer to the contamination layer.

A dry pre-contamination system has been developed to offer a new method of contamination which does not require drying. It is based on a solid spray system. A mixture of kaolin and salt is deposited on the surface using a commercial

sand-blasting nozzle [25]. A disadvantage of this method is that the ESDD levels above $0.1\text{mg}/\text{cm}^2$ are difficult to achieve [25].

A new Dry-Mixing Contamination method has also been developed where two nozzles are used to introduce solid particles and atomized liquid into a turbulent flow of air [25]. The solid particles are mixed with the atomized salt solution in the jet of air and then carried by the jet of air onto the insulator surface. This method allows one to coat the surface of the insulator with a homogeneous layer of contamination without wetting the surface [25].

In the Dry-salt-layer method of contamination an artificial wind is used to blow humid salt particles onto the test object [23]. The humid salt particles were generated using a salt injection system comprising conventional Salt-Fog nozzles [23].

The insulators which will be under test in this investigation will be contaminated by dipping the insulators into a slurry, consisting of tap water, kaolin and salt, and then allowed to dry. Certain methods will have to be employed to aid with the wetting of the hydrophobic polymer insulators.

The contamination severity of an insulator surface is defined in terms of the equivalent salt deposit density, ESDD, and the non-soluble deposit density, NSDD [12]. The NSDD and the ESDD can be calculated by calculating the conductivity of the solution and the weight of the non-soluble solution that resulted from the washing of the insulators with distilled water [6]. ESDD is expressed as milligrams of salt per unit surface area, (cm^2), and NSDD is milligrams of non-soluble deposit per unit surface area [12].

2.8.3 Short Comings of Tests

Although the tests have all been run many times and are recognized testing procedures they do not represent all environmental stresses to which the insulators could be exposed. A new test method is required to allow the outdoor insulators to be tested under extreme environmental stresses, similar to those experienced in Florida in 1991 which lead to a series of contamination flashovers [1]. These stresses consist of extreme pollution, humidity and cold temperatures.

2.9 The Aging Process of Polymers

The two important factors that determine the long term performance of outdoor polymeric insulators are the ability to minimize the leakage current, and the resistance to tracking and erosion [2]. Tracking and erosion usually occurs when the material has, either temporarily or permanently, lost its ability to minimize leakage current.

The effect of UV radiation must also be considered as it too affects the performance of polymer insulators. Polymers have side groups and crosslinks that contain organic bonds which are susceptible to UV attack [26]. UV radiation can also initiate an automatic oxidation reaction, leading to the deterioration of the surface material [14, 7]. When silicone rubber is exposed to UV radiation it displays more hydrophobicity than when it is shielded from UV radiation [26, 11, 7]. This could be because the UV radiation is increasing the rate of LMW diffusion to the pollution layer or surface [26]. EPDM insulators on the other hand show a decrease in hydrophobicity after exposure to UV radiation. This is

due to the breakage of certain C-H and C-C bonds within the EPDM material by the UV radiation [18].

2.9.1 The Effect of Water on the Insulator Surface

Water droplets act as a field enhancing factor and distort the field often leading to corona [5]. A water droplet distorts in the direction of the electric field. Usually an electric field of 400-600V/mm gives rise to corona on water drops [5]. It has been advised that corona grading rings be used on transmission lines in the coastal areas so as to reduce aging due to corona [9].

Water, being a good conductor, has the ability to short out parts of the insulator eventually leading to flashover [8]. The nature of the breakdown can depend on the conductivity of the water droplet. If the droplet has a low conductivity, breakdown will occur across the water surface, however if the water has a high conductivity breakdown will occur through the water droplet [8].

If the surface of the insulator is hydrophilic, either due to discharge activity or due to the insulator being hydrophilic in nature, like glass; the droplet will spread out over the affected area, forming water ribbons. A water drop on the surface can reduce the flashover voltage by up to 30% [8]. If the insulator surface is fully hydrophobic, flashover is induced by a gross distortion of the water droplets such that it covers more of the surface and its stress enhancing factor is increased by about 60% [8].

2.9.2 Discharge Activity

Virgin polymer insulators are strongly hydrophobic and the only currents which flow through the insulator are capacitive currents and the insulator performance is very good [5]. However as time goes by pollution collects on the surface. There is then an increase in surface roughness due to embedded pollution and UV exposure [5]. Localized corona can also increase surface roughness and so aid the build up of a pollution layer [5].

The presence of rain, dew, fog and high humidity can lead to the formation of water droplets on the polymer surfaces leading to discharge activity on the surface, resulting in a loss of hydrophobicity in polymers [5]. The water droplets on the surface also react with the polymer material and leads to a reorientation of the methyl groups leading to further temporary loss of hydrophobicity [5].

With polymer insulators the regions where the hydrophobicity is diminished the surface wets easily, dissolving some of the pollution and forming a conductive layer [5]. This process happens readily on glass insulators as they are naturally hydrophilic. Water drop ribbons can then form, allowing currents to flow more easily and thus there is an increase in the leakage current [5].

When the water droplets on the insulator dry aging will stop, and the surface will be able to start recovering in the case of silicone rubber insulators. If the recovery process is not complete, aging will begin at a more advanced level in the next cycle of electrical discharges [5].

When wetting of an energized insulator occurs a leakage current flows over the surface to ground. Due to joule heating the conducting layer dries out in certain places limiting the flow of leakage current [27]. As a result large voltages develop across the dry bands resulting in sparking across the bands (dry bad

arcing), accompanied by higher leakage current pulses. This activity leads to material degradation [27].

Dry band activity before flashover is characterized by bright, energetic discharges. These discharges grow in size when in fog conditions [12]. During heavy arcing the dry bands could span about 60% of the total leakage distance of the insulator [12]. It is only the small unbridged sections on the insulator that prevent flashover from occurring.

Discharge activity tends to increase in the presence of wind and rain. A light pollution layer also results in stress intensification at the shed tips [27]. The polymer material, being organic, in the dry band area changes due to electrical leakage current and discharge activity [24].

2.9.3 Deterioration due to Aging

The major cause of electrical failure is deterioration which includes erosion, corona cutting, chalking and crazing of the surface [4]. UV radiation and chemical changes on the polymer insulator surface can result in discolouring, chalking and crazing after a few years of exposure [4]. These phenomena increase the intensity of surface discharges and hence shorten insulator life. Continuous discharges lead to local hot spots which can lead to burns or chemical changes which result in erosion [4]. Glass insulators are not organic and therefore do not experience the same level of chemical and physical aging as polymer insulators [18]. However they still suffer from forms of erosion and tracking.

Some definitions of observed types of deterioration or damage are shown below [27].

Discolouration is a change in the base colour of the housing material of the composite insulator.

Chalking is the appearance of some filler particles of the housing material, forming a rough or powdery surface.

Crazing comprises of surface micro fractures of depths approximately 0.01 to 0.1mm.

Dry Bands are the signs left on the insulator material surface after dry band activity has taken place.

Tracking is the irreversible degradation by the formation of conductive paths on the surface of an insulator surface. These paths are conductive even under dry conditions.

Erosion is the irreversible and non-conducting degradation of the surface of the insulating material by means of loss of material [23].

Aging of insulators is an important aspect to observe because as the age of the insulator increases so does the leakage current, surface charge and wattloss [21]. It has been shown that surface roughness and porosity also increase with ageing [21]. With continued aging the insulators will finally fail due to erosion and tracking on the surface [3].

2.10 Proposed New test Method

A new test method is proposed in order to investigate the performance of outdoor insulators under specific environmental stresses. The environmental stresses encountered on the Florida coast in 1991 will be simulated for the purposes of the tests. These conditions were the cooling of severely polluted insulators followed by rapid wetting due to extreme humidity [1]. The environmental stresses encountered in Florida during 1991 are very similar to those encountered on the South African coasts and therefore the behavior of outdoor insulators in these regions needs to be investigated.

These specific environmental stresses have lead to the sudden failures of transmission line networks [1]. The majority of the failures were on ceramic or EPDM insulators [1], it is therefore of great importance to fully investigate how outdoor insulators behave under these extreme conditions.

The leakage current on the insulators under these conditions needs to be observed. Often the leakage current is a good indication of when the insulator is likely to flashover. Leakage currents in the range of 1-5A often lead to complete flashover [16]. During this investigation the leakage current is not expected to exceed 150mA.

The proposed new test method requires a cooling chamber to simulate the cooling of the insulators when they are exposed to cold front conditions. Steam is also required in order to simulate the high humidity which the insulators experience due to their proximity to the coast. The steam will be generated by boilers.

From weather data collected it has been observed that there is a possibility of having a combination of both cold temperatures and high humidity levels. For example in the Cape Town weather station in 2005, minimum temperatures of approximately 7 °C were recorded in conjunction with humidity of 97% [27]. Similar conditions occurred at Langebaan and Lambertsbaai stations. Only the weather data for a few stations could be obtained but it showed after brief analysis that the occurrence of these specific conditions indicates that it is a common occurrence and so lends itself to the possibility of contamination flashover due to sudden wetting of the insulator surface [28]. A more thorough investigation into the South African coastal weather conditions is presented in section 5.6 on page 38.

For the new test method proposed it is suggested that the cooling, or weather, chamber be cooled to temperatures ranging between 5 °C and 20 °C, and the humidity then raised above 85%. These conditions will simulate those experienced at the above mentioned stations in order to determine the electrical performance of outdoor insulators in these areas. It is expected that these cold temperatures coupled with the high humidity levels will lead to surface condensation, as discussed in further detail in chapters 3, 4 and 5.

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Chapter 3

HEAT ANALYSIS

3.1 Introduction

In order for one to determine whether heavy condensation will occur on the surface of the insulator, it is necessary to determine the behavior of the insulator surface temperature in response to the environmental conditions in which it is placed. If the surface temperature is cooler than the environmental temperature it will result in the cooling of the air in close proximity to the cooler surface. If the air in this region is cooled below dew point temperature condensation will occur on the surface of the insulator [1]. This process is called surface condensation and could possibly result in rapid wetting of the insulator surface and therefore increase the possibility of flashover of the insulator [2].

The surface temperature of the insulator can be affected by conductive heat transfer from the surrounding air and by radiative heat transfer from the sun. Both these methods of heating, or cooling, will be investigated. An equation was found in order to model the surface temperature changes experienced by a polymer insulator when exposed to the environment. The response of a glass or ceramic insulator's surface to the environmental conditions was not investigated. This is because glass has a much higher thermal conductivity than the EPDM and silicone rubber materials [3]. This means that it will be able to conduct heat easily, it will therefore heat up more easily than the EPDM and silicone rubber insulators. Investigating the polymer insulators will lead to a worst case investigation as their response to heat is more delayed, possibly leading to a greater difference in environmental and insulator surface temperature. The glass insulator has a higher surface area to weight ratio, thus leading to higher condensation rate [4]. However they will not be modeled in the heat analysis due to time constraints. The effect of the higher surface area to weight ratio of the glass insulators will be analyzed at the end of the dissertation.

3.2 Heat Analysis

Since only the surface temperature of the insulator is required the equation below could be used [3].

$$-\left(h(T - T_{sur}) + \epsilon\sigma_b(T^4 - T_{sur}^4)\right)A_s = \rho V ol_{ins} C_p \frac{dT}{dt} \quad (1)$$

Where:

h , is the convective heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)

T , is the temperature of the insulator, in Kelvin (K)

T_{sur} , is the temperature of the surrounding environment (K).

ϵ , is the emissivity of the insulator.

σ_b , is Boltzmann's constant, $5.699 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$

A_s , is the surface area of the insulator (m^2)

ρ , is the density of the insulator surface material (kg/m^3)

Vol_{ins} , is the volume of the insulator (m^3)

C_p , is the specific heat of the insulator surface material ($kJ/kg \cdot K$)

$\frac{dT}{dt}$, is the change in temperature with time

Equation (1) describes the energy balance on the outdoor insulator. The first term on the left hand side represents the energy lost or gained due to convection, while the second term represents the energy lost or gained via radiation [5]. The term on the right hand side of the equation represents the overall energy of the system [5]. Each term on the left hand side of the equation will be discussed separately in the following sections.

3.2.1 Convection

Heat can be transferred to or from an object by convection. The amount of energy transferred to the object via convection can be calculated from the equation below [5].

$$h(T - T_{sur}) \quad (2)$$

In equation (2), h is the convection heat transfer coefficient and is dependent on the material and geometry of the object in question as well as the nature of the environment in which the object exists [6]. The temperature of the object is represented by T and the temperature of the environment is T_{sur} , both expressed in Kelvin. The value of the convection heat transfer coefficient can be calculated using the equation below [6].

$$h = Nu_{D,ave} \frac{K}{D} \quad (3)$$

Where:

$Nu_{D,ave}$, is the Nusselt Number

K , is the thermal conductivity of the insulator ($W/m \cdot K$)

D , is the diameter of the insulator (m)

For the analysis a cylindrical shape was chosen to approximate the geometry of the insulator. The calculation of the Nusselt number is more complicated and can be performed using a number of different approaches [6]. For the purpose of this paper the following equation was used to calculate the Nusselt Number [6, 7].

$$Nu_{D,ave} = 0.3 + \left(\frac{(0.62 \cdot Re_D^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}}) \left(1 + \left(\frac{Re_D}{282000} \right)^{\frac{5}{8}} \right)^{\frac{4}{5}}}{\left(1 + \left(\frac{0.4}{Pr} \right)^{\frac{2}{3}} \right)^{\frac{1}{4}}} \right) \quad (4)$$

Where Re_D and Pr are the Reynolds Number and the Prandtl Number respectively. For the analysis, the value of the Prandtl Number was set to be 0.713, as was used in a similar example in [6]. The value of the Reynolds Number can be calculated using the following equation [6].

$$Re_D = \frac{V_{\infty} \cdot D}{\nu} \quad (5)$$

Where:

V_{∞} , is the velocity of the wind flowing around the insulator (m/s)

D , is the diameter of the insulator (m)

ν , is the kinematic viscosity, which is $13.93 \times 10^{-6} m^2/s$ for air [2].

From equations (2), (3), (4) and (5) one can calculate the term representing the convection associated with the insulator in the environment. Since the insulator is in a dynamic environment the magnitude and direction of the convection will change with the environmental conditions, namely the temperature and wind velocity. The change in the wind velocity will effect the value of h .

Weather data was obtained from the South African Weather Service. The data was in the form of hourly temperature, humidity, wind speed and wind direction readings over a number of years. The amount of data obtained differed from weather station to weather station. The hourly temperatures and wind speeds were used to calculate the convection term in equation (1). This term along with that found for the radiation was used to find the change in temperature of the insulator surface with time.

3.2.2 Radiation

The term describing the energy change due to radiation is shown below [5].

$$\epsilon \cdot \sigma_b (T^4 - T_{sur}^4) \quad (6)$$

ϵ , is the emissivity of the insulator.

σ_b , is Boltzmann's constant, $5.699 \times 10^{-8} W/m^2 K^4$

T , is the temperature of the insulator (K)

T_{sur} , is the temperature of the surroundings, or radiating object (K)

It should be noted that the emissivity, or ϵ , is for when the insulator is radiating heat out. When the insulator absorbs radiation the emissivity is replaced by the absorptivity, its symbol being an α [6, 7]. The absorptivity is a measure of the amount of solar radiation which is absorbed by the insulator surface [6]. Equation (6) can be expressed as as equation (7), below, for cases where it is absorbing radiation. Equation (6) is to be used in cases there the insulator is radiating heat out. Where x is the global radiation index of the sun for that specific area [5].

$$\epsilon \cdot x \quad (7)$$

The values for x were obtained from the South African Weather Service. They were the global radiation values per hour over a certain area. The radiation data was given for the Cape Town area. No further radiation data was available. The required data was therefore approximated for the other regions using the data from Cape Town as a guide to make the global radiation data estimates. The results of this equation were used to calculate the amount of heat absorbed by the insulator surface due to radiation during the day time hours. The insulator surface will also radiate heat out to the surroundings provided the insulator surface is warmer that the environmental temperature. The value of this radiative heat loss was calculated using equation (6) [5].

3.3 References

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Chapter 4

WEATHER CONDITIONS

4.1 Introduction

Certain weather conditions can play a significant role in the performance of outdoor high voltage insulators [1]. It is speculated that the process of surface condensation may lead to rapid wetting of the insulator surface. The surface temperature of the insulator had to be found so that it could be determined whether surface condensation would occur. The amount of water which will be deposited on the surface as a result of the condensation also had to be determined. This chapter contains main two equations. The first equation was developed in the previous chapter, so that the surface temperature of the insulator could be calculated. The second equation presented is used to determine the amount of water which was deposited on the surface of the insulator as a result of surface condensation.

The results of the equations will be used to indicate whether surface condensation will take place under specific weather conditions. If surface condensation does occur on the insulator surface the second equation will be used to determine the amount of water deposited on the insulator surface. The amount of water deposited on the surface will affect the surface resistance and hence the surface leakage currents on the insulator. The magnitude of the leakage current will effect the performance of the outdoor insulators; where larger currents will lead to more discharge activity and hence more likely flashover [1].

A large amount of weather data had to be analyzed to determine whether surface condensation events are likely given certain weather conditions. Due to the large amount of data which needed to be analyzed a *MatLab* program was written so that the data could be analyzed efficiently. Once the surface temperature had been calculated it is then compared with other weather data to determine whether surface condensation was likely, this was partially done by the *MatLab* program. The rest of the analysis was done manually.

4.2 The Heat Transfer Equation

The following equation was used to calculate the surface temperature of the high voltage insulator under investigation as outlined in Chapter 3 section 3.2 page 15. Equation (1) takes into account heat transfer through convection as well as heat transfer through radiation. The first term on the left is the heat transfer through convection while the term second from the left is the heat transfer

through radiation [2]. The equation calculated the change in temperature over time.

$$-\left(h(T - T_{sur}) + \epsilon\sigma_b(T^4 - T_{sur}^4)\right)A_s = \rho V C_p \frac{dT}{dt} \quad (1)$$

The above equation is quite complex and has a number of values which changed with time. The data which needed to be analyzed was extensive and consisted of hourly, temperature, humidity, wind velocity and radiation readings, often over three to four year periods. It was decided that a program would be written to perform the intensive calculations.

There are many other factors which would affect the surface temperature response to the environment, like the presence of the end fittings, the fibre glass core, electrical energization, the angle of the suns rays, to mention a few. However it was felt that these factors would not be dominant and were therefore neglected.

4.3 The Data to be Analyzed

In order to determine whether the weather data received would lead to conditions which would result in surface condensation the data had to be thoroughly analyzed. The different parameters which would affect the surface temperature most significantly were the surrounding air temperature, the wind velocity and the amount of global solar radiation. All three of these parameters were in the form of hourly readings over a period of a few years depending on the weather station under analysis. Some data was not available. Worst case data was used for the cases of missing radiation data. Periods of missing wind velocity data were not included in the analysis. Missing humidity data was set to 50% and missing temperatures were set to 22 °C.

Certain restrictions were put in place in order to reduce the amount of calculations required. Only periods where the humidity was above 85% and the insulator surface temperature was below 17 °C were considered for further analysis. It was found that the insulator surface temperature followed the environmental temperature quite closely in the case of the polymer insulators. A high humidity value indicates that the environmental temperature is close to dew point temperature [3]. A high humidity value was therefore required for surface condensation to occur, thus leading to the high humidity value used in the above restrictions.

4.4 The *MatLab* Program

Due to the large amount of data that needed to be analyzed a *MatLab* program was written to perform the calculations to find the insulator surface temperatures and to compare the results to the environmental temperatures. Equation (1) was used to determine the change in insulator surface temperature, it is an ordinary differential equation. The *ode45* solver in *MatLab* was used to evaluate the equation. The term *ode* stands for ordinary differential equation. This required that a separate function handle be constructed in order to set up the differential equation which needed to be solved. The solver was placed in the main part of the program and the function handle was made to be a separate

function which was called by the main function via the solver. The *MatLab* program which was written to load the data and perform the calculations can be found in Appendix A.

4.4.1 Loading the Data

All of the weather data was in *Excel* spreadsheets. This data had to be imported into *MatLab* so that it could be used. The main function of the program was responsible for loading the data from the specified location so that it could be used later in the program. The data which was loaded was the environmental temperature, humidity, wind speed and the global radiation. These values were either stored in a vector or a matrix depending on the data structure.

4.4.2 Calculation

When the *MatLab* program was run all the constants needed to be initialized. These included setting the dimensions of the insulator, with regards to volume and surface area, specific heat, thermal conductivity, density, Boltzmann's constant, emissivity, absorptivity and other constants required to calculate the h value as specified in Chapter 3. All these parameters were set in the function handle.

The *ode45* solver required certain input arguments. These were; the name of the function handle to be used, the time period over which to integrate and the initial conditions. The time period for integration was set to be one hour, as the weather data was hourly. The initial condition was set to be the temperature at which the insulator is initially before any heating or cooling. This was set to be room temperature, or 22 °C, for the first loop. It was then set to be the insulator temperature as was calculated in the previous loop for all further calculations.

A loop was set up so that the *MatLab* program would run through a year's worth of data calculating the insulator surface temperature for each hour as it ran. The program was made to use the wind velocity, humidity and radiation data which corresponded to the date and time of the current temperature calculation. The results of the calculations were stored in a vector, where the vector positions corresponded to the positions of the input data from the *Excel* spreadsheets. This was done so that comparison and further analysis would be easier. The environmental temperatures and the insulator surface temperatures were also plotted for ease of analysis.

4.4.3 Radiation

Further calculations were required for the radiative heat transfer term in equation (1). These further calculations were also performed in the function handle. The global radiation index for a particular date and time had to be analyzed. The data which was given was not presented in the correct units, so the program had to convert the data values so that they were in the correct units, which was Watts per square meter, W/m^2 .

The program also checked that there was a radiation value at that point. If it happened to be night time at that particular point in the data, the program would then calculate the radiative loss to the environment. If heat was lost through radiation this value was then multiplied by the emissivity, which is a

measure of a materials ability to emit radiation. Conversely if heat was gained through radiation the radiation value was multiplied by the absorptivity, which is a measure of a materials ability to absorb radiation. Appropriate emissivity and absorptivity values had to be used for the calculations.

Values for emissivity and absorptivity are usually found using lookup tables. The look up tables which were available did not always have the exact materials required. Since the polymeric insulator surface is composed of silicone rubber or EPDM it was decided to choose the values according to materials which best matched these materials. Values for hard rubber and grey silicone paint were available [4, 5]. The values of the emissivities and absorptivities were shown to be approximately 0.9 and 0.53 respectively. This was the same in both references for the hard rubber and the grey silicone paint [4, 5]. These were the values chosen to be used for the heat analysis. It was thought that these materials most closely represented silicone rubber due to the fact that it is a type of silicone based rubber, which is usually grey in colour. More specifically the silicone rubber insulators which will be under test are light grey in colour. The same values were used for the EPDM as the materials are quite similar.

Cloud cover would also affect the radiation index values. However cloud cover data was not available so it was decided to ignore the affects of cloud cover. An analysis on the error which would result from this is presented in later section of this chapter.

A certain amount of radiation data was missing. The required radiation data was made up from previous years worst case radiation data, this was the highest daily radiation levels set to span over each month of missing data. This would lead to worst case conditions as a higher radiation level would lead to a greater amount of radiative heating thus resulting in warmer insulator surface temperatures. Hence reducing the chances of the insulator surface temperature being cooler than the environmental temperature, making surface condensation unlikely.

4.4.4 Comparison of Results

Once the insulator surface temperatures have been calculated they are stored in a vector. They are then compared to the corresponding environmental temperature and the humidity. This was done in the main function. The function compares the values of the insulator surface temperature and the environmental temperature to see whether the surface temperature is one degree or more cooler than the environmental temperature. It also checks that the humidity level is above 85%, a humidity level lower than this is not likely to lead to surface condensation. If both of the above cases are true the program stores the position of the occurrence in a vector. This is done so that when the time came for further analysis it would be easier to find the event in the *Excel* spreadsheets.

4.5 The Process of Analysis

Once all the results have been stored the data could then be more thoroughly analyzed. The vector of positions of lower insulator surface temperatures was then sorted through manually. All data points which were during periods of missing wind velocity data were disregarded. The other data points were recorded

and the environmental temperature, insulator surface temperature and humidity level were recorded. A psychrometric chart was used to determine whether surface condensation was likely on the insulator surface. Once this data was analyzed it was then used to determine the amount of condensation which would result on the insulator surface.

4.6 The Condensation Rate

It is important to know the amount of water which will be deposited on the surface of the insulator as a result of surface condensation. The thickness of the water layer will affect the effective resistance of the wetted polluted insulator. This is because the cross sectional surface area, or thickness, of the pollution layer is inversely proportional to the resistance of the pollution layer [6]. This means that the thicker the water layer on the insulator surface, the lower the resistance will be and hence the higher the leakage current. This will lead to increased discharge activity [1].

A number of aspects effect the amount of water which will condense onto the surface of the insulator [7]. These include humidity levels, radiation levels, temperature, wind speed and the duration of wetting. An equation was developed in [8] which allows for an estimation of the condensation rate. Equation (8) is used to calculate the condensation rate under the surface condensation conditions. The condensation rate has the units mm/h .

$$\frac{dm}{dt} = S_c \cdot b \left(p_{sat}(T_d) - p_c(T_c) \right) \quad (8)$$

Where:

$\frac{dm}{dt}$, is the condensation rate in mm/h

S_c , is the condensing surface in m^2

b , is the mass transfer coefficient

$p_{sat}(T_d)$, is the saturation pressure at dew point temperature

T_d , is the normal dew point temperature in $^{\circ}C$

$p_c(T_c)$, is the vapor pressure over the condensing surface

T_c , is the temperature at which surface condensation takes place in $^{\circ}C$

Now $p_{sat}(T_d)$ is the vapor pressure at dew point temperature. This can be found using equation (9) below [8]:

$$H \cdot p_{sat}(T_a) = p_{sat}(T_d) \quad (9)$$

Here H is the humidity level and T_a is the ambient temperature. $p_{sat}(T_c)$ is the vapor pressure over the condensing surface at the temperature (T_c) at which condensation occurs. The values for $p_{sat}(T_c)$ and $p_c(T_c)$ differ slightly as the values depend on the degree of wettability of the surface by water [8]. It can be assumed that condensation begins when $T = T_d - T_0$, or in other words

when $p_c(T_c) = p_{sat}(T_c + T_0)$. Here T_0 was taken to equal -0.35°C [8]. The value of b can be found using equation (10) below [8].

$$b = 0.656 \cdot g \cdot a / (p \cdot C_a) \quad (10)$$

The g is a correction factor which accounts for air flow conditions around the condenser [8]. Here the p represents atmospheric pressure and C_a is the specific heat of air which is $1005\text{Jkg}^{-1}\text{K}^{-1}$ [5]. The air pressure values used corresponded to the data points which were used in the surface temperature calculations. Equation (11), below, was used to find the value of a .

$$a = k \cdot f(V/D)^{\frac{1}{2}} \quad (11)$$

Here k is another correction factor. It allows for the correction between the wind speed measured at the height of the measurement device and the height at which the condensation was occurring [8]. The wind speeds given in the weather data were measured at a height of six meters, however in all cases surface condensation only occurred when very little to no wind was present, the value for k could therefore be made to be unity. The value for f was found empirically in [8] and is equal to $4\text{WK}^{-1}\text{m}^{-2}\text{s}^{\frac{1}{2}}$. The value of D , the apparent condensing surface area, can be taken to be the square root of the surface area on which condensation will take place [8].

Once again the *ode45* solver in *MatLab* was used to perform the required calculations. The amount of dew formed in an hour was calculated and the results can be found in Chapter 5, section 5.7.

4.7 Possible errors

A number of factors may result in errors in the calculations of the insulator surface temperature as well as the surface condensation rate. Cloud cover is one of the elements which may introduce an error into the calculations. In [7] it was shown that the mass of water that condenses onto a surface is proportional to the long-wave radiation to which the surface is exposed. The long-wave radiation is in turn proportional to the cloud cover as in (12).

$$R_l = S_c \cdot \varepsilon_c \cdot \varepsilon_s \cdot \sigma_b (T_c + 273)^4 \quad (12)$$

Now S_c is the surface area, ε_c is the emissivity of the condensing surface, ε_s is the emissivity of the sky, σ_b is Boltzmann's constant and T_c is the temperature of the condenser in degrees Celsius [7].

$$\varepsilon_s = \varepsilon_{so} + (N/8)[1 - \varepsilon_{so} - 8/(T_a + 273)] \quad (13)$$

In (13), ε_{so} is the emissivity of the sky with no clouds present. N is the amount of cloud cover, measured in eighths. An N value of zero indicates no clouds and an N value of eight indicates overcast conditions.

$$\varepsilon_{so} = 0.72 + 0.005 \cdot T_a \quad (14)$$

Now if we assume the ambient temperature, T_a to be room temperature, 22°C , we get an ε_{so} value of 0.83 from equation (14). If N is given a value

of zero the resulting ε_s value is 0.83. However if the value of N is made to be 8, the resulting ε_s value is 0.972. This means that the maximum possible error in ε_s value is 14%. Therefore resulting in a maximum error, resulting from cloud cover, being 14%. This error will effect the surface temperature calculations. This will therefore effect the condensation rate calculations as they are dependent on the surface temperature value.

The effect of dew rise may also add an error to the condensation rate calculations. It has been shown that moisture from soil and plant crops can lead to an increase in the amount of dew formation on nearby surfaces as a result of dew rise [9]. Dew rise may result in a condensation rate higher than that calculated by equation (8), however it is difficult to quantify the amount by which the condensation rate will increase. It is not known what the soil and vegetation conditions were like over the periods of the given data. The insulators on the power-lines are most times a few meters off the ground level and it is therefore assumed that dew rise will have little effect on the condensation rate, as the insulators are not situated close to the soil surface.

Further errors in calculated values may arise due to inaccuracies in the weather data provided. Certain thermodynamic terms were not included in the heat analysis equation as it was felt the effect would not be significant. These include heating of the insulator due to electrical heating from the live cables, the cooling effect of evaporation of water from the insulator surface and heat released by condensation of water onto the surface. The insulator consists of a fiber glass core enclosed by the polymer sheath and sheds. The effect of the fiber glass core on the surface temperature of the insulator was also neglected.

4.8 References

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Chapter 5

ANALYSIS OF WEATHER CONDITIONS

5.1 Introduction

Weather patterns often affect the performance of outdoor insulators, especially in coastal environments. In a coastal environment the insulator surface is exposed to a large amount of pollution. Salt is often blown off the sea onto the surface of the insulators resulting in severe salt contamination layers [1]. Wind, precipitation, mists, humidity and temperature, either solely or combined, can result in wetting of the insulator surface. When the salt contamination layer on the insulator surface is wetted it can result in poor insulator performance [2]. For the purposes of this investigation the phenomena of dew formation and surface condensation will be under analysis.

A number of coastal sites within South African were selected for analysis. The reasoning behind the choice of these sites as well as the data analyzed is discussed. Two methods of surface wetting can occur as a result of specific weather conditions. The first is wetting due to dew formation, or normal condensation, and the second being wetting due to surface condensation. Wetting due to surface condensation is more rapid than that of normal condensation and it is therefore the focus of this dissertation.

This chapter shows the method of the weather analysis and consequently the results thereof. It shows examples of wetting of the insulator surface as a result of normal dew formation as well as examples of wetting as a result of surface condensation. There is a comparison between the condensation rates during normal dew formation and during surface condensation. The amount of water condensed onto the insulator surface, or condensation rate, is also determined for the polymer insulators. The results of the weather analysis will be used to set up a weather chamber which will be used to simulate the weather conditions in order to test the behavior of high voltage insulators when exposed to these weather conditions.

5.2 Significance of the Weather

The insulators which will be under investigation will be silicone rubber and EPDM insulators. Since the EPDM and the silicone rubber insulators are materially very similar only the silicone rubber insulator will be used. Insulators in coastal environments are often exposed to high relative humidity and heavy salt pollution and can therefore accumulate a severe salt contamination layer on

its surface [1]. Wind blows salt particles inland from from the sea. These salt storms can result in the rapid deposit of humid salt particles on the insulator surface, forming densely packed layers of salt on the surface [3]. It has been observed that salt deposits in marine environments can be very heavy, with a salt deposit density as high as $0.3\text{mg}/\text{cm}^2$ [1].

Sharp increases in the humidity level can result in rapid wetting of the insulator surface. If the insulator is exposed to cold environmental temperatures followed by a sudden increase in humidity, rapid wetting could result on the insulator surface due to surface condensation. Rapid wetting of insulator surface can result in them being likely to flashover fairly readily [1]. It has been observed that intensive, long duration discharges occur in coastal areas; these too can result in rapid insulator failure [4]. It is speculated that these discharges may be a result of the rapid wetting of the insulator surface accompanied by the high surface pollution levels. When the surface of salt contaminated insulators is wet the water dissolves some of the pollution layer, resulting in a conductive solution on the surface. With silicone rubber insulators the extent of this dissolution is not as significant as with glass insulators. This is because of silicone rubber's hydrophobicity[5]. However the presence of water on the surface will still dissolve some of the pollutant and the presence of an electric field may elongate these water droplets possibly leading to dry band arcing and hence reducing its flashover performance.

Many aspects of the weather can influence the behavior of outdoor insulators. However this investigation will focus on the role of cold temperatures high humidity levels.

5.3 Dew Point and Surface Condensation

There are two processes which can lead to the wetting of the insulator surface under humid conditions. The first, and most common, process is when the surrounding air reaches dew point temperature and dew forms on the surface of the insulator due to condensation.

The amount of water vapor a pocket of air can carry depends on its temperature. The warmer the air the more moisture it can carry. Conversely the cooler the air the less moisture the pocket can carry [7]. This is the basic principle behind condensation. As the air temperature cools its ability to hold water decreases. So as the temperature decreases the humidity level increases until such a point that it is saturated. At this point condensation occurs. The temperature at which this process takes place is called dew point temperature [7].

Although this method of surface wetting is common it may not necessarily lead to rapid wetting of the insulator surface. Rapid wetting is more likely to occur by means of the second process, surface condensation.

Surface condensation takes place when the temperature of the surface is colder than that of the surrounding air. As humid air comes closer to the cold surface the air begins to cool, thus increasing the humidity level [7]. If the air close to the surface of the insulator is cooled enough it will reach the dew point temperature that is required for condensation to occur. If this takes place water droplets will form on the cooler surface, as a result of surface condensation [8].

A psychrometric chart, as shown in *Figure 5.1* [9], can be used to determine whether surface condensation will occur. This can be done by locating the

environmental temperature on the horizontal axis, moving up to the required humidity curve. Once here, move horizontally towards the 100% humidity curve. When one reaches this point, drop down to the temperature axis again and read off the temperature, this is dew point temperature for the given weather conditions. Condensation will occur if the surface temperature of the insulator is below dew point temperature.

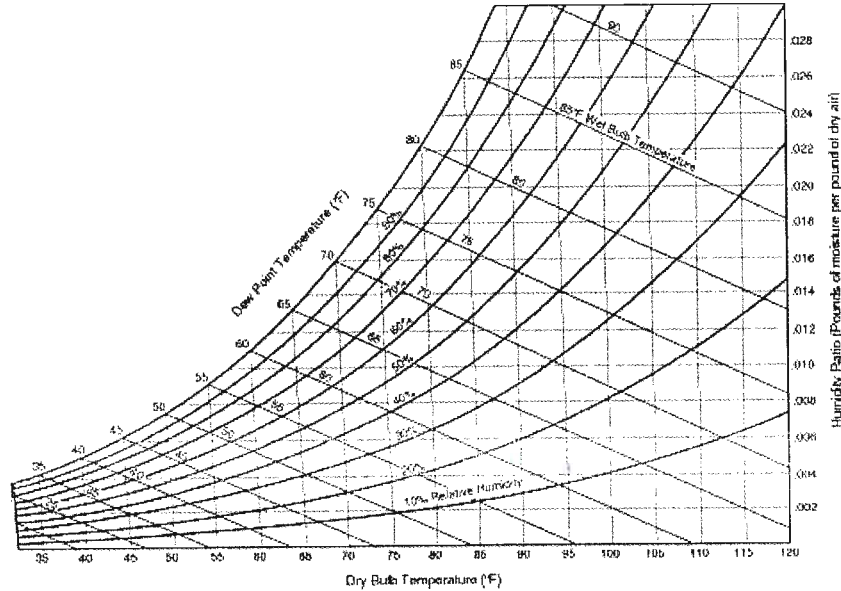


Figure 5.1: Psychrometric Chart, taken from [9]

For surface condensation to occur on the insulators under investigation the insulators first have to be exposed to cold temperatures for a while to cool the insulator surfaces. Once the temperature starts to rise the insulator surface will remain cooler than the environment due to its specific heat [10]. If this takes place accompanied by a corresponding increase in humidity surface condensation is likely to occur.

5.4 Weather Data Analyzed

Weather data was reviewed from various coastal areas through which transmission lines run. The Western Cape and Kwa-Zulu Natal provinces of South Africa were selected for analysis as both provinces have a number of transmission lines running along the coast. Data from a number of coastal weather stations from these provinces was collected. However only data from stations which were located close to the transmission lines was analyzed.

Figure 5.2 shows a map showing the location of major transmission lines in South Africa [11]. It can be seen that transmission lines run along the coast line in both the Western Cape and Kwa-Zulu Natal provinces.

The data was collected from the following weather stations in the Western Cape which were located near transmission lines: Cape Columbine, Cape

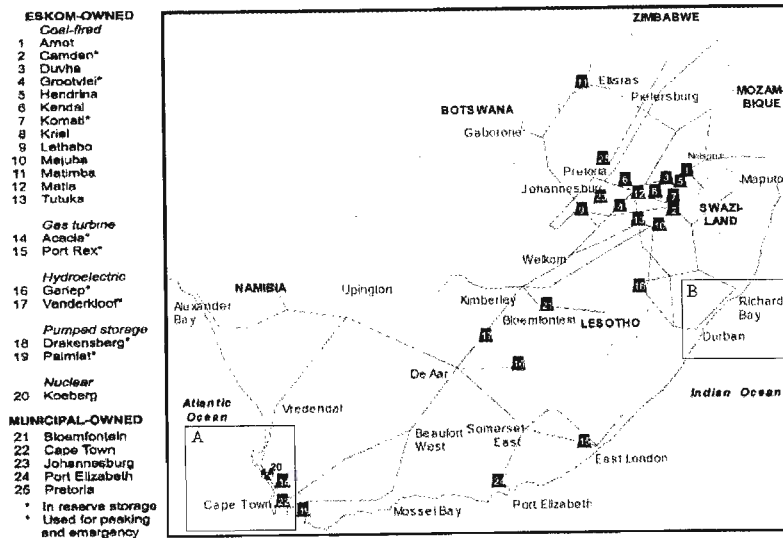


Figure 5.2: Transmission Grid of South Africa, taken from [11]

Point, Hermanus, Langebaan, Strand and Villiersdorp. Those in Kwa-Zulu Natal which were alongside transmission lines were Mount Edgecombe, Richards Bay and Virginia. Data from all of the above stations was analyzed. The time range over which they were analyzed varies depending on the availability of the data. All data was obtained from the South African Weather Service. For all stations data was obtained for at least two years. *Figure 5.3* and *Figure 5.4*¹ show the location of the weather stations with reference to the transmission lines highlighted in areas A and B in *Figure 5.2*.

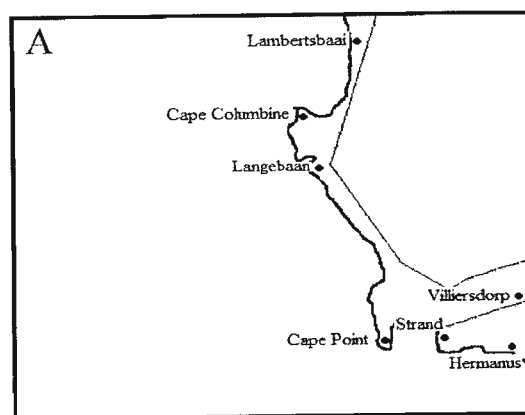


Figure 5.3: A: Western Cape Weather Stations

¹These figures were generated by the author.

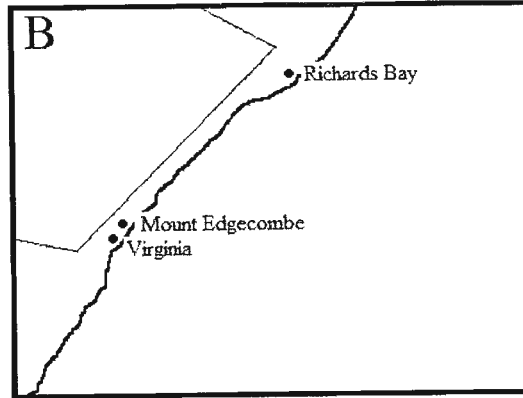


Figure 5.4: B: Kwa-Zulu Natal Weather Stations

The majority of the data was in the form of hourly temperature, wind speed, solar radiation and humidity readings for all days of the year.

For some weather stations only two years worth of data was received, others had large gaps of data missing. For the periods where data was missing the temperature was set to room temperature, 22°C , and the humidity was set to be 50%. Any results from these periods of missing data were excluded from the analysis. The results of the analysis are shown below.

5.5 Investigation into Wetting: Dew Formation

The weather data was analyzed in an attempt to determine whether or not wetting will take place on the insulator surfaces due to either dew formation or surface condensation.

The first case was dew formation, which is wetting as a result of dew point temperature being reached. The occurrence of dew formation is fairly easy to predict. Condensation on the surface of the insulators will take place when the humidity is at 100% followed by a further decrease in temperature. A few examples of these conditions will be shown from the weather data analyzed, however extensive analysis was not done on this section as it is not the main focus of this paper. The results found for the dew formation analysis follow.

5.5.1 Western Cape

Sites analyzed included Cape Columbine, Cape Point, Hermanus, Langebaan, Strand and Villiersdorp. All these weather stations are located close to the transmission system in this area. They will give a good indication of the weather experienced at the transmission lines.

Cape Columbine

The data for Cape Columbine was in the form of periodic readings taken three times a day at 8am, 2 pm and 8pm. Data was obtained for three consecutive

years, they were 2001, 2002 and 2003. From the data analyzed the following graphs show situations where water droplets are likely to form on the surface of the insulator due to normal condensation i.e. dew formation. On the 26th and the 27th of June 2001 it can be seen that the humidity reached 100% at 8 o'clock on the evening of the 26th and remains at 100% until 8 o'clock the next morning, with a corresponding temperature drop from 11.2 °C to 9 °C, thus resulting in dew formation. This can be seen in *Figure 5.5*.

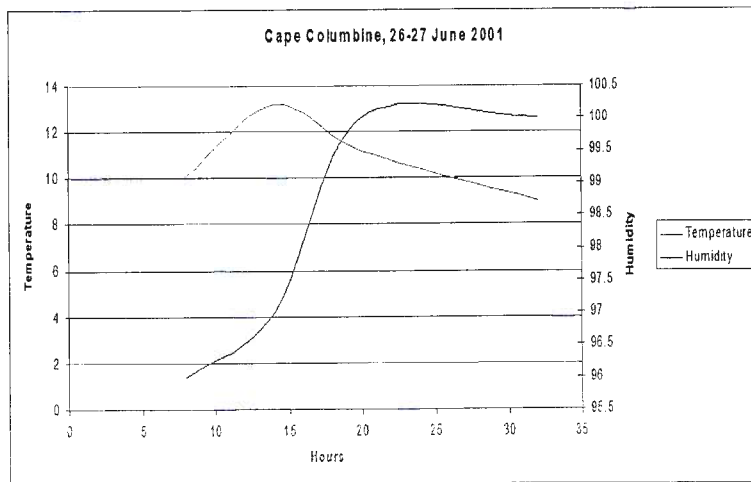


Figure 5.5: Graph of Temperature and Humidity levels at Cape Columbine

Figure 5.6 is another example of when condensation would occur on the insulator surface due to the temperature reaching dew point. The graph shows the temperature and humidity levels on the 31st of July and the next morning, the 1st of August 2003.

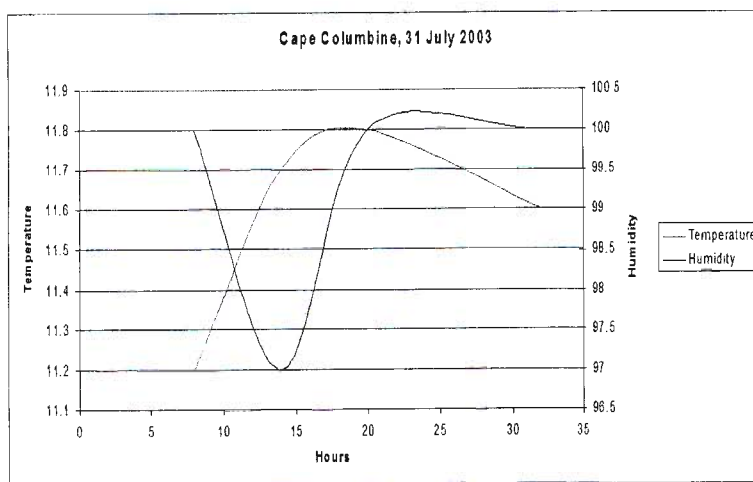


Figure 5.6: Graph of Temperature and Humidity levels at Cape Columbine

Again it can be seen that the humidity remains at 100% with a corresponding drop in temperature. The above two examples would most likely lead to condensation on the insulator surface.

Cape Point

The weather data obtained for Cape point was in the form of hourly readings every day for the years 2002, 2003 and 2005. Both *figures 5.7* and *5.8* show occasions where the humidity has been at 100% and the temperature decreases. This would lead to condensation on the surface of the insulator due to the temperature dropping below dew point. The figures show the temperature and the humidity levels on the 9th May 2001 and the 13th May 2002.

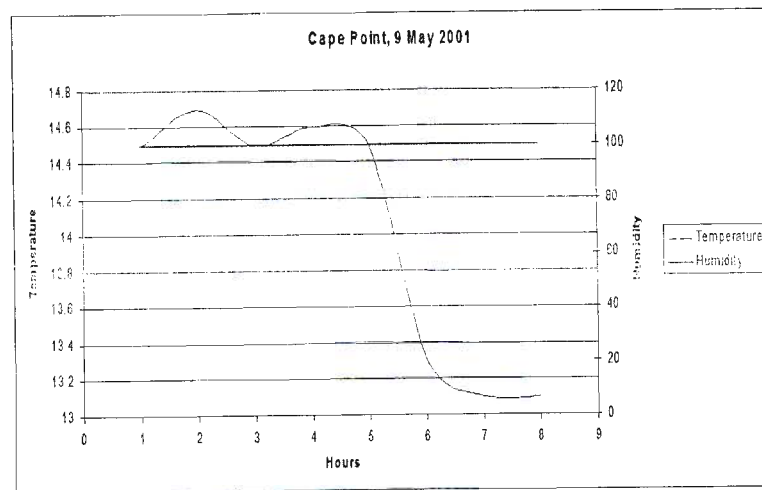


Figure 5.7: Graph of Temperature and Humidity levels for Cape Point

Hermanus

The weather data for Hermanus was in the form of hourly data recordings every day in the years 2002, 2003 and 2004. In *figures 5.9* and *5.10* the 2nd of July 2002 and 23rd of April 2003 are shown respectively. The temperature and humidity levels on these days are graphed. It can be seen on the graphs that Hermanus experiences conditions which would lead to condensation on the insulator surfaces. The humidity is at 100% followed by a drop in temperature, below dew point, which will lead to dew formation.

Langebaan

Langebaan's data was extensive. Hourly humidity and temperature readings were received for 2001 through to 2005. *Figures 5.11* and *5.12* show occasions where the temperature and humidity levels would lead to condensation on the surface of the insulator. On the 16th of May 2002 and the 13th of May 2004 the temperature decreased accompanied by a humidity level of 100%.

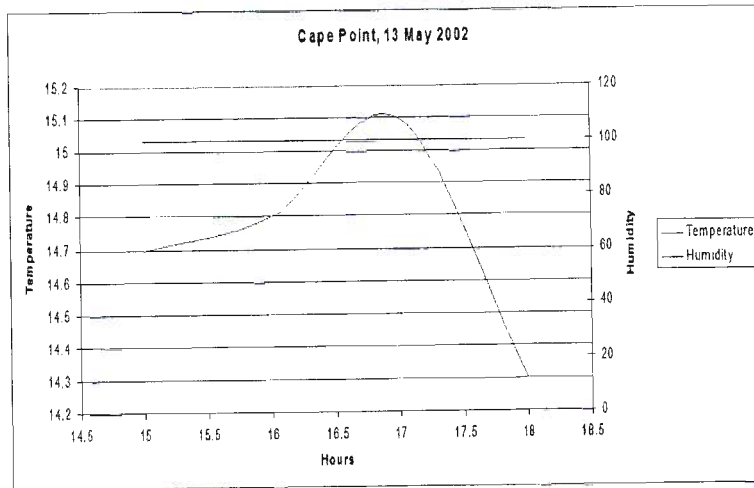


Figure 5.8: Graph of Temperature and Humidity levels for Cape Point

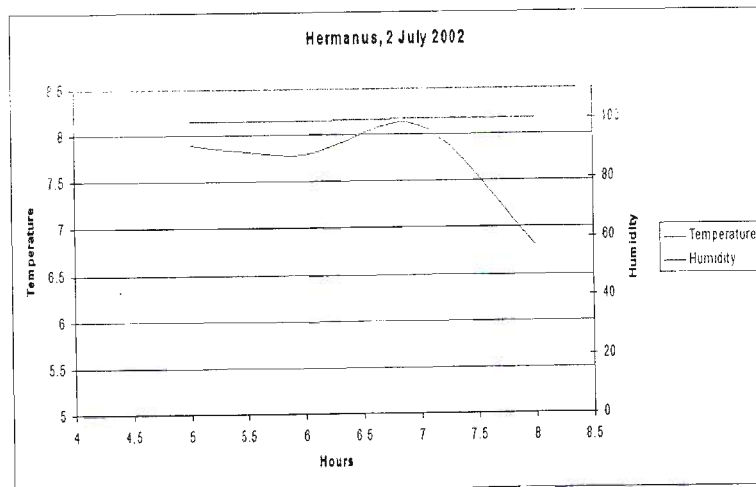


Figure 5.9: Graph of Temperature and Humidity levels for Hermanus

Strand

The weather data received for the weather station at Strand was in the form of hourly readings for the years 2002 through to 2005. *Figures 5.13 and 5.14* show temperature and humidity levels which could lead to condensation on the surface of the insulator. They show temperature drops accompanied by a 100% humidity level. This occurs on the 4th of July 2002 and the 19th of May 2004.

Villiersdorp

The data obtained from the weather station at Villiersdorp was in the form of hourly humidity and temperature readings for the years 2002 and 2003. As

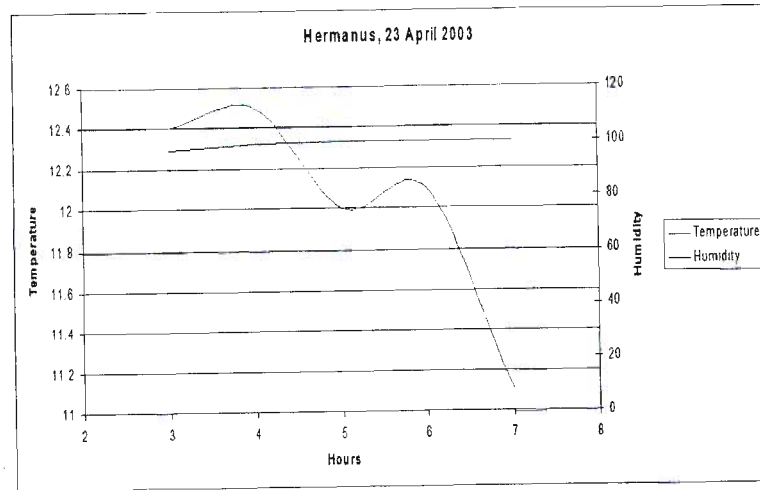


Figure 5.10: Graph of Temperature and Humidity levels for Hermanus

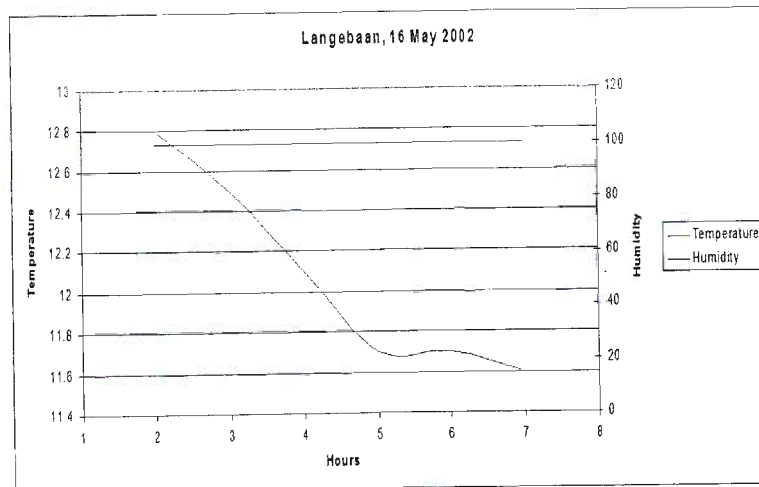


Figure 5.11: Graph of Temperature and Humidity levels for Langebaan

before the weather data for the station was analyzed in order to find situations which would lead to condensation due to the temperature dropping below dew point temperature. Figures 5.15 and 5.16 show the days of the 30th of May 2002 and the 2nd of July 2002. Here condensation is likely to occur because the humidity remains at 100% while the temperature at this time decreases.

5.5.2 Kwa-Zulu Natal

The weather stations which were analyzed in this province were Mount Edgecombe, Richards Bay and Virginia. These sites are located close to the transmission lines for the area and would therefore give a good indication of the

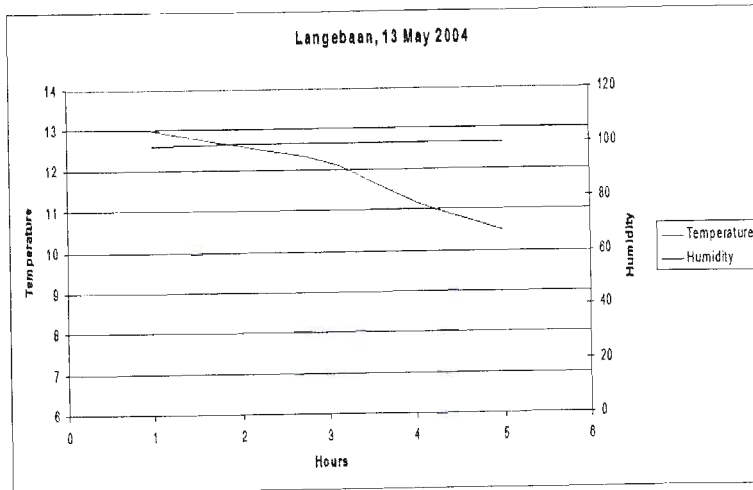


Figure 5.12: Graph of Temperature and Humidity levels for Langebaan

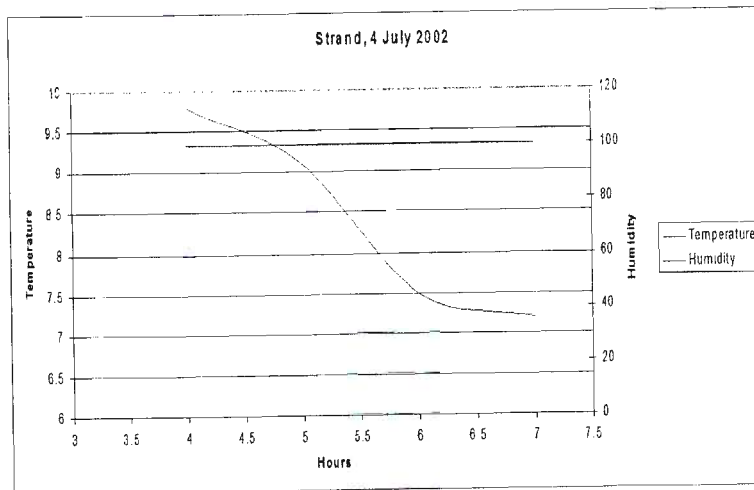


Figure 5.13: Graph of Temperature and Humidity levels for Strand

weather experienced at the transmission line site.

Mount Edgecombe

The weather data received for Mount Edgecombe was in the form of hourly temperature and humidity readings for the years 2001, 2002 and 2003. The temperature and humidity levels were again analyzed to find situations where condensation would occur resulting in wetting of the insulator surface. *Figures 5.17 and 5.18* indicate conditions which would lead to this condensation. They show the temperature and humidity levels on the 11th of August 2002 and the 10th of December 2003.

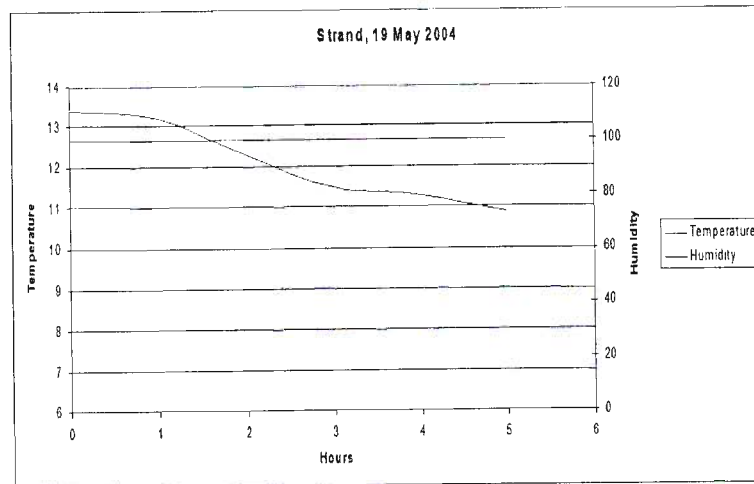


Figure 5.14: Graph of Temperature and Humidity levels for Strand

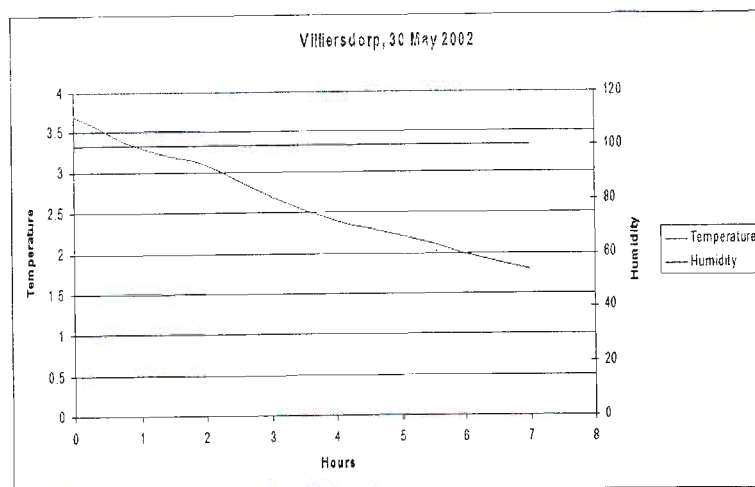


Figure 5.15: Graph of Temperature and Humidity levels for Villiersdorp

Richards Bay

The temperature and humidity readings taken by the weather station at the Richards Bay airport was in the form of hourly readings for the years 2002 to 2005. The temperature and humidity levels were analyzed to find situations where condensation would take place on the insulator surface due to dew formation. *Figures 5.19* and *5.20* show the 26th of July 2002 and the 31st of May 2004 respectively. Here it can be seen that there is a drop in temperature whilst the humidity remains at 100% indicating that condensation will take place.

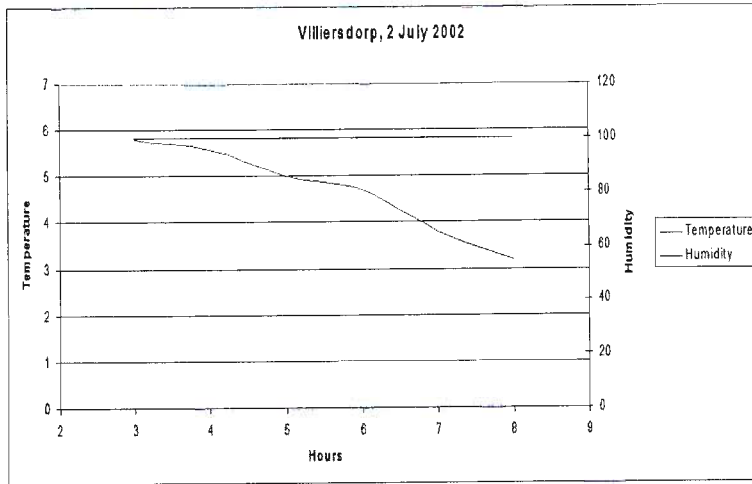


Figure 5.16: Graph of Temperature and Humidity levels for Villiersdorp

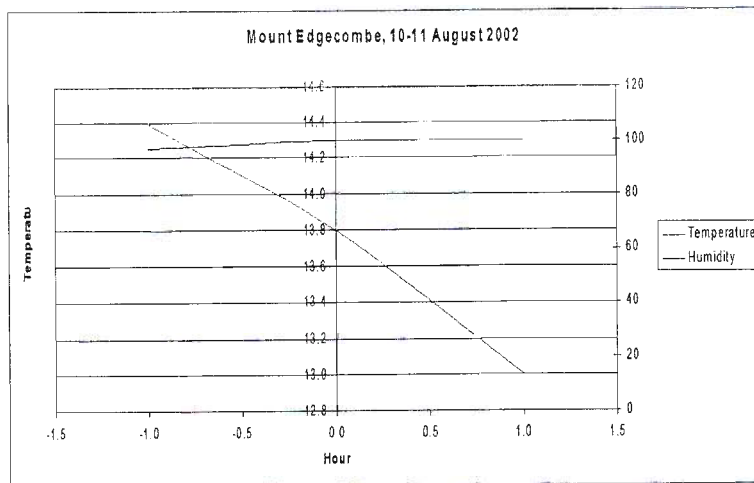


Figure 5.17: Graph of Temperature and Humidity levels for Mount Edgecombe

Virginia

The weather data obtained from the Virginia airport was in the form of hourly humidity and temperature readings for the years 2001, 2002 and 2003. The Virginia weather data was analyzed to find conditions which would lead to condensation on the surface of the insulator as a result of the temperature dropping below dew point temperature. The 14th of July 2001 and the 4th of August 2002 were found as examples of this and are graphed in figures 5.21 and 5.22 respectively.

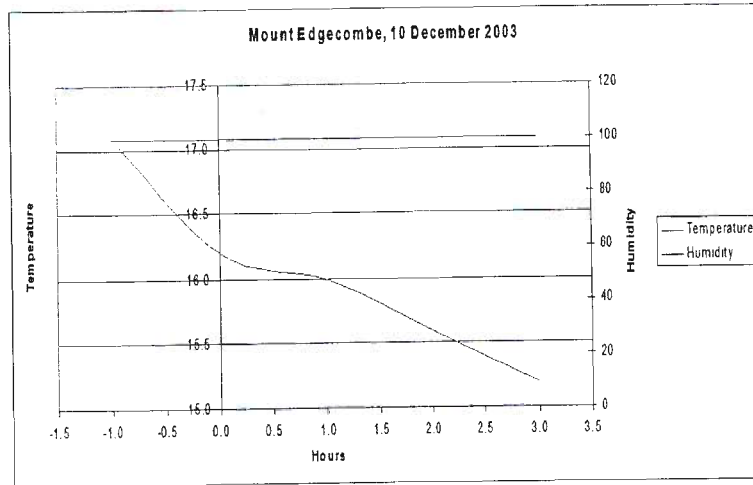


Figure 5.18: Graph of Temperature and Humidity levels for Mount Edgecombe

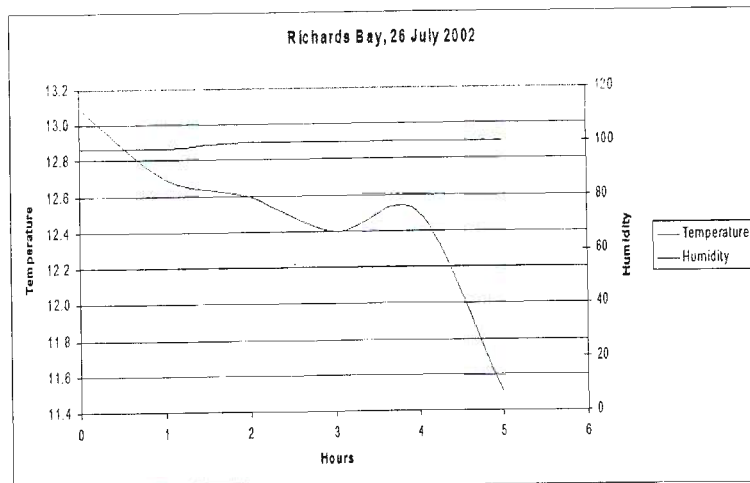


Figure 5.19: Graph of Temperature and Humidity levels for Richards Bay

5.6 Investigation into Wetting: Surface Condensation

Wetting due to surface condensation was covered more extensively. For each of the weather stations below the weather data was analyzed to look for conditions which would lead to surface condensation. A mathematical formula, presented in Chapter 3 section 3.2, was used to calculate the surface temperature of the insulator in order to determine whether it was conducive to surface condensation. Once the insulator surface temperature was known the corresponding environmental temperature and humidity level were reviewed to determine whether surface condensation would occur. Here the worst case situation is presented. The data was analyzed for the case of the polymer insulators .

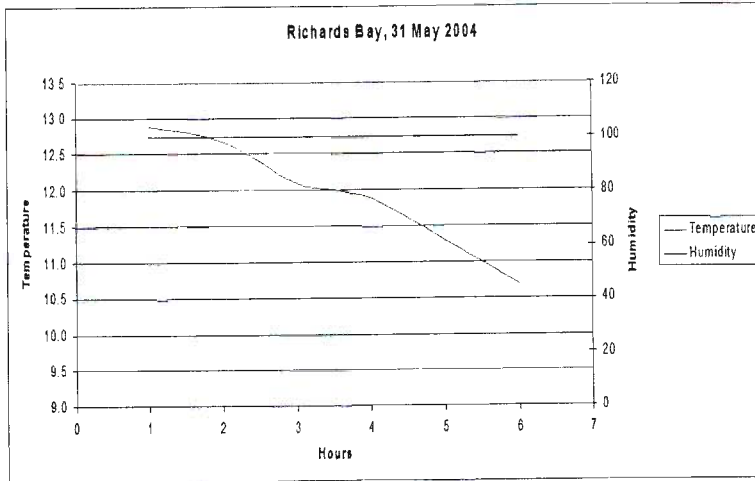


Figure 5.20: Graph of Temperature and Humidity levels for Richards Bay

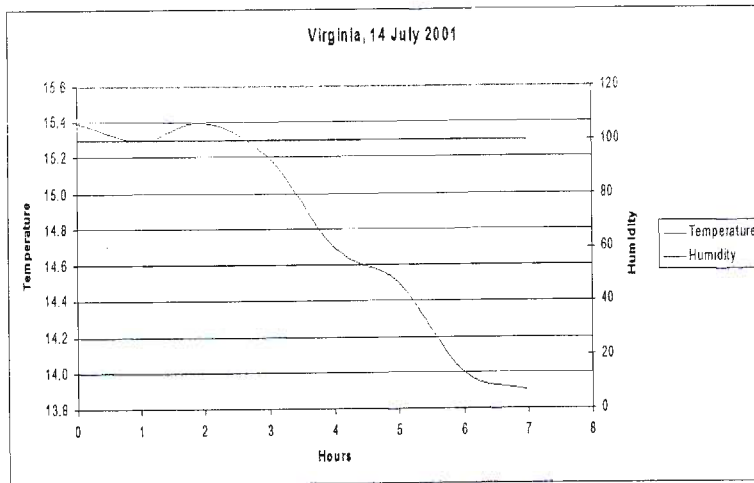


Figure 5.21: Graph of Temperature and Humidity levels for Virginia

The equation which was used to determine the surface temperature of the insulator was presented in Chapter 3 section 3.2 and is shown below as equation (1) below.

$$-\left(h(T - T_{sur}) + \epsilon\sigma_b(T^4 - T_{sur}^4)\right)A_s = \rho V ol_{ins} C_p \frac{dT}{dt} \quad (1)$$

Where:

h , is the convective heat transfer coefficient ($\frac{W}{m^2 \cdot ^\circ C}$)

T , is the temperature of the insulator, in Kelvin (K)

T_{sur} , is the temperature of the surrounding environment (K).

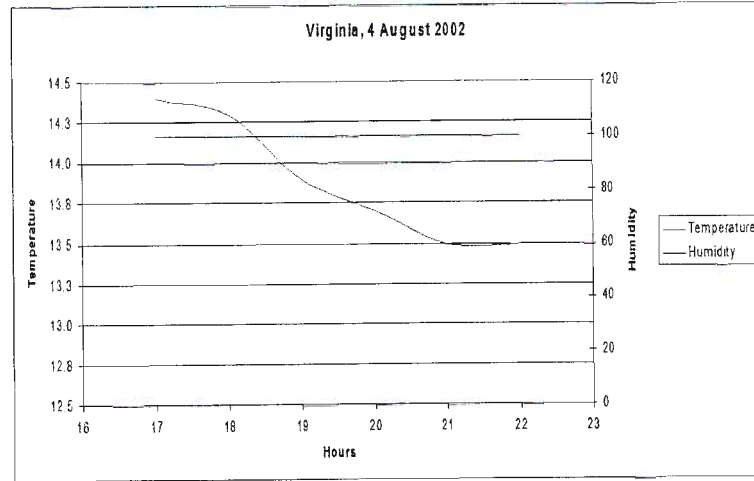


Figure 5.22: Graph of Temperature and Humidity levels for Virginia

ϵ , is the emissivity of the insulator.

σ_b , is Boltzmann's constant, $5.699 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$

A_s , is the surface area of the insulator (m^2)

ρ , is the density of the insulator surface material (kg/m^3)

Vol_{ins} , is the volume of the insulator (m^3)

C_p , is the specific heat of the insulator surface material ($\text{kJ/kg} \cdot \text{K}$)

$\frac{dT}{dt}$, is the change in temperature with time

The value of h depends on the wind velocity. For certain weather stations some of the wind velocity data over certain periods was not available. For these cases the periods over which there was no wind data, were not analyzed for surface condensation. It is believed that this will not affect the outcome of the analysis as each station offered a great deal of usable data over which to do the analysis. This usable data was also far enough away, with regards to period of time, from the missing data that it is expected that the missing data will not effect the results of the used data.

In (1) the first term on the left hand side of the equation represents the thermal energy transfer due to convection. The second term on the left hand side of (1) represents the thermal energy transfer due to radiation. For this term the global radiation index (W/m^2) was required. Unfortunately there were periods and stations where the radiation data required to perform an accurate analysis was not available. The only data which was available for the Western Cape province was for the Cape Town station for the years 2001, 2002 and 2003. It was therefore decided to compose the rest of the Western Cape radiation data from the worst cases of the Cape Town data. The radiation data which was available for the Kwa-Zulu Natal province was for the city of Durban for 2001,

2002 and 2003. The Virginia weather station is located in the Northern area of Durban and so the radiation data was used for this station. The radiation data was not available for Richards Bay and Mount Edgecombe. The rest of the Kwa-Zulu Natal data was composed of the worst case data from Virginia, as it was done with Cape Town and the Western Cape. The radiation data was in the form of hourly global radiation readings.

A *MatLab* program was written in order to perform the necessary calculations to find the surface temperature. The program was made to calculate the insulator surface temperature based on the hourly environmental temperature, wind velocity and solar radiation values. This was done for each hour of the data for each weather station. The program would then compare surface temperature at the time with its original corresponding environmental temperature. If the surface temperature was less than the environmental temperature the occurrence was recorded in a dummy vector. Once the program had run, the dummy vector was reviewed to find the dates of the occurrence. A more thorough analysis of these dates was then performed to determine whether surface condensation was likely. The environmental temperature, insulator surface temperature and the humidity were compared using a psychrometric chart [9] in order to determine whether surface condensation would take place.

Winter conditions were concentrated on as it was felt that these conditions would be more conducive to surface condensation as they would have lower temperatures which would more likely lead to air pockets reaching dew point temperature. Winter is also the time of year when cold fronts are most likely.

It was not possible to perform an analysis for surface condensation at all the weather stations as the data required for the analysis was not available. Stations that were included in the analysis were Cape Point, Villiersdorp, Langebaan, Virginia, Richards Bay and Mount Edgecombe.

In order to reduce the volume of data, so reducing analysis time, the analysis was restricted to humidity levels above 85% and insulator surface temperatures below 17°C. It can therefore be said that more cases of surface condensation would be found if these constraints were not in place.

5.6.1 Western Cape

The Western Cape experiences winter rainfall. This is brought by the cold fronts which pass over the province in winter. The cold fronts are brought up from the Antarctic regions by the southern hemisphere westerly winds. They lead to cold, wet and windy conditions.

Cape Point

Cold fronts bring cold weather to the region. If these cold periods are accompanied by high levels of humidity, the conditions may lead to surface condensation. The following examples show temperature and humidity levels which have been recorded in the Cape Point region which would most likely lead to surface condensation.

In *Figure 5.23* above the temperature at ten o'clock, the twenty second hour of the day, is 8°C and the humidity is at 96%. From equation (1) it was found that the corresponding insulator surface temperature at this time was 6.4°C. Using the psychrometric chart it was found that under these conditions surface

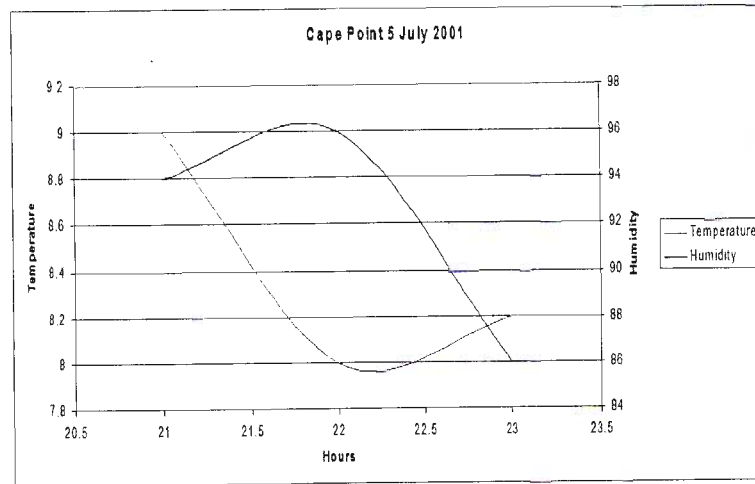


Figure 5.23: Surface Condensation at Cape Point

condensation was likely to occur if the insulator surface temperature were to drop below 7.4°C . In this case the insulator surface temperature does drop below this temperature and it can therefore be concluded that surface condensation will occur. With further analysis it was found that surface condensation would occur on a number of occasions throughout the years for which the weather data was available. The lowest environmental temperature at which surface condensation occurred was 8°C , and the highest temperature was 18.5°C . The lowest humidity level encountered which would lead to surface condensation was 87%. Occurrences were throughout the year.

Langebaan

The occurrence of surface condensation on the insulators was investigated for the Langebaan weather station. The following example was found to illustrate that surface condensation can occur due to the weather conditions in this area.

In *Figure 5.24* it can be seen that the environmental temperature is at 12.2°C at midnight of the fifth of May 2005. The humidity is at 91%. Equation (1) showed that the insulator surface temperature was at 8.9°C at this time. With the given conditions, surface condensation would have occurred on the insulator surface since the insulator surface temperature dropped below 10.9°C , which was the estimated dew point temperature found with the psychrometric chart. Similar cases of surface condensation were found throughout the data collected. Surface condensation occurred whilst temperatures ranged from 4.6°C to 17.5°C , the lowest humidity resulting in surface condensation was 86%. Again occurrences were throughout the year.

Villiersdorp

The data was analyzed further to find periods of cold weather accompanied by sharp increases in humidity which could lead to surface condensation. The

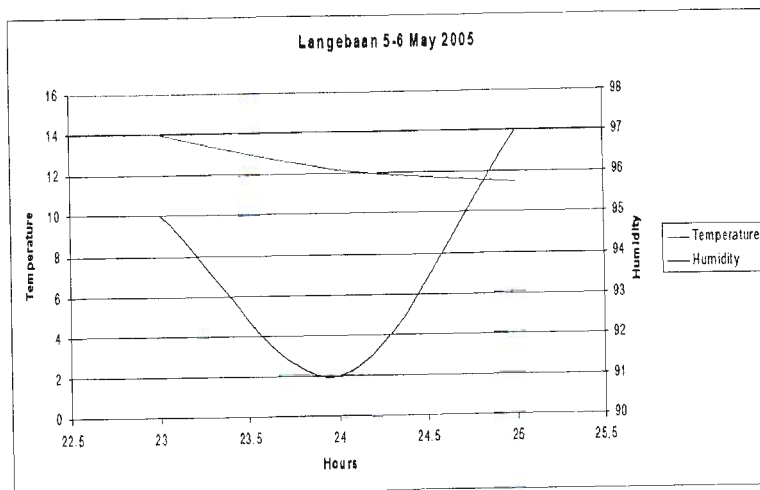


Figure 5.24: Surface Condensation at Langebaan

following example was found of temperature and humidity levels which would lead to surface condensation on the polymer insulator surface.

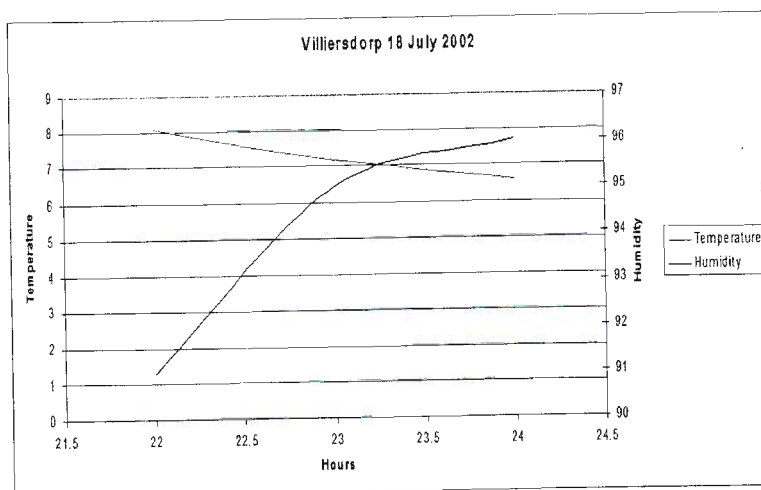


Figure 5.25: Surface Condensation at Villiersdorp

Figure 5.25 shows the temperature at eleven o'clock being 7.2°C with the corresponding humidity being 95%. From the psychrometric chart it was found that the insulator surface temperature would have to drop below 6.3°C in order for surface condensation to take place. It was found from equation (1) that the insulator surface temperature at this time was 5.9°C , thus resulting in surface condensation. Little weather data was available for Villiersdorp, an extensive analysis could therefore not be performed, however it was still possible to find a few cases where surface condensation would have occurred.

5.6.2 Kwa-Zulu Natal

The province of Kwa-Zulu Natal experiences more temperate weather than that in the Western Cape. The Kwa-Zulu Natal province is located on the east coast of South Africa. The warm Mozambique Current from the equatorial regions flows along the coast of this province which, in part, is responsible for its temperate climate. In winter the day time temperatures along the coast are usually in the lower 20°C range. When the coastal sites do experience cooler weather it is usually due to the cold fronts from the Cape which have come up the coast. The cold fronts are usually weaker when they reach the east coast and therefore the temperatures are not as low as those experienced in the Western Cape.

Other weather systems, such as tropical cyclones, could also bring similar conditions in the summer months. All seasons were reviewed for the Kwa-Zulu Natal coastal weather stations to be able to find the required weather conditions.

Due to the nature of the climate along the east coast of South Africa the temperatures seen for the surface condensation conditions selected are about 5°C warmer than those seen in the Western Cape cases.

Mount Edgecombe

Mount Edgecombe's weather data was analyzed to find whether surface condensation is likely to occur on the insulators as a result of the temperature and humidity patterns. *Figure 5.26* shows a situation where the temperature and humidity levels lead to surface condensation.

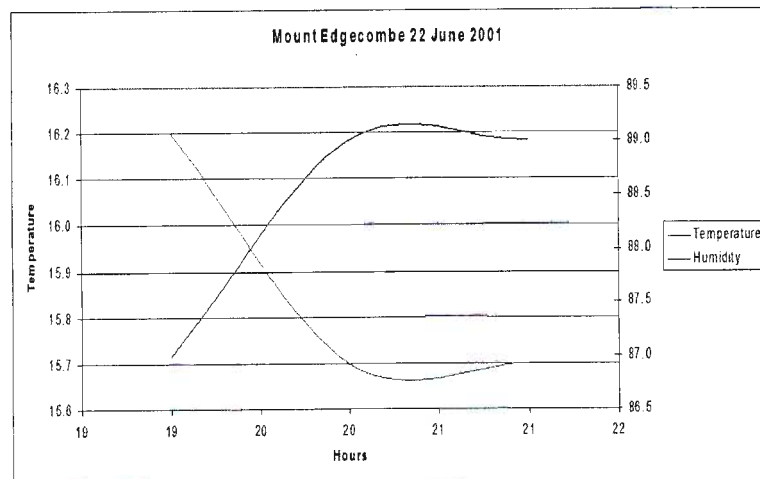


Figure 5.26: Surface Condensation at Mount Edgecombe

It can be seen that on the evening of the 22nd of June 2001 the humidity was 89% and the temperature was 15.7°C. It was calculated that the insulator surface temperature was 13°C, and surface condensation did occur because the insulator surface temperature dropped below 13.8°C, which was the dew point temperature. It was found that surface condensation would occur several times a year, mostly during the winter months. The environmental temperatures

where surface condensation occurred ranged from 13.5 °C to 21.7 °C. The lowest humidity which lead to surface condensation was 86%.

Virginia

The data was analyzed to determine whether surface condensation would take place given the temperature and humidity levels given in the data. *Figure 5.27* shows the weather conditions on the 13th of August 2001 which would have lead to surface condensation on the insulator.

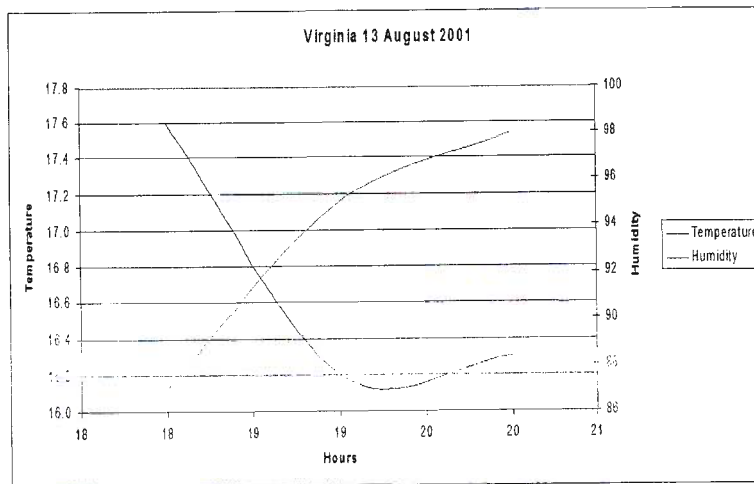


Figure 5.27: Surface Condensation at Virginia

It can be seen that the temperature was 16.2 °C and the insulator surface was at 14 °C, with the humidity at 95%. The insulator surface temperature was 1.2 °C below the dew point temperature found on the psychrometric chart, thus resulting in surface condensation. The temperatures in Virginia over which surface condensation occurred ranged from 12.8 °C to 21.9 °C. Humidity was above 86% and occurrences were mostly in the winter months.

Richards Bay

The data required to perform the analysis for surface condensation was available for the Richards Bay station. *Figure 5.28* shows temperature and humidity levels which resulted in surface condensation on the insulator.

The environmental temperature at seven o'clock was 16.2 °C while the insulator temperature was calculated to be 14 °C and the humidity was 95%. It was estimated using the psychrometric chart that the insulator surface would have to cool to below 15.2 °C in order for surface condensation to take place. The insulator surface temperature did so and it can therefore be concluded that surface condensation did take place. Again surface condensation occurred mainly in the winter months and temperatures ranged between 11.7 °C and 22.9 °C, with the lowest humidity leading to surface condensation being 88%.

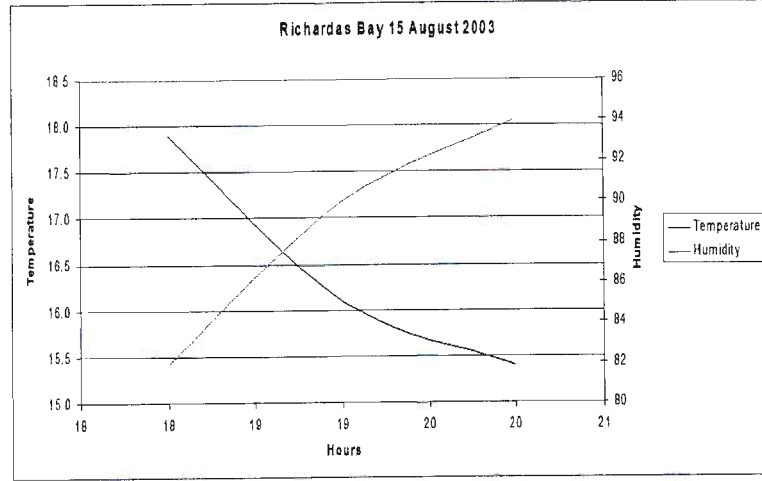


Figure 5.28: Surface Condensation at Richards Bay

5.7 Condensation Rate

Once it had been determined that surface condensation was taking place a second equation was used to find the amount of water which was condensing onto the insulator surfaces. Equation (8) was used to find the condensation rate in mm/h [12].

$$\frac{dm}{dt} = S_c \cdot b \left(p_{sat}(T_d) - p_c(T_c) \right) \quad (8)$$

Where:

$\frac{dm}{dt}$, is the condensation rate in mm/h

S_c , is the condensing surface in m^2

b , is the mass transfer coefficient

$p_{sat}(T_d)$, is the saturation pressure at dew point temperature in Pascals

T_d , is the dew point temperature in $^{\circ}C$

$p_c(T_c)$, is the vapor pressure over the condensing surface in Pascals

T_c , is the temperature at which condensation takes place in $^{\circ}C$

From here equations (10) and (11) are required to complete the solution to (8). Further details of these equations can be found in Chapter 4 section 4.6.

$$b = 0.656 \cdot g \cdot a / (p \cdot C_a) \quad (10)$$

$$a = k \cdot f(V/D)^{\frac{1}{2}} \quad (11)$$

Table 5.1: Mount Edgecombe 2001

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 18-03 | 21.7 | 16.8 | 96 | 0.035 |
| 15-05 | 14 | 12.7 | 96 | 0.007 |
| 17-05 | 16.4 | 14.3 | 92 | 0.012 |
| 21-05 | 19.4 | 15.9 | 92 | 0.022 |
| 23-05 | 17 | 14.7 | 89 | 0.013 |
| 03-06 | 18.1 | 16.6 | 93 | 0.010 |
| 09-06 | 15 | 12.4 | 95 | 0.013 |
| 22-06 | 15.7 | 13 | 89 | 0.013 |
| 25-06 | 15.5 | 12.8 | 91 | 0.014 |
| 25-07 | 14.6 | 13 | 93 | 0.009 |
| 27-07 | 15.4 | 12.6 | 92 | 0.014 |
| 17-08 | 18.5 | 16.8 | 92 | 0.012 |
| 17-09 | 14 | 10.8 | 88 | 0.014 |
| maximum | | | | 0.035 |
| minimum | | | | 0.007 |
| average | | | | 0.0145 |

Table 5.2: Mount Edgecombe 2002

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 16-04 | 18.9 | 16.5 | 94 | 0.016 |
| 22-05 | 19.2 | 16 | 94 | 0.020 |
| 06-06 | 18.2 | 14.1 | 88 | 0.022 |
| 14-06 | 14.8 | 10.9 | 94 | 0.018 |
| 05-10 | 20.2 | 14.6 | 92 | 0.034 |
| maximum | | | | 0.034 |
| minimum | | | | 0.016 |
| average | | | | 0.022 |

Table 5.3: Mount Edgecombe 2003

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 09-05 | 18.8 | 15 | 86 | 0.021 |
| 16-06 | 13.5 | 12 | 94 | 0.008 |
| 19-06 | 13.9 | 12.3 | 94 | 0.008 |
| 28-06 | 15.1 | 13.8 | 93 | 0.008 |
| 26-07 | 16.3 | 15 | 96 | 0.010 |
| 26-07 | 13.7 | 4.1 | 95 | 0.033 |
| 31-07 | 16.6 | 14.4 | 92 | 0.013 |
| 28-08 | 16.3 | 2.3 | 93 | 0.049 |
| 31-08 | 17 | 13.9 | 91 | 0.017 |
| 30-09 | 16.2 | 14 | 91 | 0.012 |
| maximum | | | | 0.049 |
| minimum | | | | 0.010 |
| average | | | | 0.018 |

Table 5.4: Richards Bay 2002

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 04-06 | 15.1 | 13.3 | 91 | 0.010 |
| 23-06 | 15.8 | 12.6 | 93 | 0.016 |
| 24-06 | 11.7 | 9.3 | 97 | 0.010 |
| 25-06 | 14.8 | 13.6 | 96 | 0.007 |
| 05-07 | 11.8 | 9.2 | 95 | 0.011 |
| 22-07 | 16.7 | 13.5 | 88 | 0.016 |
| 28-07 | 16.8 | 15.2 | 95 | 0.010 |
| 07-08 | 14.6 | 11.8 | 95 | 0.014 |
| maximum | | | | 0.016 |
| minimum | | | | 0.007 |
| average | | | | 0.012 |

Table 5.5: Richards Bay 2003

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 13-02 | 22.9 | 15.2 | 96 | 0.053 |
| 28-03 | 21.9 | 12 | 92 | 0.056 |
| 02-05 | 18.6 | 11.7 | 95 | 0.036 |
| 21-05 | 18 | 14.4 | 96 | 0.021 |
| 21-05 | 16.1 | 6.9 | 98 | 0.039 |
| 01-06 | 14.2 | 11.7 | 96 | 0.012 |
| 06-06 | 13.2 | 11.7 | 97 | 0.008 |
| 15-06 | 14.2 | 11.9 | 97 | 0.012 |
| 23-06 | 19.4 | 15.9 | 94 | 0.022 |
| 15-08 | 16.1 | 13 | 90 | 0.016 |
| 02-09 | 16.8 | 14.9 | 94 | 0.012 |
| maximum | | | | 0.056 |
| minimum | | | | 0.008 |
| average | | | | 0.028 |

Table 5.6: Virginia 2001

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 17-05 | 18.7 | 13 | 90 | 0.030 |
| 31-05 | 18.2 | 16.5 | 94 | 0.012 |
| 01-07 | 16.1 | 10.7 | 89 | 0.024 |
| 02-07 | 17.7 | 13.1 | 92 | 0.024 |
| 11-07 | 16.6 | 11.4 | 88 | 0.024 |
| 15-07 | 19.2 | 15.8 | 91 | 0.021 |
| 13-08 | 16.2 | 14 | 95 | 0.013 |
| 02-09 | 18.1 | 15 | 94 | 0.019 |
| 05-09 | 19.1 | 15.8 | 91 | 0.021 |
| 17-09 | 19.4 | 16.7 | 92 | 0.018 |
| 11-10 | 17.4 | 16.2 | 96 | 0.009 |
| maximum | | | | 0.030 |
| minimum | | | | 0.009 |
| average | | | | 0.020 |

Table 5.7: Virginia 2002

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 14-03 | 21.9 | 16.4 | 95 | 0.038 |
| 11-05 | 17.7 | 13 | 88 | 0.024 |
| 11-05 | 16.5 | 14.5 | 93 | 0.012 |
| 14-05 | 14.7 | 12.8 | 96 | 0.010 |
| 17-05 | 19.6 | 15.6 | 91 | 0.024 |
| 21-05 | 15 | 11.8 | 92 | 0.015 |
| 23-05 | 17 | 13.6 | 87 | 0.018 |
| 24-05 | 17.4 | 15 | 87 | 0.014 |
| 23-06 | 18.7 | 14.5 | 95 | 0.025 |
| 26-06 | 19 | 13.2 | 87 | 0.030 |
| 28-06 | 13.5 | 12 | 95 | 0.008 |
| 28-06 | 12.8 | 11.4 | 95 | 0.007 |
| 04-07 | 15.2 | 9.7 | 89 | 0.023 |
| 12-08 | 16.1 | 12.6 | 86 | 0.017 |
| 19-08 | 16.4 | 15.3 | 97 | 0.007 |
| 20-08 | 17.7 | 14.5 | 91 | 0.019 |
| 23-08 | 18 | 16.3 | 96 | 0.012 |
| 19-09 | 19.9 | 16.3 | 94 | 0.024 |
| 28-09 | 18 | 16.6 | 96 | 0.010 |
| maximum | | | | 0.038 |
| minimum | | | | 0.007 |
| average | | | | 0.018 |

Table 5.8: Virginia 2003

| Date | Air Temperature | Surface Temperature | Humidity | Dew Rate (mm/h) |
|---------|-----------------|---------------------|----------|-----------------|
| 21-05 | 15.6 | 14 | 92 | 0.009 |
| 18-07 | 20.4 | 7.7 | 88 | 0.058 |
| 18-11 | 19.9 | 16.3 | 93 | 0.023 |
| maximum | | | | 0.058 |
| minimum | | | | 0.009 |
| average | | | | 0.030 |

Table 5.9: Dew Rate

| Environmental Temperature | Dew Rate (mm/h) |
|---------------------------|-----------------|
| 20 | 0.002552 |
| 19 | 0.0023949 |
| 18 | 0.0022465 |
| 17 | 0.0021066 |
| 16 | 0.0019745 |
| 15 | 0.00185 |
| 14 | 0.0017325 |
| 13 | 0.0016219 |
| 12 | 0.0015177 |
| 11 | 0.0014195 |
| 10 | 0.0013271 |

The results of the condensation rate calculations are tabulated below. Atmospheric pressure values were only available for the Kwa-Zulu Natal stations and therefore only these stations are displayed.

From the data in *Tables 5.1 to 5.8* it can be seen that the condensation rate is usually in the order of one one hundredth of a millimeter per hour, averaging 0.020mm/h over all the years for all stations analyzed, with the maximum condensation rate being 0.058mm/h. This is the condensation rate that will be used in later computer simulations. It can also be seen that the larger the temperature difference between the environmental temperature and the insulator surface temperature, the greater the condensation rate. Higher humidity levels also result in a greater condensation rate .

5.8 Comparison

A brief comparison was performed to compare the amount of water which condenses onto the surface of the insulators as a result of either normal dew formation or surface condensation. For the comparison, the air pressure was kept constant. Initially the humidity level was set to be at 100% for both cases. *Table 5.9* shows the dew rate as a result of normal dew formation conditions, the atmospheric pressure was 1000 millibar and the temperature was set to 20 °C and then decreased to 10 °C by one unit each time. The dew rate resulting from normal dew formation was calculated using equation (8).

Figure 5.29 shows the graph of the tabulated data. It can be seen that under normal condensation conditions the dew rate does not rise above 0.0026mm/h under the given environmental conditions.

The condensation rates which result from surface condensation were also tabulated and graphed. *Table 5.10* shows the surface condensation rates resulting at different humidity levels and different temperatures. The difference in the environmental temperature and the insulator surface temperatures was taken to be 3 °C. The temperature indicated in the table represents the environmental surface temperature. The resulting condensation rates (CR) are then shown for four different humidity values. The same was done for a difference

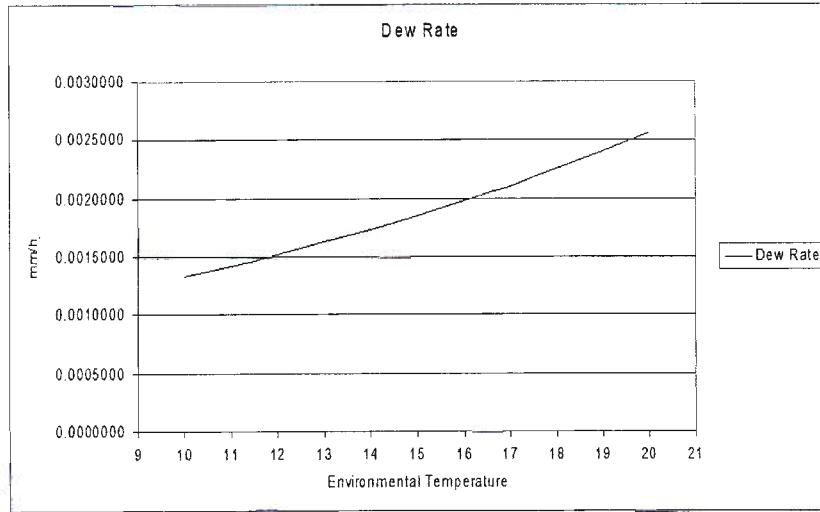


Figure 5.29: Graph of Dew Rate

Table 5.10: Condensation Rate A: 3 °C difference

| Temperature | CR: 85% | CR: 90% | CR: 95% | CR: 100% |
|-------------|---------|---------|---------|----------|
| 20 | 0.0185 | 0.02002 | 0.02113 | 0.02224 |
| 19 | 0.01773 | 0.01877 | 0.01982 | 0.02086 |
| 18 | 0.01662 | 0.0176 | 0.01858 | 0.01956 |
| 17 | 0.01558 | 0.01649 | 0.01741 | 0.01833 |
| 16 | 0.01459 | 0.01545 | 0.01631 | 0.01717 |
| 15 | 0.01366 | 0.0145 | 0.01527 | 0.01608 |
| 14 | 0.01279 | 0.01354 | 0.01429 | 0.01505 |
| 13 | 0.01196 | 0.01267 | 0.01337 | 0.01408 |
| 12 | 0.01119 | 0.01185 | 0.0125 | 0.01316 |
| 11 | 0.01046 | 0.01107 | 0.01169 | 0.0123 |
| 10 | 0.00977 | 0.01035 | 0.01092 | 0.0115 |

it temperature between the environment and the surface being only 1 °C. The results are shown in *Table 5.11*.

From these results it can be seen that with the lowest humidity level of 85% and the smallest temperature difference of 1 °C the surface condensation rate is still approximately four times greater than the corresponding dew rate. *Figures 5.30* and *5.31* show the graphs of *Tables 5.10* and *5.11* respectively.

These graphs serve to show that a higher humidity value leads to a greater surface condensation rate, and lower environmental temperatures result in a lower condensation rate. *Figure 5.32* shows the change in surface condensation rate with different dT values. The dT indicates the difference in temperature between the environmental temperature and the insulator surface temperature, the surface temperature being the lower of the two.

It can be seen that a greater difference in environmental and surface temperature leads to a greater surface condensation rate. The above four graphs

Table 5.11: Condensation Rate B: 1°C difference

| Temperature | CR: 85% | CR: 90% | CR: 95% | CR: 100% |
|-------------|---------|---------|---------|----------|
| 20 | 0.0081 | 0.00858 | 0.00906 | 0.00953 |
| 19 | 0.00761 | 0.00805 | 0.0085 | 0.00895 |
| 18 | 0.00713 | 0.00755 | 0.00797 | 0.00839 |
| 17 | 0.00669 | 0.00708 | 0.00748 | 0.00787 |
| 16 | 0.00627 | 0.00664 | 0.00701 | 0.00737 |
| 15 | 0.00587 | 0.00622 | 0.00656 | 0.0069 |
| 14 | 0.0055 | 0.00582 | 0.00614 | 0.00647 |
| 13 | 0.00515 | 0.00545 | 0.00575 | 0.00605 |
| 12 | 0.00481 | 0.0051 | 0.00538 | 0.00566 |
| 11 | 0.0045 | 0.00477 | 0.00503 | 0.0053 |
| 10 | 0.00421 | 0.00446 | 0.0047 | 0.005 |

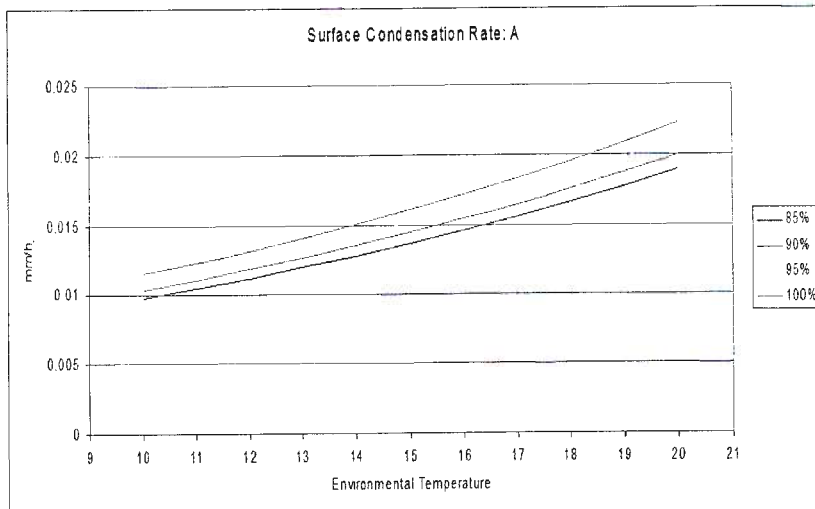


Figure 5.30: Graph of Condensation Rate: A

and three tables show that surface condensation will lead to more rapid wetting of the insulator surface than if normal dew formation were to take place.

5.9 Cloud Cover

There are other factors which affect the condensation rate. The amount of cloud cover is one factor which affects condensation rate. Less cloud cover results in more radiative cooling and therefore the insulator surface temperature should cool more quickly than with cloud cover [13]. This would theoretically result in a greater condensation rate on cloudless nights. However it has been observed that that greatest condensation rates occur when it is partly cloudy. This is because a high relative humidity is required for high condensation rates. Yet high relative humidity often indicates the presence of clouds [13]. For the calculations used for this research the required cloud cover data was not available

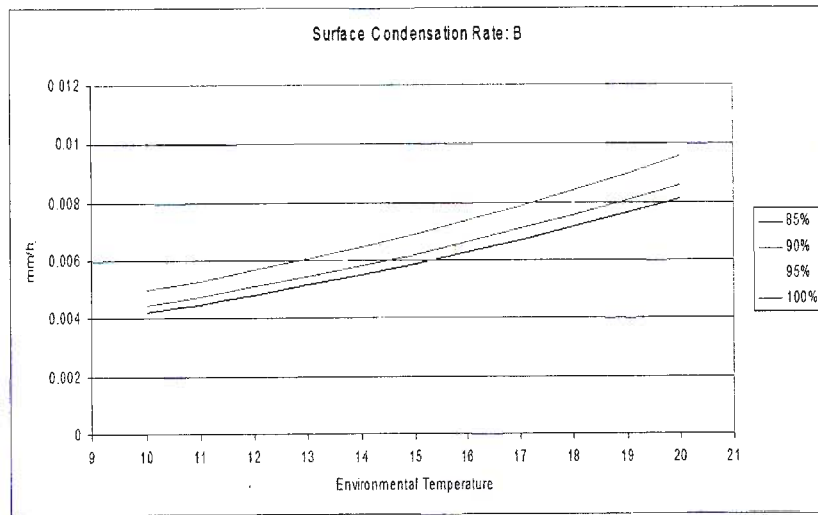


Figure 5.31: Graph of Condensation Rate: B

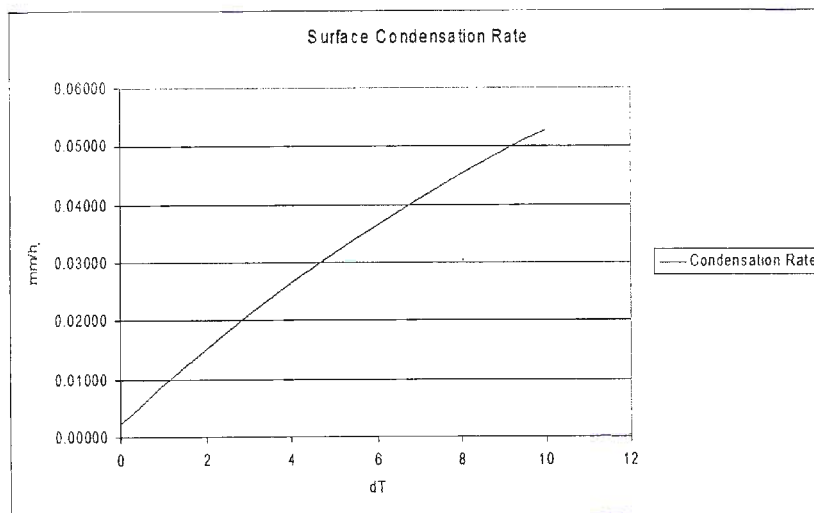


Figure 5.32: Graph of Condensation Rate

and was therefore not included in the equations. It was found that not taking the effect of cloud cover into account would lead to a maximum possible error of 14% on the condensation rate, as mentioned in section 4.7 of Chapter 4.

5.10 Wind Speed and Dew Rise

It has been observed that dew formation is more likely during events of weak or zero wind activity [13]. This is consistent with the findings in this dissertation. The results of the temperature analysis indicated that surface condensation was

only likely to occur at periods of no wind.

Another factor which can increase the amount of water that condenses onto a surface is dew rise. Dewrise is a result of moisture within the underlying soil which evaporates and can often result in dew formation. It has been observed that moisture from soil and plant crops can significantly increase the amount of dew which results from condensation [14]. The effects of dewrise, if applicable at insulator height, will perhaps be investigated at a later time. The presence of dewrise will only serve to increase the amount on surface condensation and therefore result in an increase in discharge activity.

5.11 Weather Chamber

The weather data which was received from the South African Weather Service was analyzed so that an accurate weather chamber could be constructed in order to test the performance of outdoor insulators under specific conditions. The conditions which will be used for the testing will be: marine pollution in the form of a salt pollution layer; cold temperatures ranging between 10 °C and 22 °C; increases in the humidity level from about 80% to 100%.

Extreme cases of surface condensation were presented. These extreme weather conditions can be simulated in the weather chamber to be constructed for testing. It is proposed that the simulation of these extreme humidity and temperature conditions will lead to rapid wetting of the insulator surface due to surface condensation.

The weather conditions will be simulated in a refrigeration container equipped with equipment capable of reproducing the correct humidity levels, in this case steam boilers. Dipping in a salt, kaolin and tap water slurry will be used to contaminate the surface of the insulators.

5.12 References

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Chapter 6

MAXWELL SIMULATIONS

6.1 Introduction

The behavior of high voltage insulators is often determined by the amount of pollution and wetting on the surface of the insulator [1]. This Chapter covers the implementation and results of the finite element method program, *Maxwell* to simulate the unpolluted and polluted insulators. Specifically the effect of different conductivities of the wetted pollution layer on the current density and surface resistances. The program was used to predict the voltage fields, electric fields and leakage current densities for a variety of high voltage insulators.

6.2 Maxwell the program

Maxwell 3D version 11 was used to simulate and solve three-dimensional electromagnetic field problems, it does this by using the finite element method (FEM). The program requires the user to construct a three-dimensional representation of the problem they wish to simulate. For this project this included the drawing of the various high voltage insulators, assigning the appropriate materials, boundaries, meshes and excitations.

6.3 Insulator Profiles

Four types of high voltage insulator profiles were used in this project. Three of the insulators were polymer insulators, one with a silicone rubber housing and two with an EPDM housing. All the polymer insulators had fiber glass cores. The fourth was a glass cap-and-pin type insulator. The geometry and permittivities of the four different types of insulators are presented as well as the pollution layer thicknesses and conductivities.

6.3.1 Silicone Rubber

The silicone rubber insulator, which was rated for 22kV, had a fiber glass core which was covered by a 2mm thick silicone rubber housing. *Figure 6.1* shows the dimensions of the 22kV silicone rubber insulator, it had six sheds and deeper set end fittings. The unpolluted and the polluted insulators were modeled in *Maxwell* to obtain the electric field and the current density plots respectively.

Table 6.1: Conductivities used for Pollution Layer

| Pollution Severity | Conductivity Range | Conductivity Used |
|--------------------|--------------------|-------------------|
| Light | 0 - 0.0075 S/m | 0.006 S/m |
| Medium | 0.0076 - 0.02 S/m | 0.015 S/m |
| Heavy | 0.0201 - 0.035 S/m | 0.0275 S/m |

For the Purposes of this dissertation the silicone rubber insulator which will be used in the *Maxwell* simulations and the practical testing will be labeled SiR1.

A value of 5.3 was used for the permittivity of the fiberglass and a value of 3.5 was used for the permittivity of the silicone rubber housing. The conductivity of the pollution layer was set to vary between a light pollution severity and a heavy pollution severity. *Table 6.1* shows the different conductivities used for the different pollution severities as in accordance with IEC 60815 [2]. The thickness of the pollution layer was made to be 0.058mm as was found in Chapter 5 section 5.7.

6.3.2 EPDM

Two EPDM high voltage insulators were simulated for the purposes of comparison. The one EPDM insulator was rated for 22kV system voltage and the other for 33kV system voltage. Both EPDM high voltage insulators consisted of a fiber glass core enclosed by a 2mm thick EPDM housing. The one insulator had eight sheds, the other had six sheds. Both had steel end fittings. *Figures 6.2* and *6.3* shows the dimensions of the EPDM insulators. Again both unpolluted and polluted EPDM insulators were modeled in *Maxwell*. For the Purposes of this dissertation the 22kV EPDM insulator, which will be used in the *Maxwell* simulations and the practical testing, will be labeled EPDM1. The 33kV EPDM insulator will be labeled EPDM2.

A value of 2.3 was used for the permittivity of the EPDM housing. The permittivity of the fiber glass core was set at 5.3 as before. As with the silicone rubber insulator the conductivity of the pollution layer was set to have varying pollution severities, as in accordance with IEC 60815 and seen in *Table 6.1*. The thickness of the pollution layer was made to be 0.058mm as was found in Chapter 5 section 5.7.

6.3.3 Glass Cap-and-Pin

The glass cap-and-pin insulator simulated was a single unit. A string of anymore units required too much computational power to be analyzed efficiently. The segment consisted of the standard glass shed and the steel cap and pin. *Figure 6.4* shows the basic dimensions of the glass insulator. The cement which is usually used to join the glass with the metal caps and pins was assumed to be metal in order to simplify the *Maxwell* simulations. For the Purposes of this dissertation the glass cap-and-pin type disc insulator which will be used in the *Maxwell* simulations and the practical testing will be labeled Glass1.

The glass was set to be the standard glass in the *Maxwell* materials library. It had a permittivity of 1. The metal cap and pins were set to be steel. Again the pollution layer on the glass cap-and-pin insulator was set to have varying

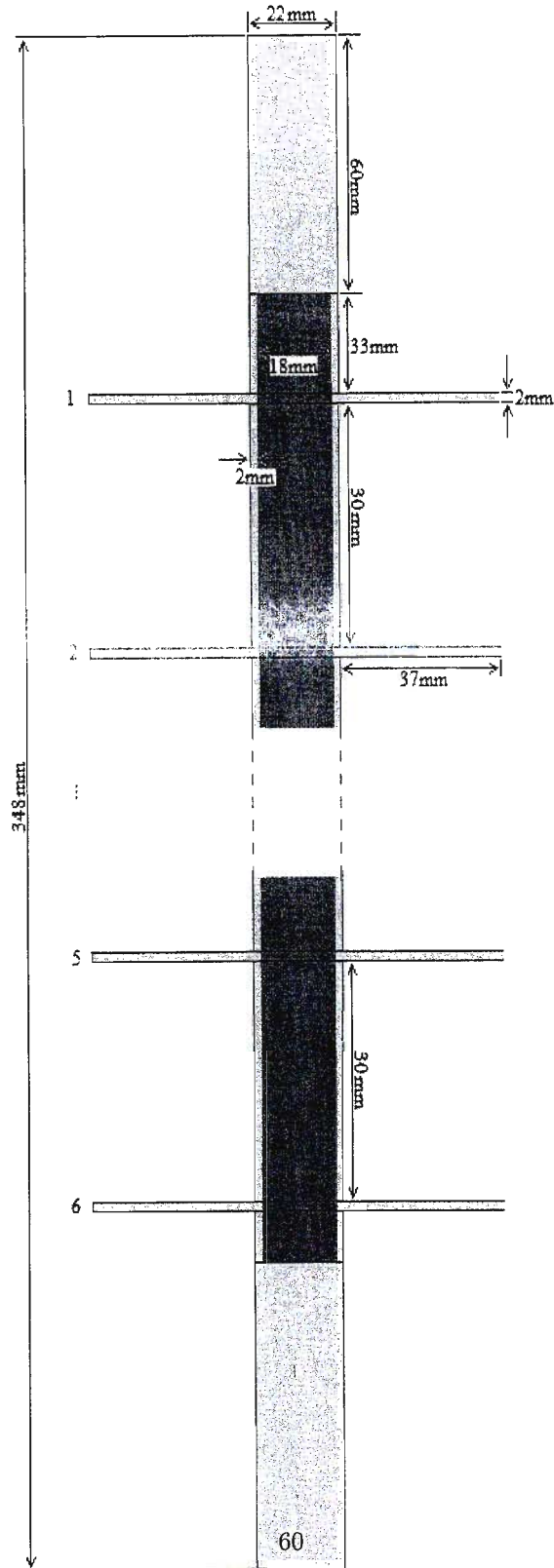


Figure 6.2: EPDM1 Insulator Profile

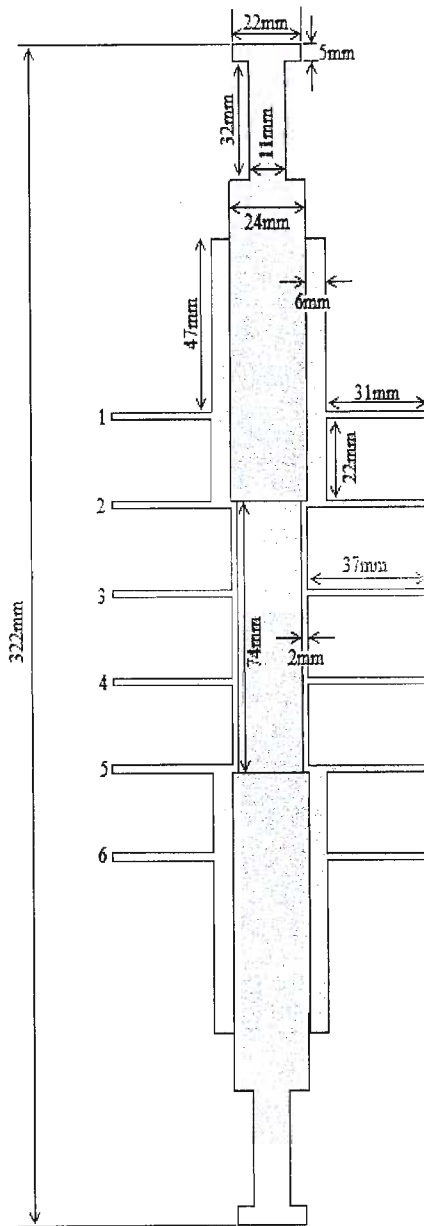


Figure 6.1: SiR1 Profile

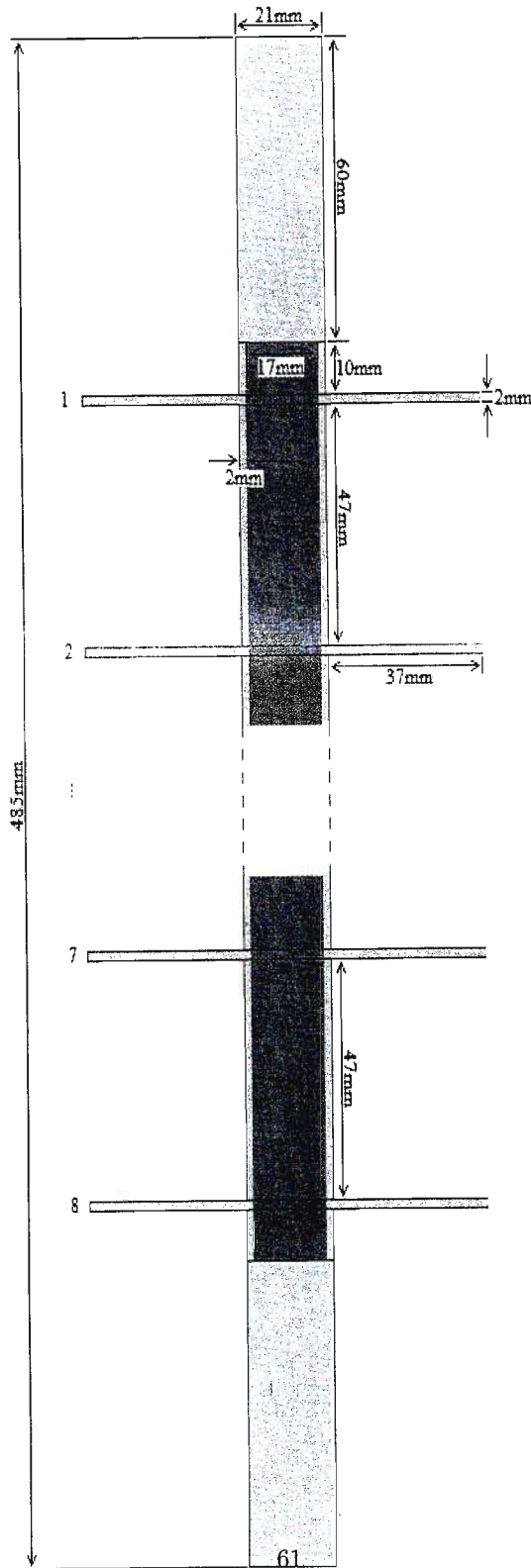


Figure 6.3: EPDM2 Insulator Profile

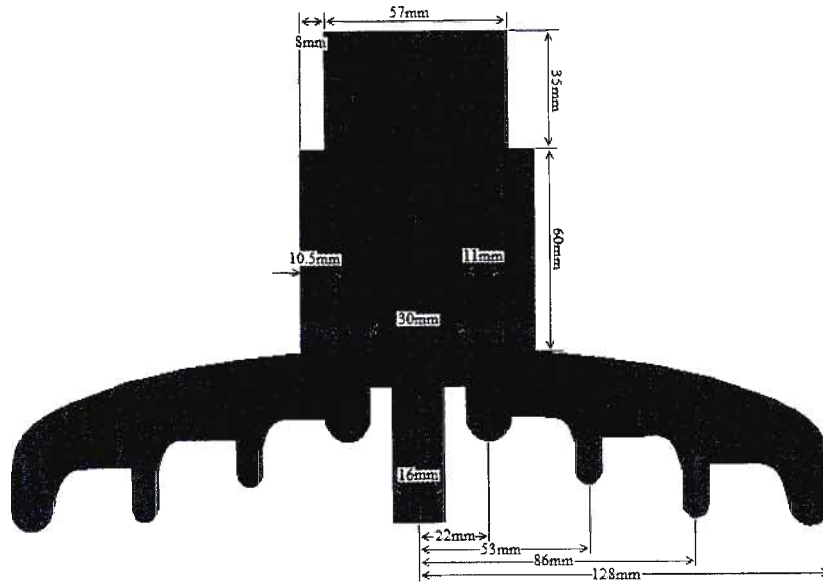


Figure 6.4: Glass1 Insulator Profile

pollution severities as indicated in *Table 6.1*. The thickness of the pollution layer was made to be 0.058. However due to the complexity of the shed geometry it was difficult to maintain an even pollution layer thickness. The thickness of the pollution layer is consistent for the majority of the insulator surface and is only slightly uneven over the tops of the glass sheds, here the thickness does not vary by more than 50%.

6.4 Project Set-up

A number of different parameters were required for the final analysis of the high voltage insulators using *Maxwell*. The solution setup was used to define the number of passes to be made during the analysis of the given project. The program was set to do a maximum of 24 passes whilst calculating the output data for the EPDM1, EPDM2 and SiR1 insulators. Only 10 passes were set for the Glass1 insulator. The solution error not exceeding 0.1% for the polymer insulators and 1% for the glass cap-and-pin insulators. The minimum amount of refinement per pass was set to 30% and a minimum of two passes could be made.

A certain amount of mesh refinement was required to obtain an accurate solution for the polymer insulators. The mesh was set to have a maximum length of 0.01mm and up to 10 000 000 tetrahedrons. The constraints of the computer did not allow for a more refined mesh nor a greater number of passes in the solution setup of the polymer insulators nor any kind of mesh operation for the Glass1 insulator. It is felt the the output given these constrains is accurate enough to be used for comparison purposes.

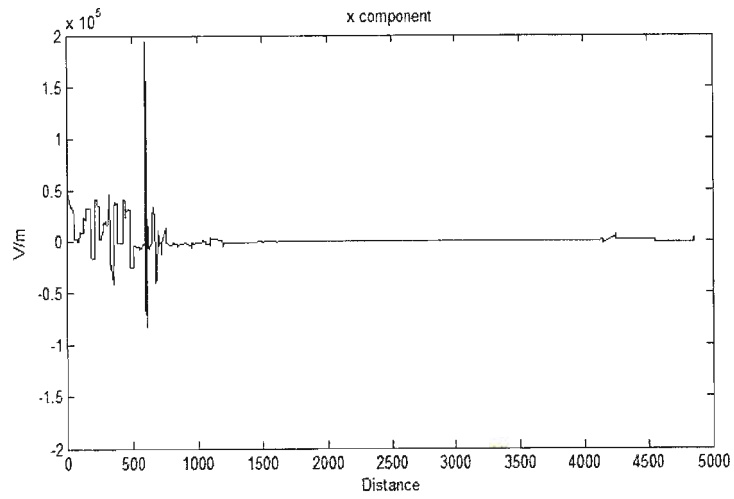


Figure 6.5: EPDM2 Electric Field: x component

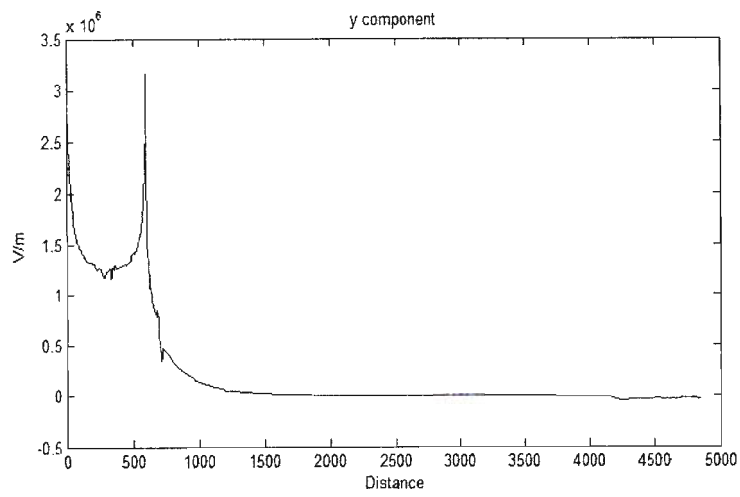


Figure 6.6: EPDM2 Electric Field: y component

The solution type was set as electric. For the unpolluted insulators an electrostatic solution was required as no current was expected to flow. The DC conduction solution was required for the polluted insulators as a current was expected to flow through the pollution layer.

The excitation used for the unpolluted insulators was a voltage source. For each unpolluted insulator a voltage of 30kV was applied to the high voltage end fitting. The other end fitting was set to ground potential. All of the insulators were centered inside a cubic meter box at ground potential. The excitation for the polluted insulators was in the form of a 1A current source applied at one end of the pollution layer. A sink was placed at the opposite end of the pollution layer.

Two sets of polylines were drawn on the insulators depending on the analysis to be performed. For the polluted insulators a line was drawn to follow the contour of the insulator profile so that the current density along that line could be calculated. The other line was either a straight line drawn from the base of the insulator to the top, inline with the surface of the sheath, used for the polymer insulators, or a straight line drawn through the center of the insulator from the base of the pin to the top of the cap, of the glass insulator. This was used for the unpolluted simulation. This line was used to aid with the plotting of voltage gradient and the electric field resulting from the voltage source.

6.5 EPDM Results

The EPDM1 and EPDM2 insulators were simulated in *Maxwell*. The EPDM high voltage insulators were simulated using a 30kV voltage source for the unpolluted insulator and a 1A current source for the polluted insulators. The current density was plotted for a wetted light, medium and heavy pollution layer for the EPDM insulators.

6.5.1 EPDM2: Unpolluted

The voltage field and electric field generated by the 30kV source at the high voltage end of the insulator are shown in *Figures 6.5 through 6.9*. *Figures 6.5, 6.6 and 6.7* show the x, y and z components of the electric field respectively. *Figure 6.8* shows the magnitude of the electric field and *Figure 6.9* shows the voltage gradient for the insulator.

The z electric field component, *figure 6.7*, is the electric field of interest, as it is the electric field along the length of the insulator.

6.5.2 EPDM2: Polluted

The current density along the insulator surface was plotted given the different pollution layers highlighted above. In all cases the pollution layer thickness was set to 0.058mm. The voltage which would have to be applied across the wetted, polluted insulator in order for a 1A current to flow, can be calculated by taking the integral, along the length of the insulator surface, of the electric field. This calculation was performed using the *Fields Calculator* in the *Maxwell* program. Since the electric field is the current density divided by the conductivity, it follows that equation (15) can be used to calculate the required voltage [3].

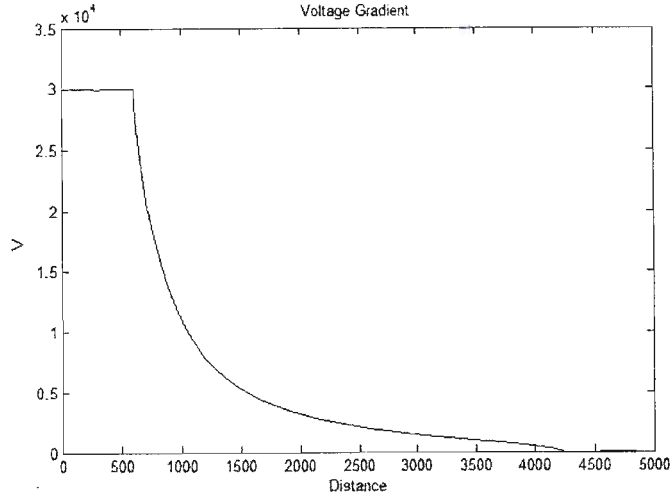


Figure 6.9: EPDM2 Voltage Gradient

$$V = - \int J/\sigma \cdot ds \quad (15)$$

Where V is the voltage applied to the polluted insulator, J is the current density and σ is the conductivity of the wetted pollution layer. The integral is integrated along the line which follows the contour along the length of the insulator.

Figures 6.10 through to 6.12 show the current density plots generated by Maxwell, for the different pollution severities. The x-axis represents the distance along the contour of the insulator, in meters, and the y-axis shows the current density value at that point, in A/m^2 .

Some of the graphs plotted show inconsistencies, in the form of random spikes on the current density curve. This can be attributed to meshing errors or an insufficient number of passes made during the analysis. Computational capability did not allow for a more refined analysis, however it is felt that the small errors in the current density plots will not significantly impact the results.

It can be seen in figures 6.10 through to 6.12 that the current density is not constant. This was expected. The plot loosely resembles a sinusoidal wave which is clipped at the top. The plot takes this shape because of the relationship between the current density and cross-sectional area as indicated in equation (16) [3].

$$J = -I/A \quad (16)$$

Here I is the current flowing through the conducting material, the wetted pollution layer in this case, and A is the cross-sectional area of the conducting material. It can be seen that if the value of A were to increase the current density, J , would decrease. This is what is being depicted in the plot of the current density.

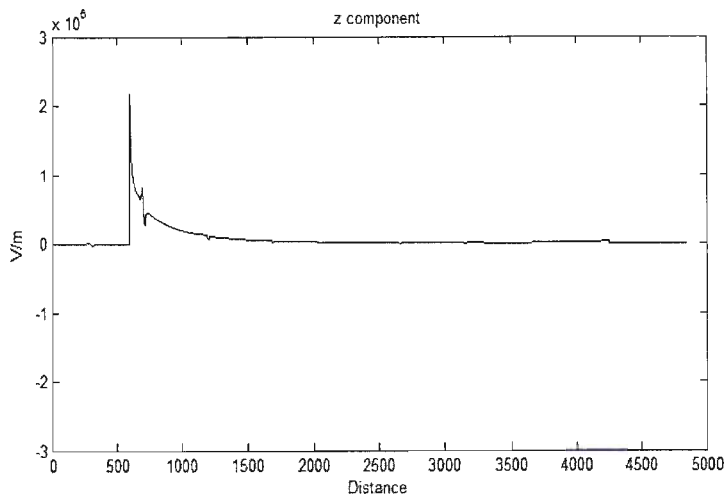


Figure 6.7: EPDM2 Electric Field: z component

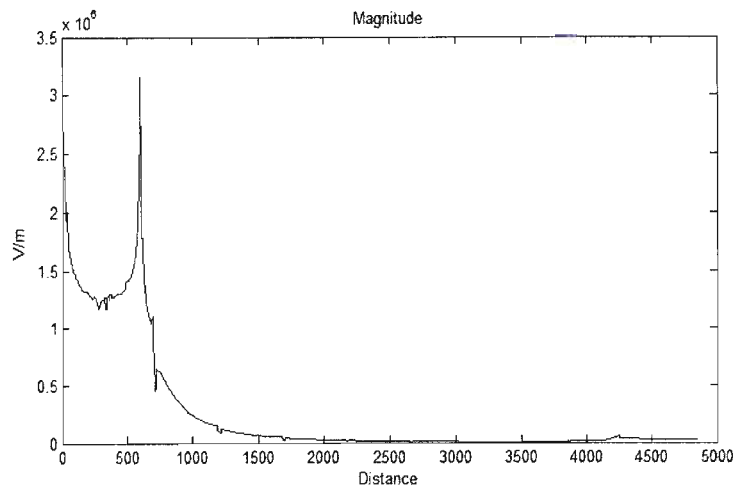


Figure 6.8: EPDM2 Electric Field: magnitude

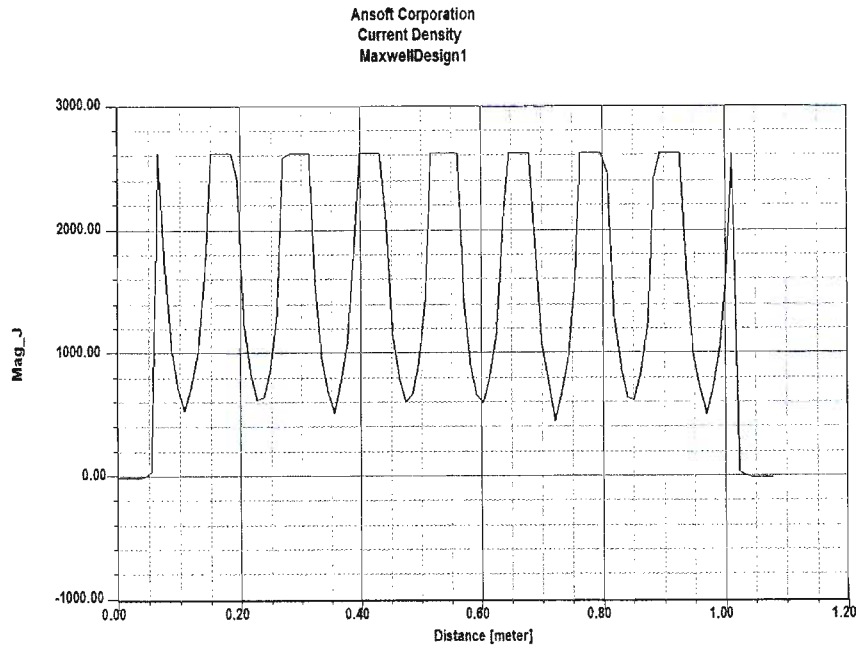


Figure 6.12: EPDM2 with a heavy pollution layer, current density

The distance shown on the x-axis indicates the distance traveled along the contour line. The pollution layer starts at 50mm from the start of the contour line. This is where the current density is shown to increase for the first time. Ideally the increase in current density should be instantaneous, however the computational capabilities of the computer running the *Maxwell* program and time constraints did not allow for sufficient meshing to accurately display this. From the first peak the current density is shown to decrease, this indicates that the cross-sectional area of the pollution layer is increasing. As the current moves out along the underneath of the first shed the cross sectional area increases as the diameter of the insulator housing profile increases. It then travels over the edge of the shed tip and back towards the sheath. Here the current density is seen to increase again. Once the current reaches the sheath it travels up along the surface to the next shed. The current density shown for this length is constant as there is no change in housing diameter and hence conducting layer cross-sectional area. This can be seen in *figure 6.10* as the "flattened" peaks of the curve. The general shape of all the current density plots is expected to be similar for the different pollution layer conductivities on the polymer insulators, as the profile of these insulators remains similar. The current density plot for the glass insulator is expected to be quite different from this as the profile is dissimilar.

Equation (15) was used to calculate the voltage which would have to be applied to enable a 1A current to flow over the surface of the wetted, polluted insulator. The *Fields Calculator* available in *Maxwell* was used to perform the calculations required to determine this voltage. *Table 6.2* shows the results of this voltage calculation.

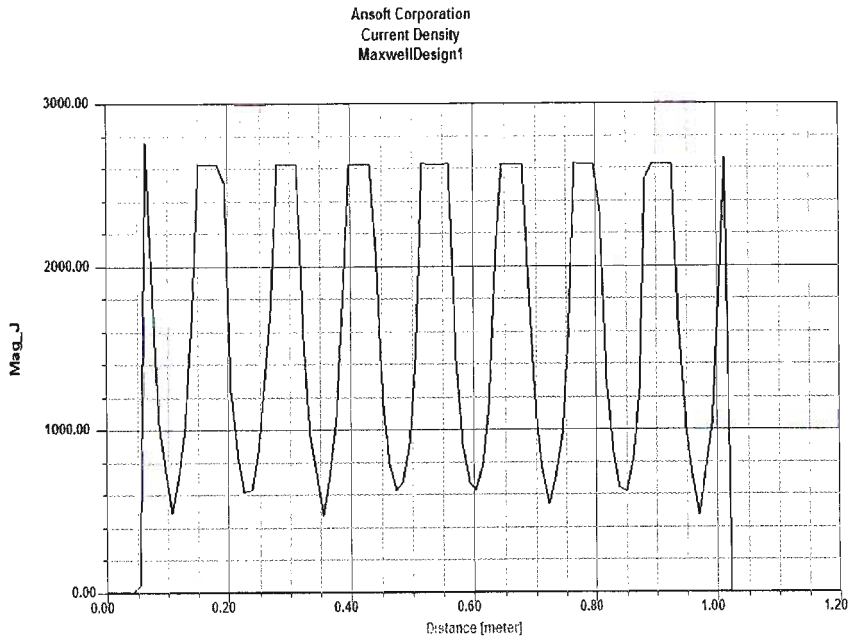


Figure 6.10: EPDM2 with a light pollution layer, current density

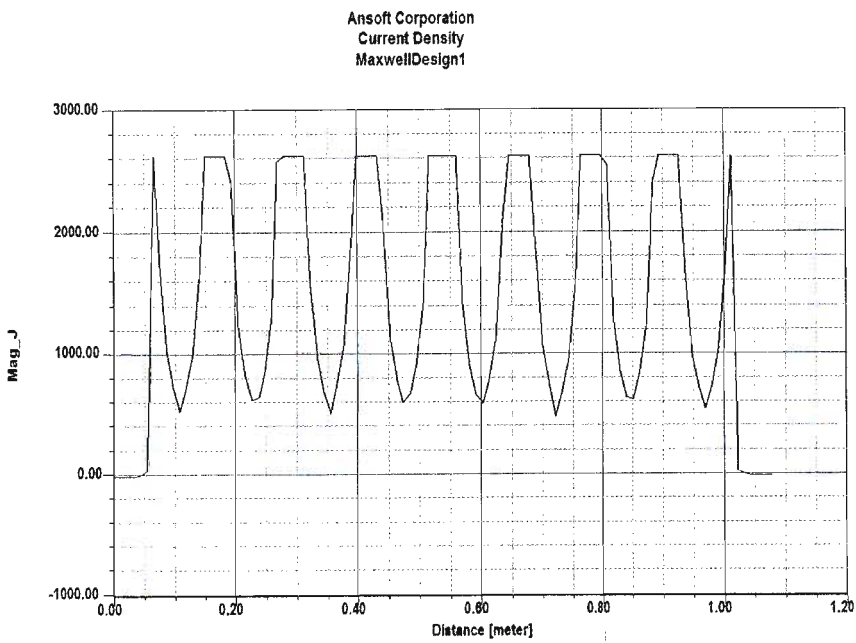


Figure 6.11: EPDM2 with a medium pollution layer, current density

Table 6.2: EPDM2 Voltage Calculation Results

| Pollution Severity | Applied Voltage |
|--------------------|-----------------|
| Light | 15.4MV |
| Medium | 6.1MV |
| Heavy | 3.3MV |

As the results in *Table 6.2* indicate, the voltage that would have to be applied decreases with increasing conductivity of the wetted pollution layer. This is explained by equation (17), which shows the relationship between the conductivity of a material and its resistance [3].

$$R = \frac{L}{\sigma \cdot A} \quad (17)$$

Here L is the length of the resistance layer, σ is the conductivity and A is the cross-sectional area through which the current will flow.

If the conductivity increases the resistance decreases hence allowing a greater current to flow. A decrease in the resistance of the wetted pollution layer would result in a decrease in the voltage which would have to be applied to achieve the fixed current of 1A. The insulator with the medium pollution layer therefore requires less applied voltage to achieve a current of 1A than the insulator with the light pollution layer.

6.5.3 EPDM1: Unpolluted

The voltage and electric fields resulting from the 30kV applied voltage source at the high voltage end of the insulator, are shown in *Figures 6.13* through *6.17*. *Figures 6.13*, *6.14* and *6.15* show the x, y and z components of the electric field respectively. *Figure 6.16* shows the magnitude of the electric field and *Figure 6.17* shows the voltage gradient for the insulator.

The z electric field component, *Figure 6.15*, is the electric field of interest, as it is the electric field along the length of the insulator.

6.5.4 EPDM1: Polluted

The current density along the insulator surface was plotted for the different pollution layers above. Again the pollution layer thickness was set to 0.058mm.

Figures 6.18 through to *6.20* show the current density plots generated by *Maxwell*. The x-axis represents the distance along the contour of the insulator, in meters, and the y-axis shows the current density value at that point, in A/m^2 .

Again some of the graphs plotted display random spikes on the current density curve. This can be attributed to meshing errors or an insufficient number of passes made during the analysis.

Equation (15) was used to calculate the voltage which would have to be applied to enable a 1A current to flow over the surface of the wetted, polluted insulator. *Table 6.3* shows the results of this voltage calculation.

As the results in *Table 6.3* indicate, the voltage that would have to be applied decreases with increasing conductivity of the wetted pollution layer.

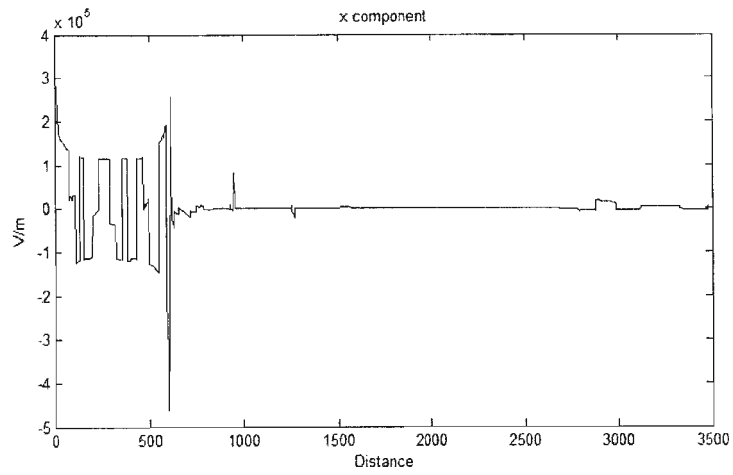


Figure 6.13: EPDM1 Electric Field: x component

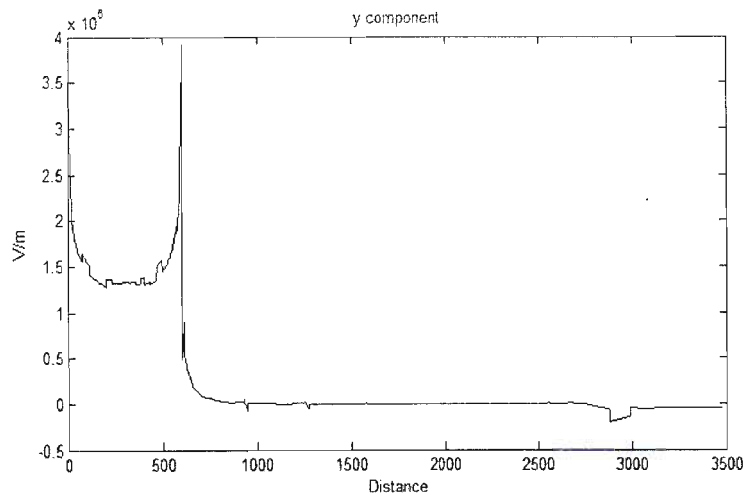


Figure 6.14: EPDM1 Electric Field: y component

Table 6.3: EPDM1 Voltage Calculation Results

| Pollution Severity | Applied Voltage |
|--------------------|-----------------|
| Light | 9MV |
| Medium | 3.6MV |
| Heavy | 2MV |

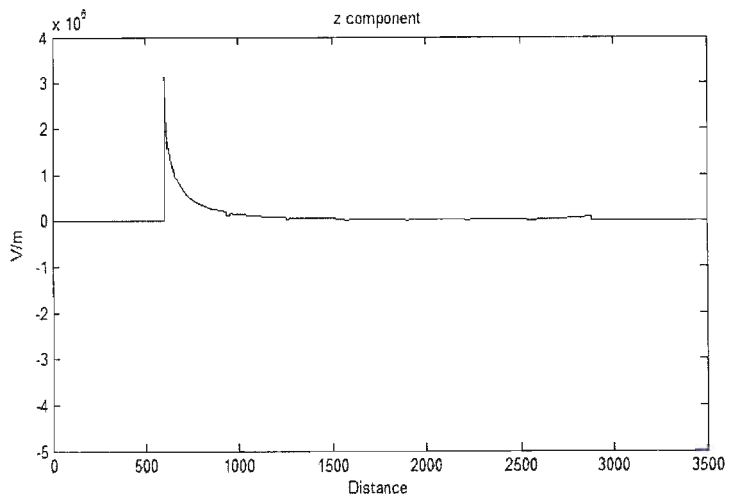


Figure 6.15: EPDM1 Electric Field: z component

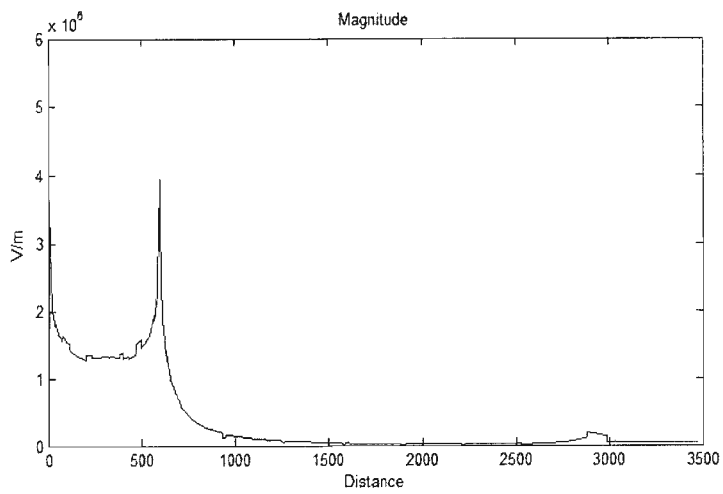


Figure 6.16: EPDM1 Electric Field: magnitude

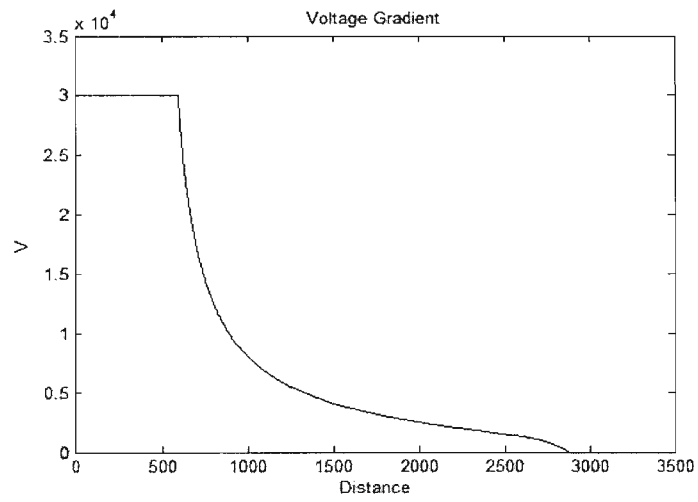


Figure 6.17: EPDM1 Voltage Gradient

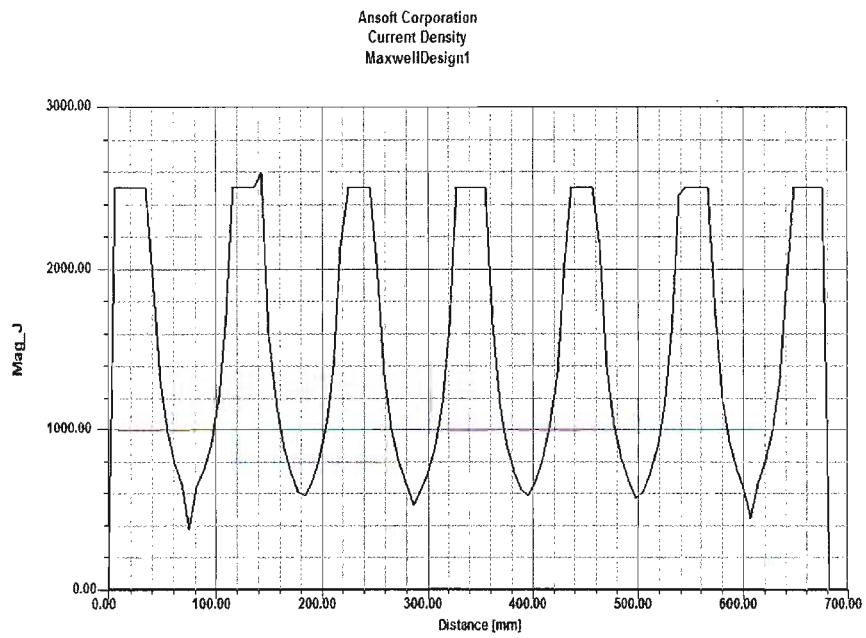


Figure 6.18: EPDM1 with a light pollution layer, current density

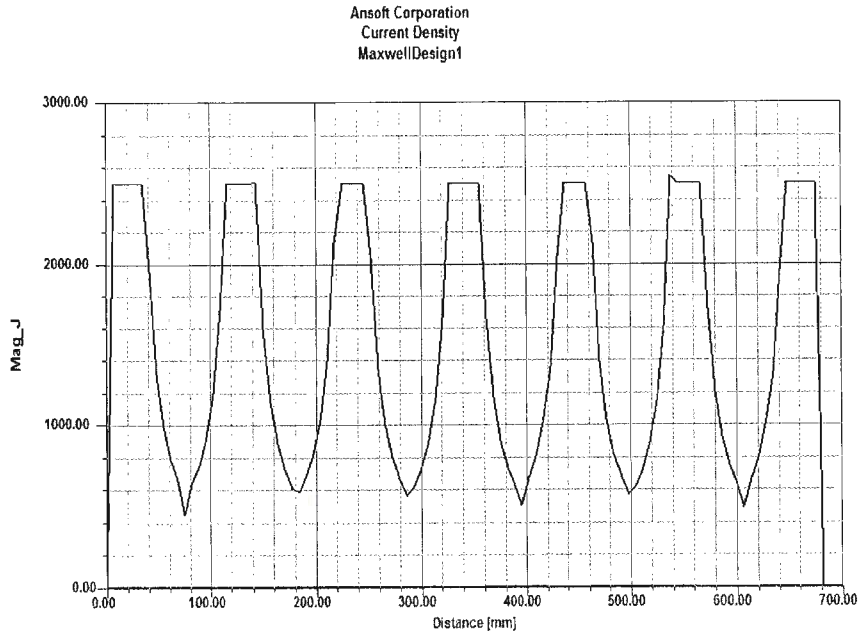


Figure 6.19: EPDM1 with a medium pollution layer, current density

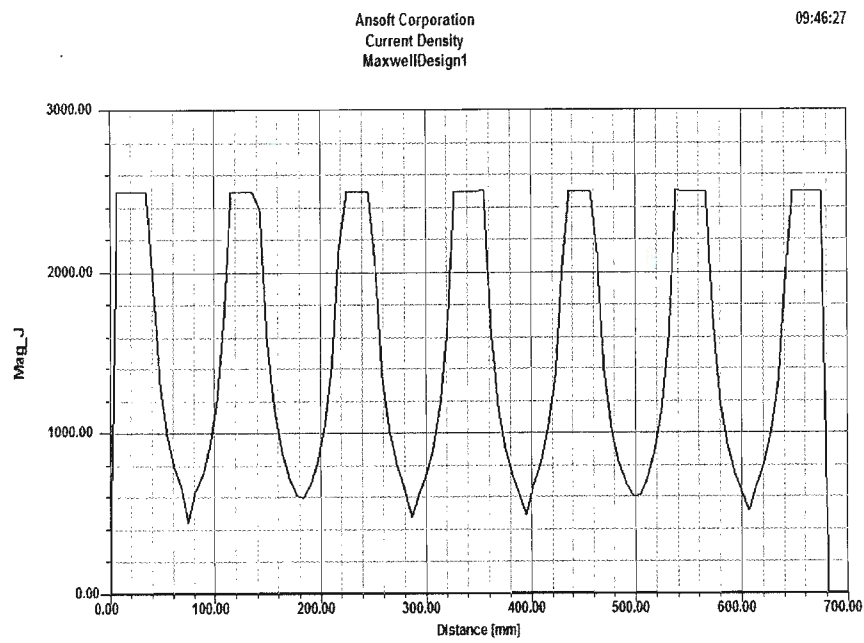


Figure 6.20: EPDM1 with a heavy pollution layer, current density

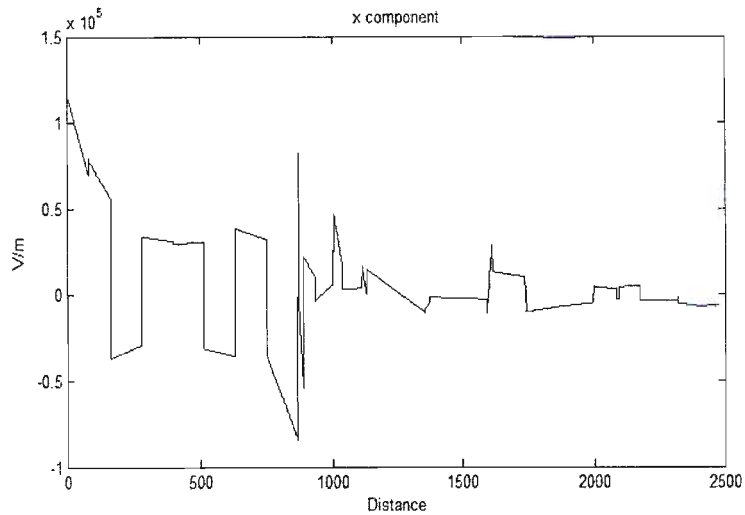


Figure 6.21: SiR1 Electric Field: x component

6.6 Silicone Rubber Results

The SiR1 high voltage insulator was simulated using a 30kV voltage source for the unpolluted insulator. The current density was plotted for pollution layers with varying conductivities ranging from a light pollution layer to a heavy pollution layer.

6.6.1 SiR1: Unpolluted

Figures 6.21 through 6.25 show the voltage fields and electric fields generated by the simulation. Figures 6.21, 6.22 and 6.23 show the x, y and z components of the electric field respectively. Figure 6.24 shows the magnitude of the electric field and Figure 6.25 shows the voltage gradient for the insulator.

The z electric field component, Figure 6.23, is the electric field of interest, as it is the electric field along the length of the insulator.

6.6.2 SiR1: Polluted

Again a 1A current was made to flow through the conductive, wetted pollution layer. The current density along the insulator surface was plotted for the different pollution severities highlighted above.

As with the EPDM insulators some of the graphs plotted show inconsistencies, in the form of random spikes on the current density curve. This too can be attributed to meshing errors or an insufficient number of passes made during the analysis.

Figures 6.26 through to 6.28 show the current density plots for the different pollution severities. The distance is measured in meters and the current density in A/m^2 .

The *Fields Calculator* in *Maxwell* was used to evaluate the solution to equation (15) so that it could be deduced what voltage would have to be applied to

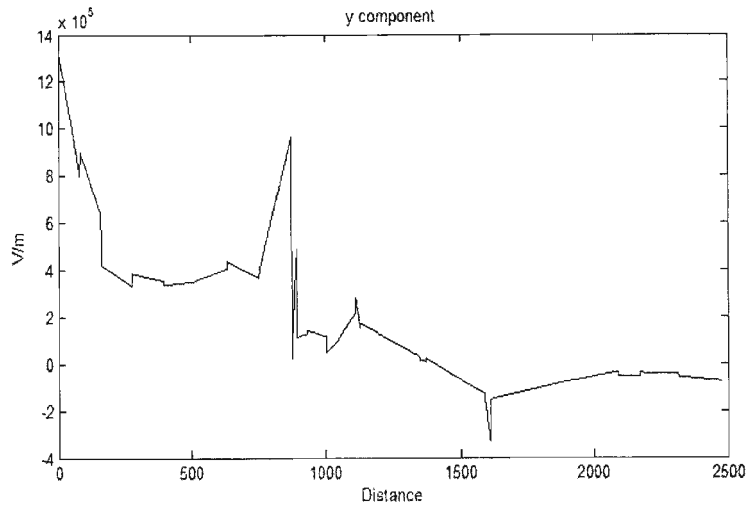


Figure 6.22: SiR1 Electric Field: y component

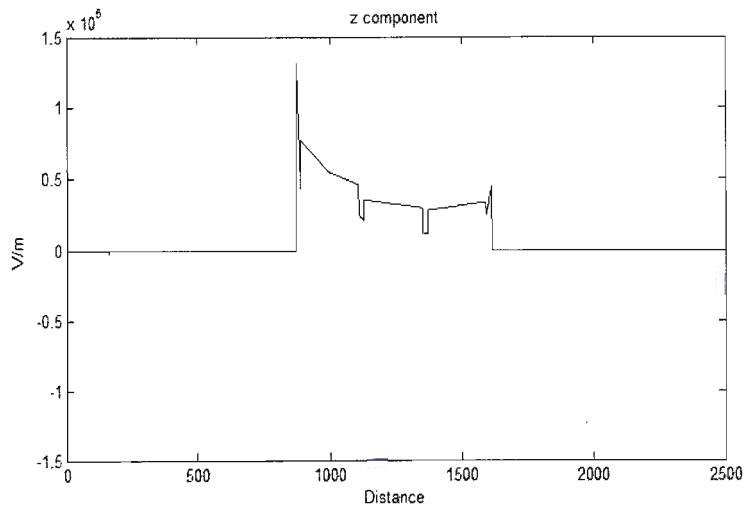


Figure 6.23: SiR1 Electric Field: z component

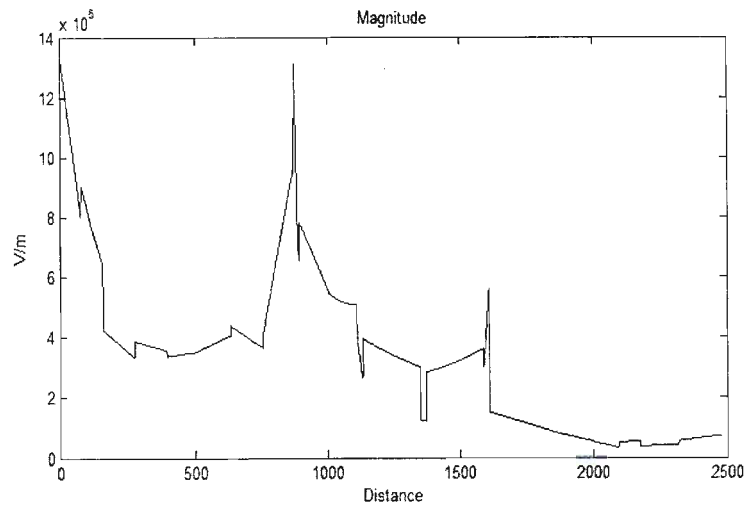


Figure 6.24: SiR1 Electric Field: magnitude

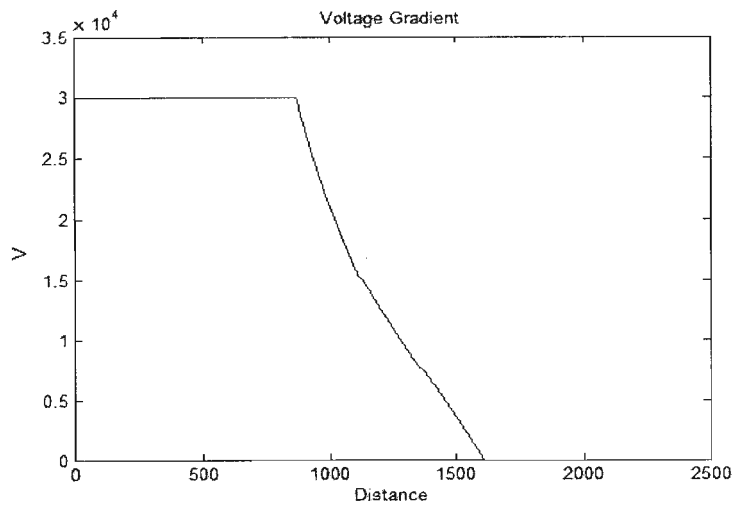


Figure 6.25: SiR1 Voltage Gradient

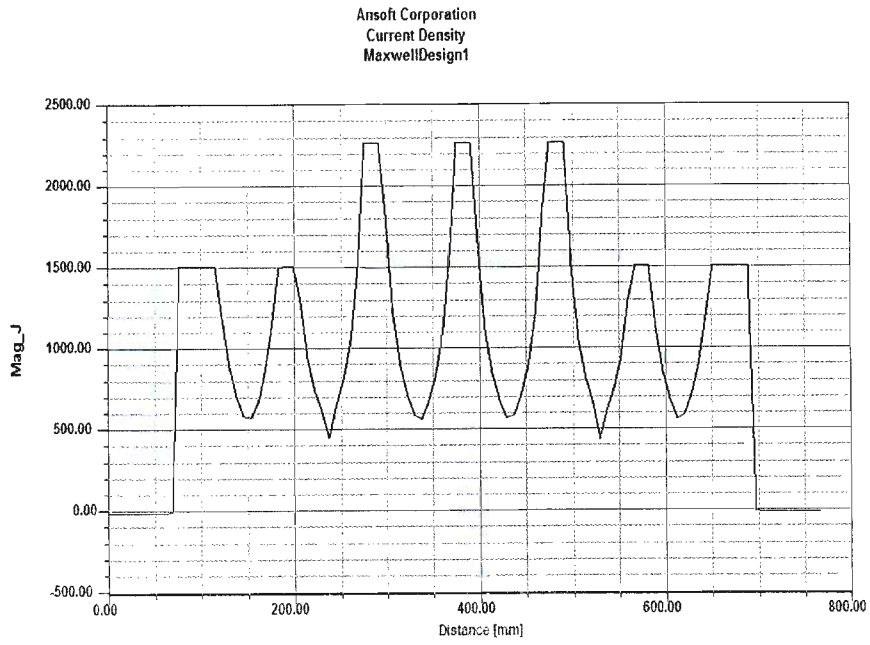


Figure 6.26: SiR1 with a light pollution layer, current density

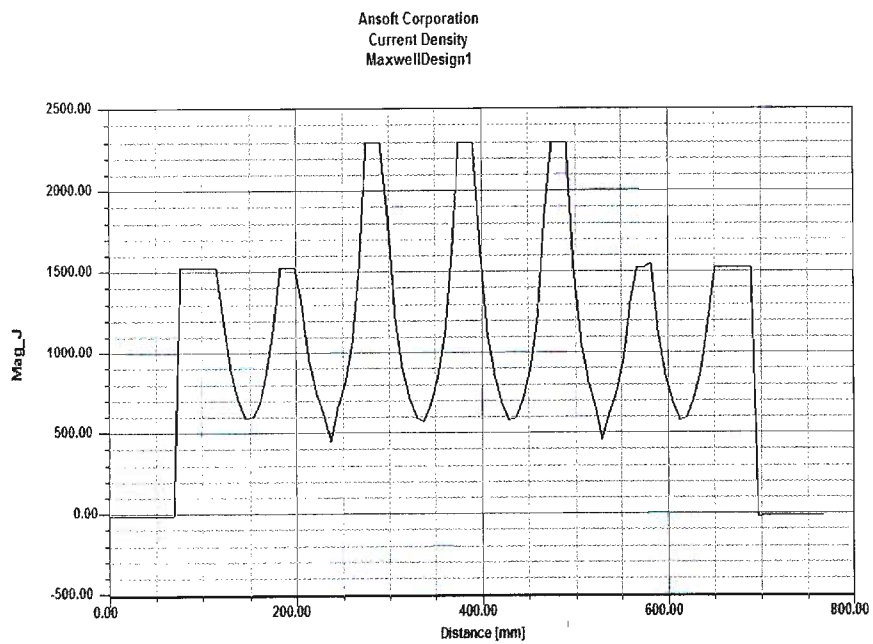


Figure 6.27: SiR1 with a medium pollution layer, current density

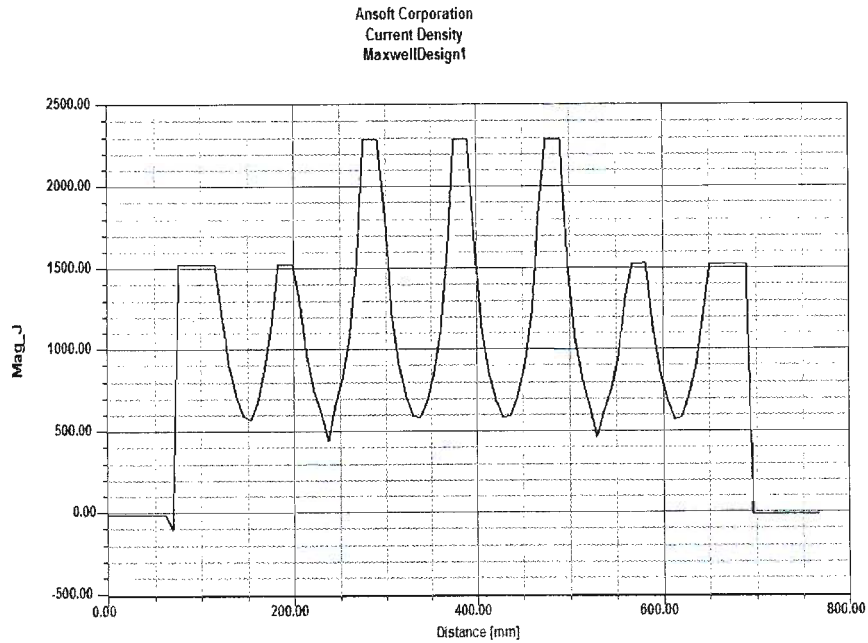


Figure 6.28: SiR1 with a heavy pollution layer, current density

Table 6.4: SiR1 Voltage Calculation Results

| Pollution Severity | Applied Voltage |
|--------------------|-----------------|
| Light | 6MV |
| Medium | 2.4MV |
| Heavy | 1.3MV |

the polluted insulators so that a current of 1A would flow. *Table 6.4* shows the results of these calculations.

Again the more heavily polluted insulators require a smaller voltage to be applied to render the 1A current.

6.7 Glass Cap-and-Pin Results

The Glass1 insulator was simulated using a 30kV voltage source for the unpolluted insulator and a 1A current source for the polluted insulators. The current density was plotted for a wetted light, medium and heavy pollution layer on the glass insulators.

6.7.1 Glass1: Unpolluted Insulator

The voltage field and electric field generated in the unpolluted *Maxwell* simulation are shown in *figures 6.29* through *6.33*. *Figures 6.29*, *6.30* and *6.31* show the x, y and z components of the electric field respectively. *Figure 6.32*

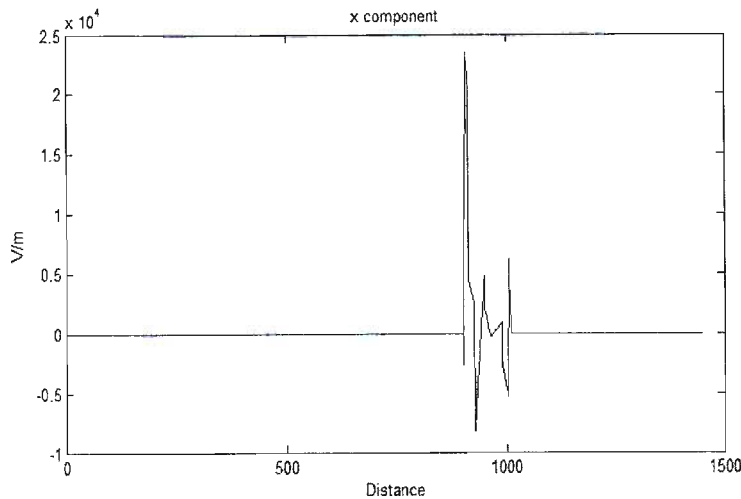


Figure 6.29: Glass1 Electric Field: x component

shows the magnitude of the electric field and *Figure 6.33* shows the voltage gradient for the insulator.

The z electric field component, *Figure 6.31*, is the electric field of interest, as it is the electric field along the length of the insulator.

6.7.2 Glass1: Polluted

A 1A current was applied to one end of the polluted insulator and the *Maxwell* simulation was analyzed. The current density along the insulator surface was plotted for the three different pollution layers indicated above. The pollution layer was set to be 0.058mm thick. These plots show inconsistencies. This is because the geometry of the glass cap-and-pin insulators was substantially more complicated than the non-ceramic insulators. The *Maxwell* simulations therefore required a lot more memory to perform the analysis. Unfortunately not enough memory was available to perform the number of passes or meshing operations required to achieve a more accurate plot. However the general shape of the plots is correct.

Figures 6.34 through to *6.36* show the current density plots for the different pollution severities. Again the x-axis represents the distance along the contour of the insulator, in meters, and the y-axis shows the current density value at that point, in A/m^2 .

The *Fields Calculator* in *Maxwell* was used to evaluate the solution to equation (15) so that it could be deduced what voltage would have to be applied to the polluted insulators so that a current of 1A would flow. *Table 6.5* shows the results of these calculations.

Again the polluted insulators with a higher conductivity require a smaller voltage to be applied to render the 1A current.

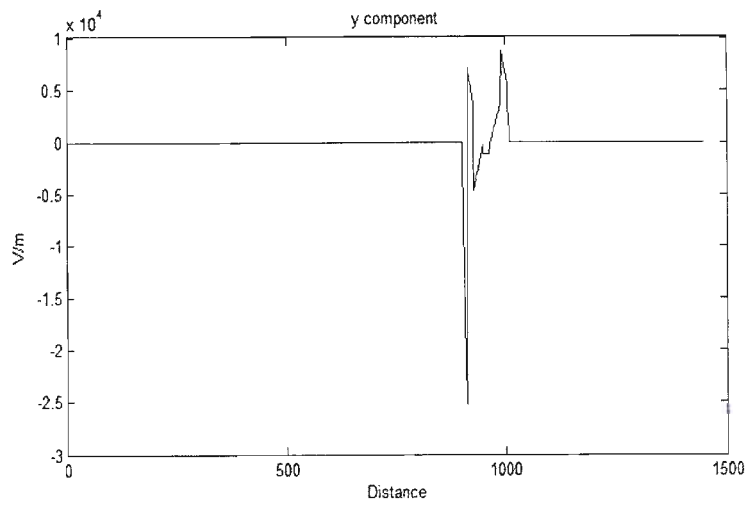


Figure 6.30: Glass1 Electric Field: y component

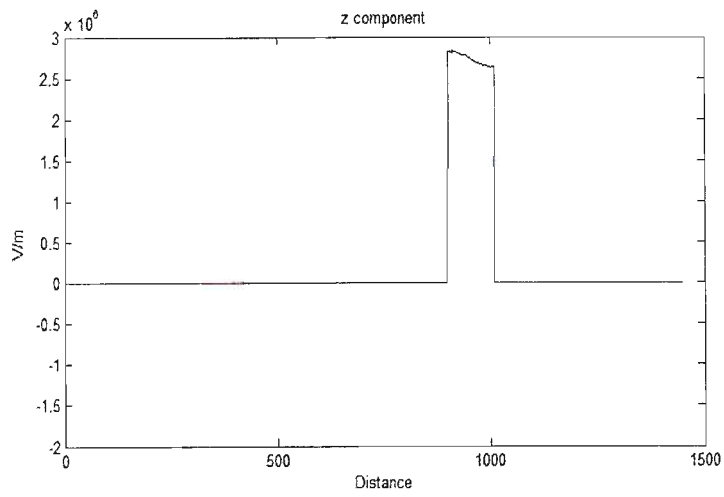


Figure 6.31: Glass1 Electric Field: z component

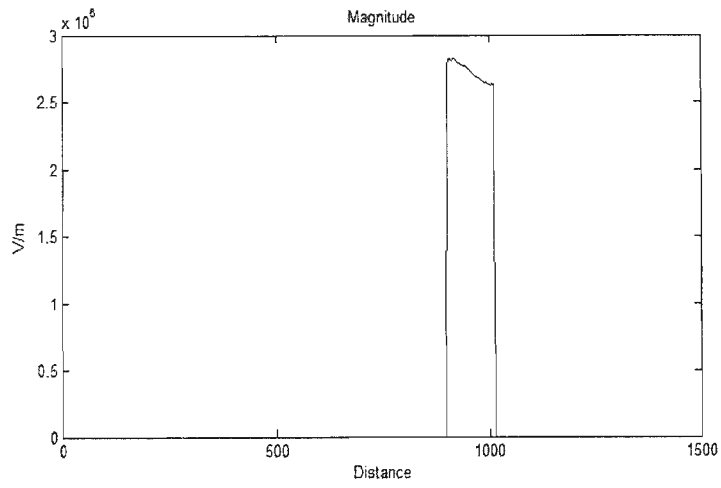


Figure 6.32: Glass1 Electric Field: magnitude

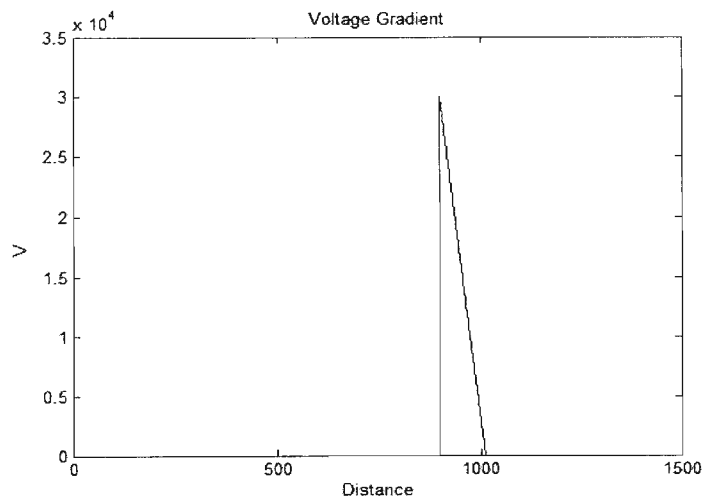


Figure 6.33: Glass1 Voltage Gradient

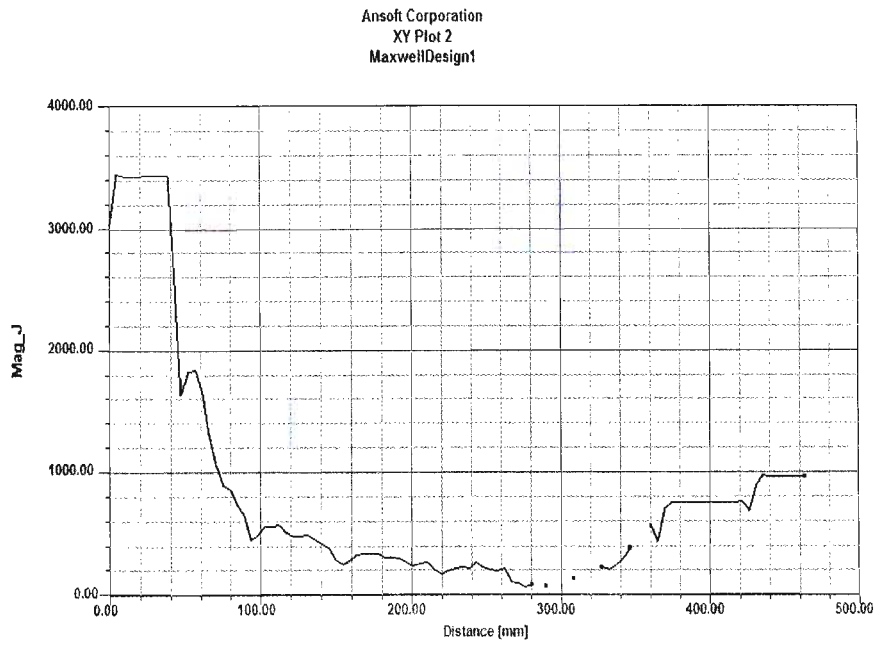


Figure 6.34: Glass1 with a light pollution layer, current density

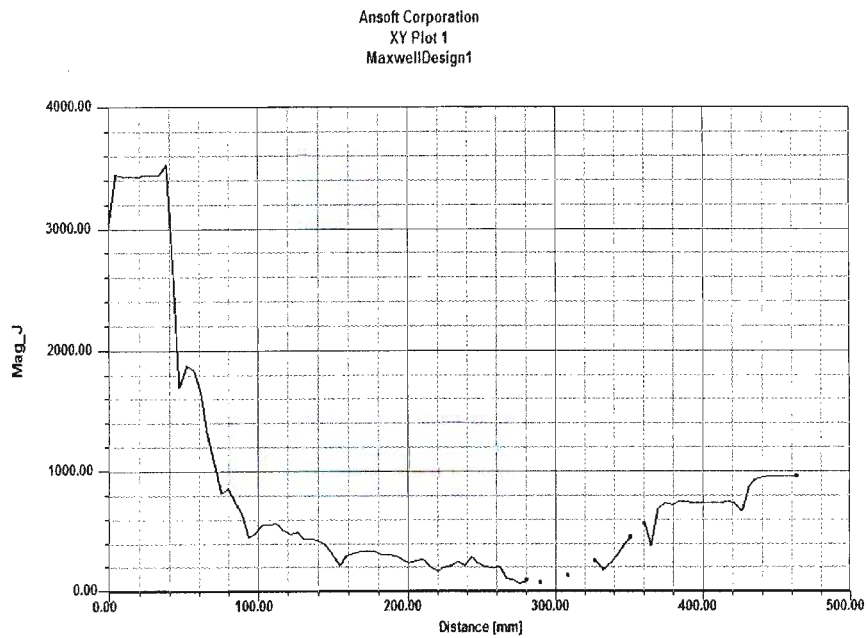


Figure 6.35: Glass1 with a medium pollution layer, current density

6.8 References

- [1] T Sörqvist, AE Vlastós. "Performance and Aging of Polymeric Insulators". IEEE Transactions on Power Delivery, Volume 12, Number 4. October 1997.

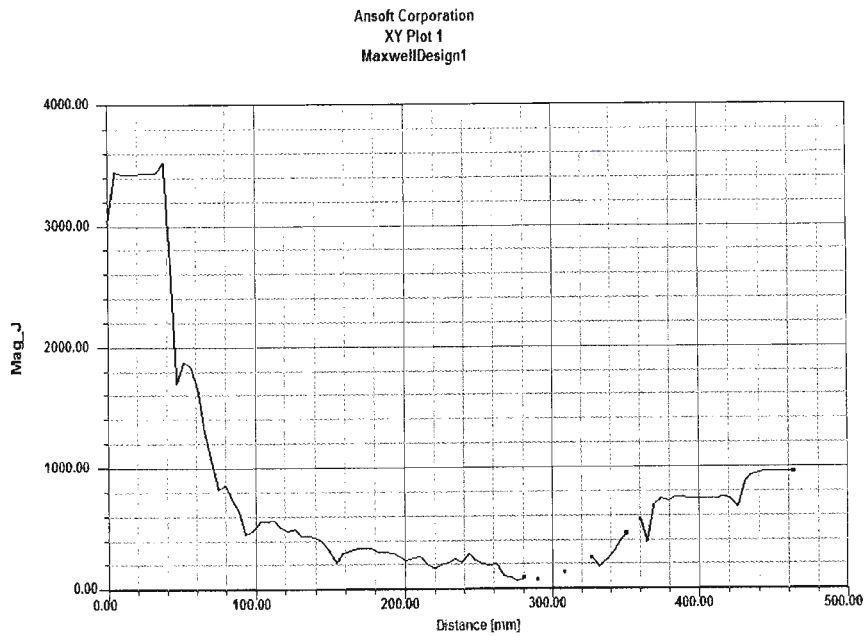


Figure 6.36: Glass1 with a heavy pollution layer, current density

Table 6.5: Glass1 Voltage Calculation Results

| Pollution Severity | Applied Voltage |
|--------------------|-----------------|
| Light | 3.2MV |
| Medium | 1.2MV |
| Heavy | 687KV |

[2] ABB OVR-3 Recloser Passes Severe Environment Testing. [http://library.abb.com/GLOBAL/SCOT/scot235.nsf/VerityDisplay/C2692765935E24A1C12572BA0065C9E5/\\$File/OVR-3%20KIP%20TS%20Test%20Results%20Rev%20A.pdf](http://library.abb.com/GLOBAL/SCOT/scot235.nsf/VerityDisplay/C2692765935E24A1C12572BA0065C9E5/$File/OVR-3%20KIP%20TS%20Test%20Results%20Rev%20A.pdf). April 2007.

[3] Serway, Beichner. *Physics for Scientists and Engineers*. Saunders College Publishing, Orlando, Fifth Edition, 2000. Chapter 27.

Chapter 7

ANALYSIS OF *MAXWELL* SIMULATIONS

7.1 Introduction

The finite element method program *Maxwell*, by *Ansoft*, was used to simulate various insulators under wetted polluted and dry unpolluted insulator conditions. Silicone rubber, EPDM and glass cap-and-pin insulators, SiR1, EPDM1, EPDM2 and Glass1, were simulated. The aim of the simulations was to tie in with work done to investigate the effect of cold temperatures and high humidity on outdoor high voltage insulators. This chapter contains an analysis of the *Maxwell* simulations.

The unpolluted insulators were simulated with a 30kV source applied to the high voltage end of the insulator. The voltage and electric fields which resulted were then plotted. The polluted insulators were simulated with a 0.058mm thick pollution layer on the surface, as this was found to be the surface condensation rate present under high humidity and cold temperature conditions. This was found in Chapter 5 section 5.7. The conductivity of the wetted pollution layer was varied so as to achieve pollution severities ranging from light to heavy as indicated in IEC 60815 [1].

7.2 Comparison of Results

A comparison between the different wetted polluted and unpolluted insulators is made. The difference in current density plots for the different types of wetted polluted insulators is also examined as well as the voltage which would have to be applied to induce a 1A current in the pollution layer. The surface resistances of the different polluted insulators was also examined.

7.2.1 Unpolluted Insulators

The Unpolluted insulators were simulated with a 30kV source applied to the high voltage terminal. The voltage and electric fields which resulted were then plotted. These values were plotted along the length of a polyline which ran along the length of the insulators. Two different EPDM insulators were simulated and one silicone rubber and one glass cap-and-pin insulator were simulated. The voltage gradient plotted for the polymer insulators were all similar and all showed a uniform exponential decay from the high voltage end as shown in *Figure 7.1*, which shows the voltage plot for the unpolluted EPDM2 insulator.

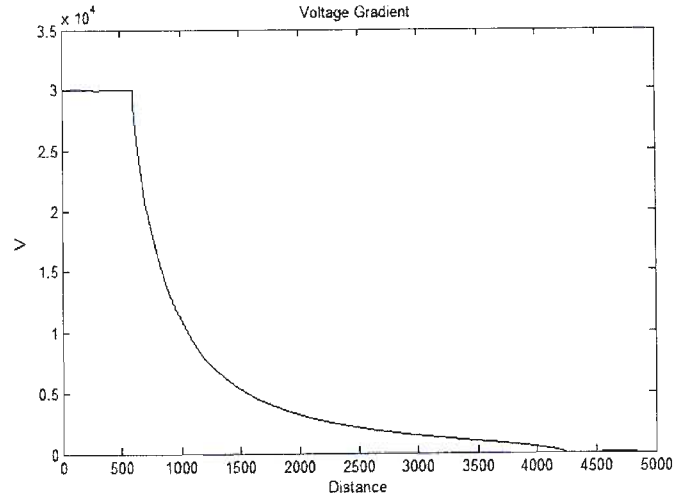


Figure 7.1: Voltage Gradient of EPDM2 Insulator

The electric fields plotted for the polymer insulators were also similar. The x , y and z electric field components were plotted. The insulators were aligned along the length of the z axis in the *Maxwell* programs. The z direction electric field components were therefore of most interest as they indicated the nature of the electric field along the length of the insulators. *Figure 7.2* shows the z component of the electric field plot for the EPDM1 unpolluted insulator.

It can be seen in *Figure 7.2* that the electric field decays along the length of the insulator. The "spikes" which can be seen in the plot indicate where the sheds of the insulator exist. The electric field in a medium depends on the permittivity. Permittivity describes the ability of a material to transmit an electric field [2]. The vacuum, in which the insulator is simulated, has a different permittivity to the housing material of the insulators, this will manifest itself as a change in electric field value as one moves along the polyline and through the different mediums.

In the electric field plot for the Glass1 insulator, the sudden increase in the electric field occurs when the polyline passes through the top of the glass as shown in area A in *Figure 7.3*. The electric field is zero within the metal of the cap and pin and non-zero in the glass separating the cap and pin.

A plot of the z component of the electric field associated with the energized Glass1 insulator can be seen in Chapter 6, section 6.7.1. All other electric field and voltage plots can also be found in Chapter 6.

7.2.2 Polluted Insulators

The shape of the insulators has a significant effect on the current density in the wet pollution layer [3]. The EPDM2 insulator current density plots, shown in section 6.5.2, Chapter 6, starts with a short spike, this is because there is only a short length of EPDM sheath before the first shed. The current density can therefore only reach a maximum over a short length before the cross sectional

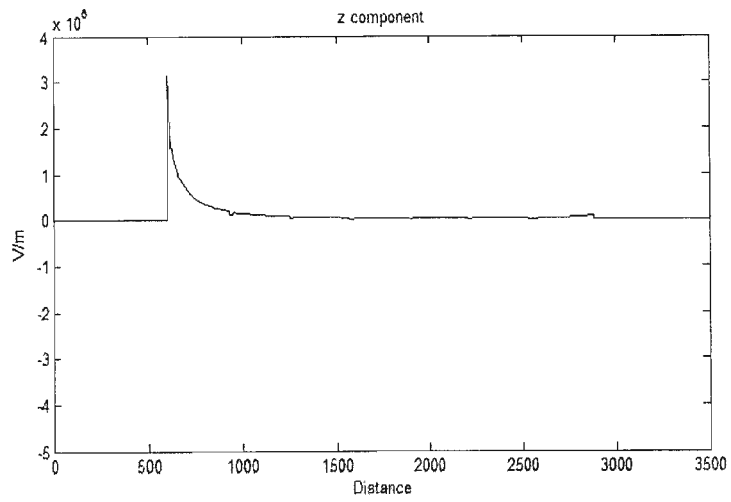


Figure 7.2: Electric Field of EPDM1 insulator: z component

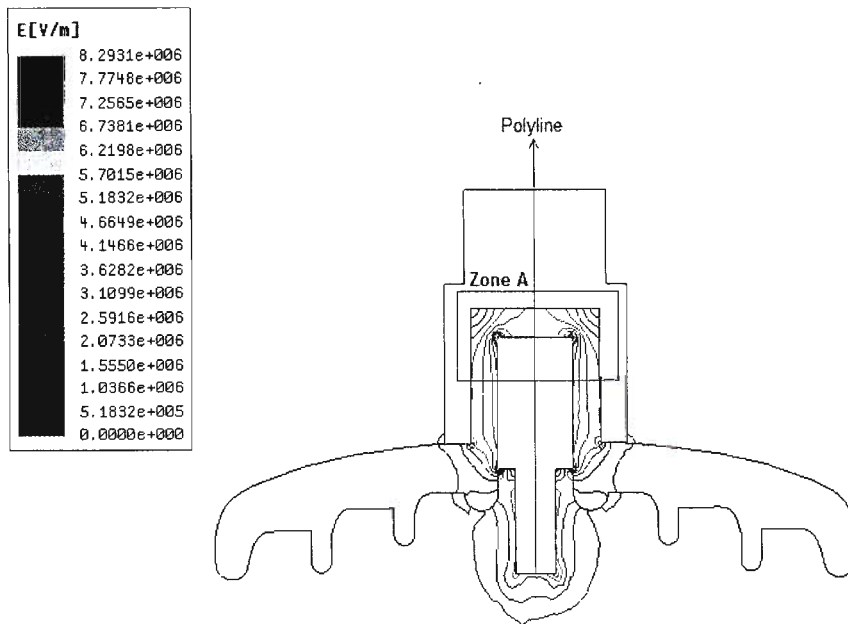


Figure 7.3: Glass1 Electric Field

Table 7.1: Voltages calculated for different insulator types

| Pollution Severity | EPDM1 | EPDM2 | SiR1 | Glass1 |
|--------------------|-------|--------|-------|--------|
| Light | 9MV | 15.4MV | 6MV | 3.2MV |
| Medium | 3.6MV | 6.1MV | 2.4MV | 1.2MV |
| Heavy | 2MV | 3.3MV | 1.3MV | 0.69MV |

area starts to increase, where the shed is located, and so the current density will decrease, as described by equation (16) below [3].

$$J = -I/A \quad (16)$$

The EPDM1 insulator, on the other hand, has a longer length of sheath material before the first shed and therefore the current density is at a maximum for a longer distance before it starts to decrease at the position of the first shed, as can be seen in the current density plots shown in section 6.5.4 of Chapter 6. The peaks plotted for the SiR1 insulator, shown in section 6.6.2 of Chapter 6, are not all the same height, this is due to a change in the diameter of the central rod. After the second shed the diameter of the rod decreases resulting in a higher current density value.

Another difference between the plots of the SiR1 and EPDM polluted insulators is the length for which the tops of the peaks remain flattened. This too is due to the length of sheath between sheds. The EPDM2 insulator has a larger shed spacing and hence the current density plots show a longer flattened region than those plots of the EPDM1 and SiR1 insulators, which have a smaller shed spacing.

The most obvious difference between the polymer insulators is the voltage which would have to be applied to the insulators to produce a 1A current in the wetted pollution layer. The voltages required to produce this current are significantly lower for the EPDM1 and the SiR1 insulators than they are for the EPDM2 insulator. This is due to the fact that the creepage distance on the EPDM2 is longer than that on the EPDM1 and SiR1 insulators. This would result in the current path on the EPDM2 insulator having a higher resistance and hence a higher voltage would have to be applied to achieve a current of 1A.

The Glass1 insulator's current density plot, shown in section 6.7.2 of Chapter 6, is far more irregular than the polymeric insulators. Firstly this is due to an insufficient number of passes or mesh operations being performed in the simulation as mentioned in the previous chapter.

Secondly, the current density plots seem more irregular because the diameter of the Glass1 insulator is constantly changing along the contour of the insulator. The current density decreases as the diameter of the insulator increases. So as the current moves out along the underside of the insulator the current density will decrease because the diameter, or cross-sectional area, is increasing [3]. Since only a single insulator was modeled no repetition of the current density plot was expected. However if more than one disc was modeled it is expected that the same shape of current density plot will be repeated for each disc. Table 7.1 shows the voltages calculated by the *Maxwell Fields Calculator* required to produce a 1A current for the different types of insulators.

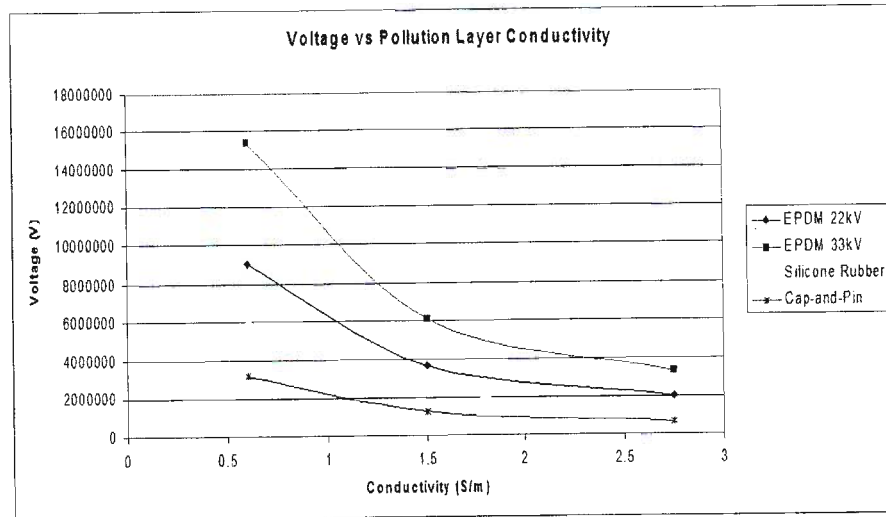


Figure 7.4: Voltage vs Conductivity

Figure 7.4 shows a graph displaying the voltages required to produce a 1A current in the pollution layer versus the conductivity of the pollution layer.

This graph further indicates the relationship between conductivity and resistance, the higher the conductivity, the lower the resistance, as shown previously in Chapter 6 equation (17). A higher conductivity level will therefore require a smaller voltage to be applied.

Table 7.2 shows the estimated surface resistance of the wetted insulators as calculated from the currents and voltages calculated in Maxwell.

The results in Table 7.2 show that a higher conductivity will result in a larger leakage current flowing over the surface of the insulator given a constant applied voltage. Figure 7.5 shows a plot of the leakage current versus the conductivity of the wetted pollution layer, assuming a constant voltage of 30kV is applied to all the insulators.

The currents shown in the graph are exaggerated in order to show the effect of the conductivity level on the leakage currents. It is expected that the leakage currents obtained in the experiments will be in the range between 1 to 100mA [4]. The voltages which will be applied to the insulators under test will be approximately 10kV.

Table 7.2: Surface resistance calculated for different insulator types

| Light | | | |
|--------|----|--------|----------------|
| | I | V | R |
| EPDM1 | 1A | 9MV | 9.04M Ω |
| EPDM2 | 1A | 15.4MV | 15.4M Ω |
| SiR1 | 1A | 6MV | 6.04M Ω |
| Glass1 | 1A | 3.2MV | 3.2M Ω |
| Medium | | | |
| | I | V | R |
| EPDM1 | 1A | 3.6MV | 3.6M Ω |
| EPDM2 | 1A | 6.1MV | 6.1M Ω |
| SiR1 | 1A | 2.4MV | 2.4M Ω |
| Glass1 | 1A | 1.2MV | 1.2M Ω |
| Heavy | | | |
| | I | V | R |
| EPDM1 | 1A | 2MV | 2M Ω |
| EPDM2 | 1A | 3.3MV | 3.3M Ω |
| SiR1 | 1A | 1.3MV | 1.3M Ω |
| Glass1 | 1A | 0.69MV | 0.69M Ω |

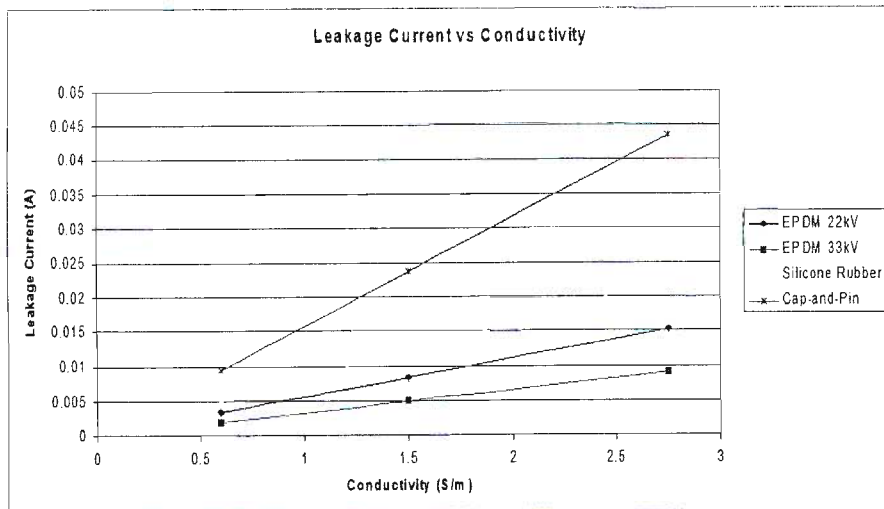


Figure 7.5: Leakage Current vs Conductivity

7.3 References

- [1] ABB OVR-3 Recloser Passes Severe Environment Testing. [http://library.abb.com/GLOBAL/SCOT/scot235.nsf/VerityDisplay/C2692765935E24A1C12572BA0065C9E5/\\$File/OVR-3%20KIPTS%20Test%20Results%20Rev%20A.pdf](http://library.abb.com/GLOBAL/SCOT/scot235.nsf/VerityDisplay/C2692765935E24A1C12572BA0065C9E5/$File/OVR-3%20KIPTS%20Test%20Results%20Rev%20A.pdf). April 2007.
- [2] Article: Permittivity. <http://en.wikipedia.org/wiki/Permittivity>. April 2007.
- [3] Serway, Beichner. "Physics for Scientists and Engineers". Saunders College Publishing, Orlando, Fifth Edition, 2000. Chapter 27.

[4]Personal correspondance.Dr DA Hoch. Former Lecturer at University of Kwa-Zulu Natal. Department of Electrical, Electronic and Computer Engineering. March 2007.

Chapter 8

EXPERIMENTAL WORK

8.1 Introduction

A number of computer simulations were performed so that the effect of various wetted pollution layers on the performance of a number of different high voltage outdoor insulators, could be examined. A practical experiment had to be set up in order to compare the results found in the computer simulations. The aim was to determine the effect of the temperature of the insulator surface on the amount of condensation due to humidity; the effect of surface conductivity on the polluted insulators performance. A weather chamber was required to simulate the weather conditions experienced in coastal areas. The insulators were tested at different temperatures and the effect of the different test temperatures was noted.

Coastal insulators are also often subjected to salt contamination [1]. The insulators to be tested had to be artificially polluted so as to compare with coastal insulators in service. The insulators were polluted by means of dipping in a slurry. The effects of the different pollution layer conductivities were also investigated. The tests were performed on the insulators modeled in the *Maxwell* program, they were the glass cap-and-pin, the 22kV EPDM, the 33kV EPDM and the 22kV Silicone Rubber insulators, labeled Glass1, EPDM1, EPDM2 and SiR1 respectively.

8.2 Polluting the Insulators

The insulators were polluted by means of dipping into a wet slurry. The slurry was made up with tap water, kaolin and salt and was contained in the appropriate container for dipping. The amount of kaolin added to the slurry was 40g/liter of water as recommended in [2]. The amount of salt added depended on the required conductivity of the pollution layer, and is detailed in section 3.1. All amounts were weighed out on an electrical scale as shown in *Figure 8.1*.

8.2.1 Glass Artificial Pollution Process

The container used for the dipping of the Glass1 insulator units was a bucket containing 8 liters of slurry. The slurry was composed of 8 liters of tap water, 320g of kaolin and salt to achieve the required conductivity level.

The Glass1 insulators were initially washed with standard dish washing liquid, to remove any grease on the insulator surface hence aiding with the uniform wetting of the insulators [3]. They were then ready for the dipping process, where they were dipped in the pollution slurry. Once the insulator was wet it was then allowed to dry. Once dry the insulators could be used for testing or ESDD measurements.

8.2.2 Polymer Artificial Pollution Process

The container used for the dipping of the EPDM1 and EPDM2 insulators was a disused insulator boiling cylinder. The cylinder held 16 liters of slurry. The slurry contained 16 liters of tap water, 640g of kaolin and salt to achieve the required conductivity level.

The EPDM1 and EPDM2 insulators were still hydrophobic due to the silicone release agent used during manufacturing still present on the surface of the insulator. It was proposed that sandblasting the insulator surface will help remove the traces of silicone and so help the insulator to wet more easily [4]. This is what was done to the EPDM1 and EPDM2 insulators and it was found that they wet well after sand blasting. Once the EPDM1 and EPDM2 insulators were dipped the excess liquid was allowed to run off and they were placed aside to dry in the horizontal position. The EPDM1 and EPDM2 insulators were rotated during the drying process in order to achieve a more uniform pollution layer.

The container used for the dipping of the SiR1 insulator was a glass beaker containing 2 liters of tap water, 80g of kaolin and the appropriate amount of salt. Sandblasting the surface of the SiR1 insulator would have little effect on the wettability of the silicone rubber surface. This is because the deeper layers of the silicone rubber material are also hydrophobic unlike those found on with EPDM material, and hence with time the hydrophobicity would be



Figure 8.1: Electric Scale

Table 8.1: Conductivity Ranges for Pollution Layers

| Pollution Severity | Conductivity Range | ESDD |
|--------------------|--------------------|---------------------|
| Light | 0 - 0.75 S/m | <0.06 mg/cm^2 |
| Medium | 0.76 - 2 S/m | 0.06-0.12 mg/cm^2 |
| Heavy | 2.01 - 3.5 S/m | 0.12-0.24 mg/cm^2 |
| Very Heavy | >3.51 S/m | >0.24 mg/cm^2 |

Table 8.2: Salt to be added to achieve given ESDD level

| Pollution Severity | Salt to be added to slurry | Predicted ESDD Value |
|--------------------|----------------------------|----------------------|
| Very Light | 5 g/l | 0.01 mg/cm^2 |
| Medium | 80 g/l | 0.0955 mg/cm^2 |
| Heavy | 160 g/l | 0.1867 mg/cm^2 |

transferred to the surface again. It would require constant sandblasting to achieve constant wettability of the silicone rubber insulator, which would have been time consuming and expensive. A wetting agent was therefore added to the slurry intended for the dipping of the SiR1 insulators [5]. The wetting agent which was used in this case was 99% pure ethanol. The amount of ethanol added made up 20% of the slurry mixture. It was found that this concentration allowed for good wetting of the SiR1 surface.

8.3 Making the Pollution Slurry

The conductivity of the pollution layer had to fit in with the IEC 60815 recommendations for pollution severities as shown in *Table 8.1* [6].

Salt was added to the tap water and kaolin slurry to achieve the desired conductivity. ESDD, equivalent salt deposit density, tests had to be performed to ensure that the right pollution severity was achieved on the insulator surface.

8.3.1 Making the Solution

The insulators had to be polluted so as to achieve the ESDD levels as specified in IEC 60815 [6]. Very little data could be found which indicated the amount of salt which would have to be added to the slurry in order to achieve the required ESDD values. The process used was trial and error. First 5 grams of salt was added per liter of slurry. The ESDD value was then measured, then further salt was added to the slurry to make a salt concentration of 10 grams per liter, again the ESDD value was measured. The average ESDD value for each different salt concentration in the slurry was calculated and a graph was plotted from these values. *Figure 8.2* shows the plot of the graph which shows the amount of salt which would have to be added to the slurry to result in the desired ESDD value. The line of the graph was extrapolated so that higher salt concentrations and ESDD values could be viewed. *Table 8.2* shows the amount of salt which needed to be added, per liter of water, to get the predicted ESDD values, in mg/cm^2 , as indicated in the graph plotted in *Figure 8.2*.

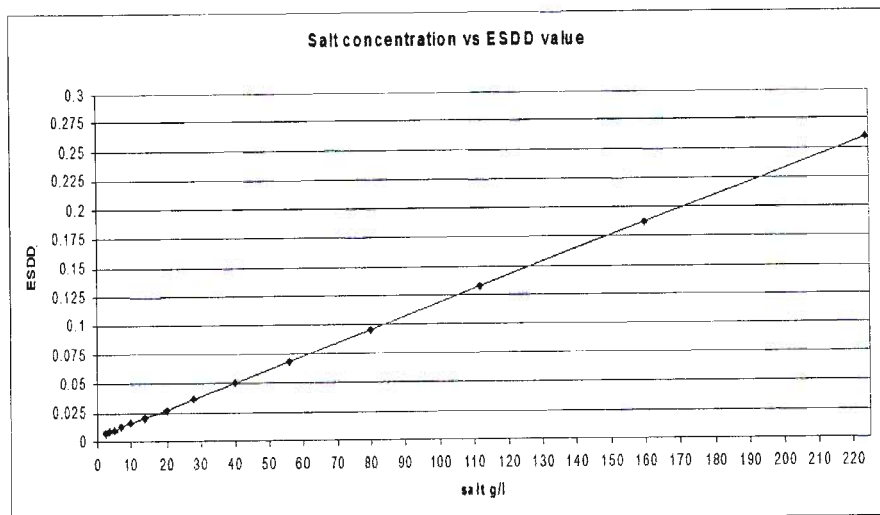


Figure 8.2: Graph of Salt concentration verses ESDD values

The salt which was added was first dissolved in some of the original slurry and then this was added back to the main slurry and mixed in. This was done to ensure that all the salt particles were dissolved properly before dipping commenced .

8.3.2 Testing of ESDD

Once the insulators had been dipped and dried the surface pollution layer ESDD was calculated. This was done to check that the pollution layer will have the correct ESDD value, as well as to check the repeatability of the dipping process. Equations (18 - 20) were used to calculate the ESDD [7].

$$ESDD = (Vol \cdot S_a)/A \quad (18)$$

$$S_a = (5.7 \cdot \sigma_{20})^{1.03} \quad (19)$$

$$\sigma_{20} = \sigma_t \cdot (1 - 0.02277(t - 20) \cdot e^{-0.01956(t-20)}) \quad (20)$$

Where:

Vol , is the volume of deionized water in cm^3

S_a , is the salinity in kg/m^3

A , is the area of the wiped insulator surface in cm^2

σ_{20} , is the conductivity at $20^\circ C$ in $\mu S/cm$

σ_t , is the measured conductivity at $t^\circ C$ in $\mu S/cm$

t , is the temperature of the solution in $^\circ C$



Figure 8.3: Wiping of Glass Insulator

The ESDD values for the polluted insulators were calculated and recorded to determine the repeatability of the pollution process. Lens cloth was dipped in deionized water and then used to clean off the pollution on the top half of the Glass1 insulator or the polymer sheds, as shown in *Figure 8.3*. The lens cloth was then placed back in the deionized water and allowed to soak so that all salt particles could dissolve fully. The conductivity was then measured with a standard conductivity meter as shown in *Figure 8.4*.

Once this had been done the ESDD of the underside of the Glass1 cap was calculated using the method above, each time using fresh deionized water. Deionized water was used for the light pollution conductivity measurements. Tap water was then used for the medium and heavy conductivity measurements. It was decided to pollute the insulators with only a light, medium and heavy pollution layer. The very heavy pollution layer was not included due to difficulties in the pollution process.¹

The graph which was plotted proved to be accurate in its ESDD value predictions. Appendix B shows the ESDD values measured for the insulators dipped into the different pollution slurries. The average ESDD value, standard deviation and variance are also indicated.

The standard deviation of the ESDD was calculated for each of the pollution severities used. The ESDD measurements were all performed by the same person, at the same location, using the same equipment and method and over a reasonably short period of time for each pollution severity level. The repeatability of the dipping could therefore be expressed as the standard deviation of the ESDD tests for each pollution severity level. *Table 8.3* shows the average ESDD values measured and the standard deviations calculated for the different

¹It was found that because the salt concentration for the very heavy pollution slurry was so high, the salt would crystalize out of the slurry mixture between pollution and ESDD measurement sessions. This resulted in the conductivity of the slurry changing and hence an unrepeatable pollution process.



Figure 8.4: Measuring the Conductivity with the Conductivity Meter

pollution severities for the different insulator types.

The results from the above ESDD tests confirmed that the pollution process was repeatable and voltage testing could begin. It is expected that the majority of the ESDD values will fall within 64% of the average for the light pollution layer, 14% for the medium pollution layer and 21% for the heavy pollution layer. These numbers are based on the percentage from which the standard deviation differs to the average values. The highest percentage of standard deviation was used for each pollution class. Variations from these values were not uncommon.

8.4 Experimental Setup

The experimental setup was comprised of two parts: the weather chamber and the test circuit. In Chapter 4 the effects of surface condensation due to colder insulator surface temperatures was discussed. The weather chamber was set up so that weather conditions experienced in coastal areas could be simulated for the sake of testing. The effect of a colder insulator surface temperature and extreme humidity on the behavior of the leakage current could then be investigated. The test circuit was setup so that a voltage could be applied to the insulator and the leakage current and applied voltage could be monitored.

8.4.1 Weather Chamber

A standard cold drink fridge was used as the cooling chamber. The fridge interior and insulator were chilled to either 10°C or 15°C. Once this temperature was reached a kettle containing 1 liter of boiling water was placed inside the weather chamber, or fridge, and allowed to continue boiling for 10 minutes. At which stage the voltage was applied to the insulator and the leakage current and applied voltage were measured. *Figure 8.5* shows a graph indicating the heating and cooling times of the fridge. This graph was used to establish the

Table 8.3: Average and Standard deviation of ESDD levels

| Very Light | | |
|------------|--------------|--------------------|
| | Average ESDD | Standard deviation |
| EPDM1 | 0.0097 | 0.0023 |
| EPDM2 | 0.022 | 0.014 |
| SiR1 | 0.0096 | 0.0033 |
| Glass1 | 0.006 | 0.002 |
| Medium | | |
| | Average ESDD | Standard deviation |
| EPDM1 | 0.113 | 0.006 |
| EPDM2 | 0.103 | 0.0099 |
| SiR1 | 0.119 | 0.016 |
| Glass1 | 0.1 | 0.009 |
| Heavy | | |
| | Average ESDD | Standard deviation |
| EPDM1 | 0.185 | 0.039 |
| EPDM2 | 0.189 | 0.028 |
| SiR1 | 0.17 | 0.029 |
| Glass1 | 0.22 | 0.013 |

amount of time it would take for the fridge to cool down and what the effect of opening the door would be, on the internal temperature.

The fridge was switched off and allowed to warm to room temperature, it was then switched on at time equals zero and allowed to cool. It can be seen that the fridge cools down within 10 minutes. The cycling of the temperature is due to the thermostat trying to achieve a relatively constant temperature. At time 21 minutes the fridge door was opened for 30 seconds. Once the door was closed again the fridge cooled down within two minutes. From this data it was decided to allow the fridge (with the insulator inside) to cool for approximately 20 minutes. The boiling kettle is then placed inside the fridge to introduce a steam fog. The volume of the fridge was 496 liters, or $0.496m^3$. The kettle was a 1200W kettle, this gave a steam fog rate of $2400W/m^3$, or $4,84kg/h \cdot m^3$.

8.4.2 Test Circuit

A voltage had to be applied to the insulators so that the leakage currents under wet conditions could be recorded. Two test circuits were used for the experimentation, the testing circuits were setup as shown in *Figure 8.6* and *8.7*.

The first test circuit, shown in *Figure 8.6*, was used to perform the initial set of tests, where the insulators with different pollution levels were heavily wet by hand, with a spray bottle. The leakage current and applied voltage were then measured when the voltage was applied. The results of these tests were to be used for comparison purposes.

The second test circuit, shown in *Figure 8.7*, was used for the actual tests in the weather chamber. This circuit was used as the voltage probe allowed for the voltage to be measured at the high voltage terminal of the insulator under test, as opposed to before the current limiting resistor. This was done because higher

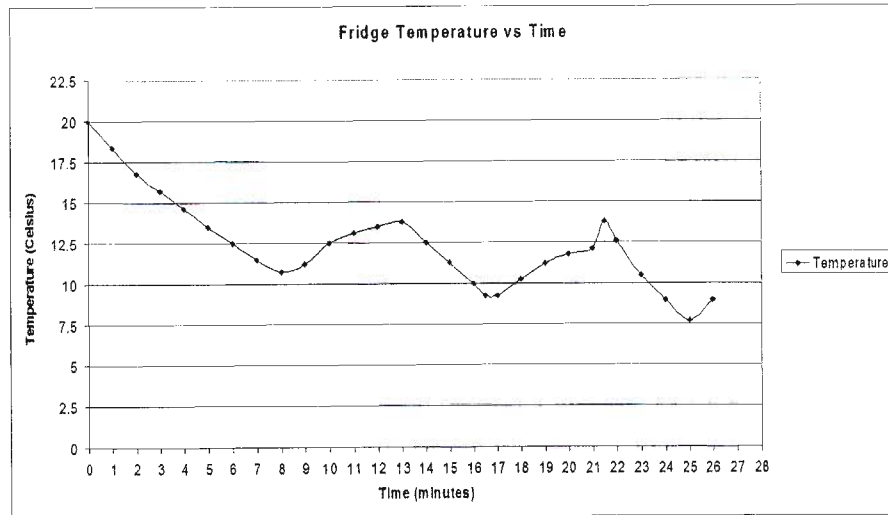


Figure 8.5: Temperature cycle of the fridge

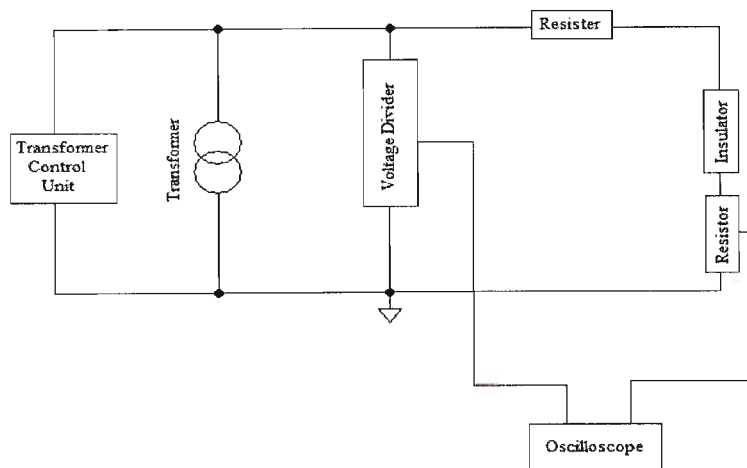


Figure 8.6: Testing Circuit 1

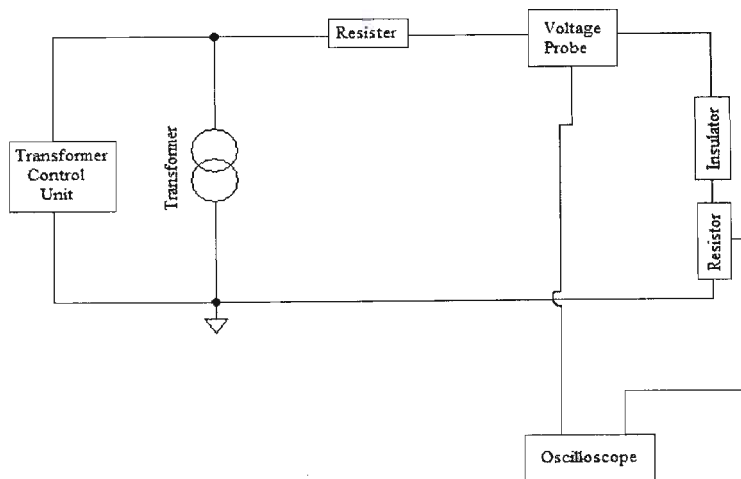


Figure 8.7: Testing Circuit 2

currents were expected and hence the voltage drop across the current limiting resistor was excluded, and hence a more accurate voltage reading could be taken.

The voltage applied to the insulator under test was approximately 10kV. A voltage divider was used to view the applied voltage in the first circuit and a *Tektronix* voltage probe was used for the applied voltage measurements in the second circuit. The output of the voltage divider or voltage probe was connected to channel one of an oscilloscope. A current limiting resistor was placed in series in the circuit for safety reasons. The insulator under test was also in series in the circuit. The current in the cable connecting the low voltage end of the insulator to earth was measured through a 100Ω resistor. This current was the leakage current which flowed as a result of the wet, polluted insulators. The voltage measured across this resistor was connected to channel two of the oscilloscope for data recording.

The voltage to be applied was controlled by the variac on the transformer control unit. Once the desired voltage was achieved the oscilloscope was stopped and the captured data was saved to a floppy disc for later analysis. For the weather chamber tests the applied voltage was reduced to below 10kV so as to reduce the risk of flashover.

8.5 The Testing Method

The method employed to perform the testing was routine. Once the insulators had been polluted and the correct ESDD levels were achieved the testing could commence. The polluted insulators were first heavily sprayed with water using a spray bottle and then tested. This was done so that one could observe the nature of the results and compare these results to those generated in the weather chamber. Once this had been checked testing in the weather chamber could commence. The leakage current results of the manual wetting of the light,

Table 8.4: Average Surface Resistance of Manually Wet Insulator

| Pollution Severity | EPDM1 | EPDM2 | SiR1 | Glass1 |
|--------------------|----------------|----------------|----------------|----------------|
| Light | 4.7M Ω | 9.9M Ω | 16M Ω | 1.2M Ω |
| Medium | 0.59M Ω | 0.77M Ω | 0.3M Ω | 0.4M Ω |
| Heavy | 0.45M Ω | 0.46M Ω | 0.28M Ω | 0.45M Ω |

medium and heavy pollution severity are shown in Appendix C. *Table 8.4* shows the results of the voltage testing of the polluted insulators when heavily wet by hand with a basic spray bottle. It shows the average resistance of the wet pollution layer.

From the initial test data it can be seen that the average resistance of the wet pollution layer decreases with increasing pollution severity. This is expected because as the conductivity of the wet pollution layer on the insulator surface increases, the resistance of the pollution layer decreases. This agrees with the general trend which resulted from the *Maxwell* simulations. An effort was made to take all voltage and current readings before dry band arcing took place, however this was not always possible as some insulators, the SiR1 one specifically, dried out very quickly making measurement difficult.

A *MatLab* program was written so that the test data recorded on the oscilloscope could be plotted and analyzed. The program was written so that the noise on the leakage current signal recorded could be filtered out. A seventh order butterworth filter was used to perform the filtering. The RMS voltage and the RMS leakage current were calculated. The RMS being worked out as the peak-to-peak value divided by $2 \cdot 2^{1/2}$. The resistance of the conduction layer, before dry band arcing, was also calculated. The applied voltage and the leakage current data were plotted. A slightly different *MatLab* program was written for the weather chamber test results. This needed to be written for the weather chamber test results to account for the different method of voltage measurement used as discussed in section 8.4.2 of this chapter. Appendix D shows the *MatLab* programs written.

The leakage currents of the weather chamber and manual wetting tests were recorded as soon after energization as possible. This was done so that there was little time for the surface water to evaporate due to the effects of Joule heating. The amount of time taken to take a reading may have had an effect on the overall result of the test. If too much water was allowed to evaporate the overall surface resistance of the insulator would increase, due to a reduction in contamination layer thickness.

8.6 Results of Weather Chamber Testing

The Glass1, EPDM1, EPDM2 and SiR1 insulators were tested in the weather chamber. Once the insulators were placed in the chamber the door was closed and they were allowed to chill for 20 minutes. At which point a boiling kettle of water was placed inside the chamber and allowed to boil for 10 minutes in order to introduce a steam fog. At this stage the voltage was applied and the leakage current and applied voltage were measured. It should be noted that the application of the voltage was not instantaneous. The voltage was first switched

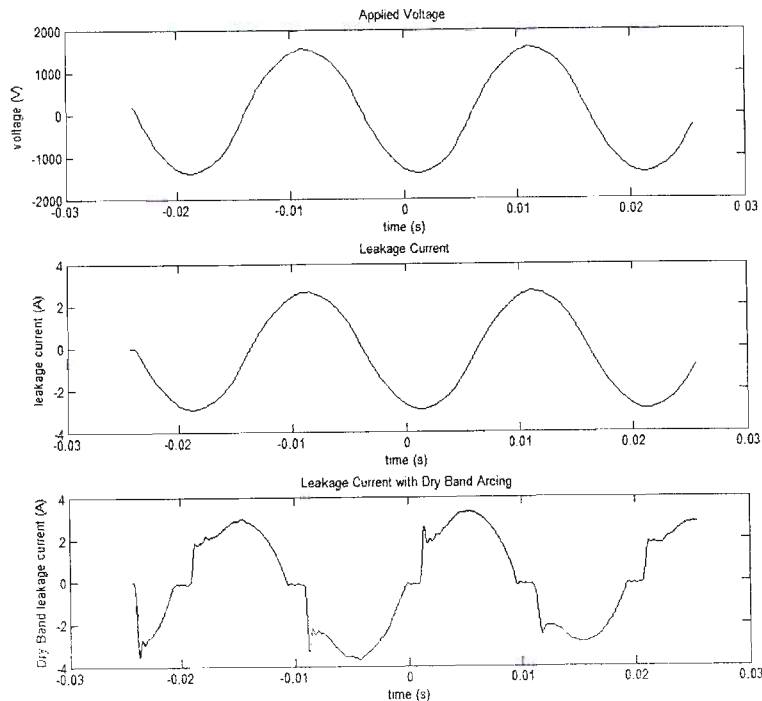


Figure 8.8: Example of measured voltage and leakage current signals

in at a very low level and then quickly raised to the desired level.

Two sets of tests were performed for each pollution level for each insulator. The one test was performed when the weather chamber temperature was at 10 °C and the other test was performed when the weather chamber temperature was at 15 °C. The insulators were tested at two different temperatures with the aim of determining what the effect of the warmer insulator surface would be on the leakage currents. The greater the difference in the fog temperature and the insulator surface temperature the greater the amount of surface condensation as seen in section 5.7 and [8], this was the parameter that was under investigation, with reference to the two different weather chamber testing temperatures.

An effort was made to take the voltage and current readings as soon as possible after the voltage was applied to the test object. This was done so that the effects of Joule heating would not be too pronounced [9]. The voltage and leakage current readings that were taken were resistive and in phase with each other. *Figure 8.8* shows an example of a voltage and leakage current plot. This plot was taken from the weather chamber test performed on the EPDM1 insulator with a heavy pollution layer. The voltage and leakage current signals are in phase and sinusoidal and the dry band leakage current waveform is typical of a dry band waveform. The sharp spikes on the leakage current waveform indicates sparking.

It was noticed during the weather chamber testing that the wetting on the

| Weather Chamber | | | | | | | | | | | | | | |
|------------------------------|--------|---------|-------|---------|------------------------------|--------|--------|-------|--------|------------------------------|--------|--------|-------|--------|
| Light | | | | | Medium | | | | | Heavy | | | | |
| 10 degrees | | | | | 10 degrees | | | | | 10 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 7735 | 0.0233 | 362520 | | | 7735 | 0.0466 | 200080 | | | 5911 | 0.094 | 73319 | 14033 | 0.085 |
| 11989 | 0.0156 | 860980 | 8117 | 0.0063 | 2817 | 0.0356 | 75874 | 5080 | 0.0338 | 2817 | 0.044 | 63123 | 6852 | 0.044 |
| 9942 | 0.0173 | 64789 | 11324 | 0.0127 | 5027 | 0.0426 | 143520 | 14033 | 0.0324 | 5080 | 0.0518 | 156860 | 9998 | 0.0431 |
| 11324 | 0.0074 | 1840200 | | | 6682 | 0.0371 | 179050 | 9722 | 0.0277 | 2542 | 0.04 | 72021 | 9613 | 0.05 |
| Average Resistance: 782122.3 | | | | | Average Resistance: 149631 | | | | | Average Resistance: 91330.75 | | | | |
| 15 degrees | | | | | 15 degrees | | | | | 15 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 11101 | 0.0238 | 525730 | 14033 | 0.0197 | 8174 | 0.0291 | 331990 | 14033 | 0.0187 | 5798 | 0.0362 | 148710 | 13092 | 0.0222 |
| 11710 | 0.0255 | 496820 | 14033 | 0.0196 | 9114 | 0.0395 | 280130 | 14033 | 0.0197 | 3150 | 0.0505 | 74715 | 7841 | 0.0436 |
| | | | | | 9115 | 0.0275 | 399430 | 14033 | 0.0397 | 3040 | 0.0582 | 60158 | 14033 | 0.0486 |
| 12099 | 0.0186 | 763520 | | | | | | | | | | | | |
| Average Resistance: 551340 | | | | | Average Resistance: 337183.3 | | | | | Average Resistance: 94527.67 | | | | |
| Spray Bottle | | | | | | | | | | | | | | |
| Light | | | | | Medium | | | | | Heavy | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 10951 | 0.0062 | 2037800 | 11230 | 2037800 | 9280 | 0.0247 | 491990 | 10680 | 0.0007 | 11137 | 0.028 | 493000 | 12295 | 0.0077 |
| 9838 | 0.0081 | 1428100 | 10953 | 1365000 | 9950 | 0.0254 | 382820 | 10291 | 0.0265 | 10439 | 0.0163 | 711000 | 12759 | 0.0055 |
| 10201 | 0.0117 | 903430 | 11157 | 42020.8 | 9964 | 0.0216 | 501620 | 13453 | 0.0203 | 9756 | 0.0316 | 352840 | 10201 | 0.0055 |
| 13929 | 0.0103 | 1691400 | 13691 | 1516200 | 9518 | 0.0304 | 321240 | 9964 | 0.02 | 9756 | 0.0315 | 361880 | 14151 | 0.0055 |
| 15087 | 0.0112 | 1585100 | | 1423800 | 10439 | 0.0267 | 428290 | 12770 | 0.0205 | 11597 | 0.0354 | 367050 | 11835 | 0.0211 |
| 13914 | 0.0103 | 2299900 | 15592 | 1251600 | | | | | | 12072 | 0.027 | 526760 | 14612 | 0.0159 |
| Average Resistance: 1657622 | | | | | Average Resistance: 425192 | | | | | Average Resistance: 469088.3 | | | | |

Figure 8.9: Test results for the Glass1 insulator

insulators was uniform, in the sense that the surface condensation occurred over the entire surface of the insulator, however the effects of gravity did result in the collection of excess water in certain areas. The latent heat of condensation also resulted in the heating of the insulator surface which had the effect of reducing the condensation rate as the insulator got warmer. There were some inconsistencies in the surface resistance values found. The reasoning for this will be discussed in the following chapter.

8.6.1 Glass1

The Glass1 insulator was tested with a light, medium and heavy pollution layer. *Figure 8.9* shows the *Excel* spreadsheet of the results of the Glass1 insulator testing, it shows both the results for the weather chamber tests and the results for the manual heavy wetting using a hand held spray bottle. In both cases the Glass1 insulators were dipped in the pollution slurry, were allowed to dry and then they were tested. For the light pollution layer weather chamber tests, approximately 10kV was applied to the high voltage end of the insulator under test. As the conductivity of the pollution layer was increased the applied voltage was decreased so as to reduce the likelihood of flashover occurring.



Figure 8.10: Wetting on the Glass1 insulator in the weather chamber

It can be seen in the spreadsheet results that the wetted surface resistance decreases with increasing pollution severity. It can also be seen that the surface resistance is drastically reduced for the tests done in the weather chamber as opposed to those performed with heavy wetting using a hand held spray bottle.

During the weather chamber tests it was observed that the Glass1 insulators wet out very nicely after 10 minutes in the weather chamber during steaming, and there was very little beading on the surface. *Figure 8.10* shows the pattern of wetting on the Glass1 surface as a result of surface condensation.

8.6.2 EPDM1 and EPDM2

The EPDM insulators were also tested with a light, medium and heavy pollution layer. The insulators were dipped in the pollution slurry and then allowed to partially dry for 20 minutes and then they were tested. They were only allowed to dry partially as this aided in getting a continuous wet layer on the insulator surface, it is not expected that this will have too much of an effect on the thickness of the wetted pollution layer as a very small amount of water remained on the insulator surface prior to testing. This small amount of water on the surface would have a negligible effect on the condensation rate as well, as it is not expected to effect the insulator surface temperature, and if so the effect would be very slight and therefore negligible. The insulators tested in the weather chamber were tested using a 10kV voltage for the light pollution layer, again as the pollution severity increased the applied voltage was reduced to reduce the chance of flashover. *Figures 8.11* and *8.12* show the test results of the EPDM1 insulator and the EPDM2 insulator respectively. They show the results of the tests performed with manual heavy wetting of the insulator surface with a hand held spray bottle and the results of the tests performed in the weather chamber.

Again it can be seen that the wetted surface resistance decreases with in-

| Weather Chamber | | | | | | | | | | | | | | |
|---------------------|--------|----------|-------|---------|---------------------|--------|----------|-------|--------|---------------------|--------|----------|-------|--------|
| Light | | | | | Medium | | | | | Heavy | | | | |
| 10 degrees | | | | | 10 degrees | | | | | 10 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 12042 | 0.0074 | 2092200 | 12873 | 0.005 | 6463 | 0.0239 | 294630 | 12265 | 0.0157 | 1549 | 0.0189 | 24931 | 6353 | 0.018 |
| 10716 | 0.0088 | 1407300 | 13315 | 0.0062 | 6519 | 0.0321 | 249520 | | | 1216 | 0.0199 | 46069 | 7014 | 0.0248 |
| 11215 | 0.0135 | 921130 | 12982 | 0.007 | 4695 | 0.0196 | 300920 | 9998 | 0.0098 | 1658 | 0.0247 | 62648 | 11158 | 0.0253 |
| 10165 | 0.009 | 1247900 | 11490 | 0.007 | 2871 | 0.0292 | 113440 | | | 1435 | 0.0222 | 62035 | 4306 | 0.0205 |
| 12155 | 0.0178 | 758690 | | | | | | | | | | | | |
| Average Resistance: | | 1285444 | | | Average Resistance: | | 239627.5 | | | Average Resistance: | | 46420.75 | | |
| 15 degrees | | | | | 15 degrees | | | | | 15 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 10607 | 0.0061 | 2089100 | 11324 | 0.0041 | 5084 | 0.0272 | 182910 | | | 1711 | 0.0361 | 40292 | 8650 | 0.027 |
| 9503 | 0.0106 | 1022700 | | | 3150 | 0.0241 | 127790 | 8510 | 0.0207 | 1548 | 0.0231 | 23447 | 1270 | 0.0251 |
| 10165 | 0.0088 | 1355300 | 12427 | 0.0089 | 3482 | 0.0255 | 185690 | 12594 | 0.0296 | 1934 | 0.0345 | 43630 | 6296 | 0.0172 |
| 10603 | 0.0113 | 1029100 | 10992 | 0.0064 | 3426 | 0.0248 | 168050 | 10387 | 0.0245 | | | | | |
| Average Resistance: | | 1374050 | | | Average Resistance: | | 166110 | | | Average Resistance: | | 35789.67 | | |
| Spray Bottle | | | | | | | | | | | | | | |
| Light | | | | | Medium | | | | | Heavy | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 14062 | 0.0049 | 4173200 | 14389 | 0.0012 | 16007 | 0.018 | | 15770 | 0.0161 | 7200 | 0.0077 | 666720 | 12072 | 0.022 |
| 12429 | 0.0038 | 10177000 | 12993 | 0.00059 | 13929 | 0.0165 | | 14389 | 0.0187 | 13453 | 0.041 | 321520 | 13453 | 0.031 |
| 14523 | 0.0035 | 6065800 | 14849 | 0.0012 | 15310 | 0.0157 | | 16468 | 0.0122 | 11612 | 0.0182 | 398580 | 14152 | 0.0239 |
| 14003 | 0.0029 | 8137600 | 15681 | 0.0013 | 12533 | 0.0255 | 563820 | 15785 | 0.0141 | | | | | |
| 14849 | 0.0024 | 10452000 | 14300 | 0.0012 | 13927 | 0.0226 | 624070 | 19720 | 0.0187 | | | | | |
| 8954 | 0.0019 | 6372800 | 8865 | 0.00043 | | | | | | | | | | |
| 9236 | 0.0022 | 5268800 | 9473 | 0.00046 | | | | | | | | | | |
| 9845 | 0.002 | 5722000 | 10112 | 0.00094 | | | | | | | | | | |
| Average Resistance: | | 7046150 | | | Average Resistance: | | 593945 | | | Average Resistance: | | 462273.3 | | |

Figure 8.11: Test results for the EPDM1 insulator

| Weather Chamber | | | | | | | | | | | | | | |
|------------------------------|--------|----------|-------|----------|------------------------------|--------|--------|-------|--------|------------------------------|--------|--------|-------|--------|
| Light | | | | | Medium | | | | | Heavy | | | | |
| 10 degrees | | | | | 10 degrees | | | | | 10 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 9005 | 0.0064 | 1654600 | 9337 | 0.0048 | 4143 | 0.0249 | 159680 | 9832 | 0.0133 | 2432 | 0.0238 | 62875 | 12318 | 0.016 |
| 9776 | 0.0107 | 1080300 | 10550 | 0.007 | 6353 | 0.0218 | 349370 | | | 2542 | 0.0225 | 75106 | 7570 | 0.0161 |
| 9836 | 0.0099 | 1154500 | 12155 | 0.0063 | 4419 | 0.0222 | 226910 | 11657 | 0.0101 | 1768 | 0.0218 | 56467 | 9114 | 0.027 |
| 10607 | 0.0095 | 1297000 | 13149 | 0.0084 | 4144 | 0.0248 | 199150 | 12703 | 0.0143 | 2429 | 0.0289 | 84707 | 13258 | 0.0199 |
| Average Resistance: 1296600 | | | | | Average Resistance: 233777.5 | | | | | Average Resistance: 69788.75 | | | | |
| 15 degrees | | | | | 15 degrees | | | | | 15 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 11215 | 0.0054 | 2459800 | 11766 | 0.0034 | 3592 | 0.0244 | 141930 | 11437 | 0.0205 | 2376 | 0.0235 | 92953 | | |
| 11049 | 0.006 | 2681400 | 11490 | 0.0039 | 3259 | 0.0182 | 147510 | 8454 | 0.0117 | 2153 | 0.0233 | 95383 | 8450 | 0.0186 |
| | | | | | 6244 | 0.0215 | 363550 | | | 1545 | 0.0198 | 71205 | 7679 | 0.0219 |
| | | | | | 2432 | 0.0202 | 110140 | 2376 | 0.0192 | | | | | |
| Average Resistance: 2570600 | | | | | Average Resistance: 190782.5 | | | | | Average Resistance: 86513.67 | | | | |
| Spray Bottle | | | | | | | | | | | | | | |
| Light | | | | | Medium | | | | | Heavy | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 18086 | 0.0024 | 11311000 | 18235 | 0.000046 | 17626 | 0.0261 | 727900 | 20418 | 0.02 | 6504 | 0.0089 | 393080 | 15785 | 0.0271 |
| 18562 | 0.0024 | 12188000 | 18472 | 0.00067 | 18324 | 0.0255 | 855070 | 20878 | 0.0205 | 6727 | 0.0145 | 217660 | 21338 | 0.0262 |
| 19022 | 0.0019 | 13067000 | 19066 | 0.00074 | 17166 | 0.0193 | 821690 | 18086 | 0.015 | 14374 | 0.031 | 444710 | 14389 | 0.022 |
| 20418 | 0.0018 | 11784000 | 20418 | 0.00068 | | | | | | | | | | |
| Average Resistance: 12087500 | | | | | Average Resistance: 801553.3 | | | | | Average Resistance: 351816.7 | | | | |

Figure 8.12: Test results for the EPDM2 insulator

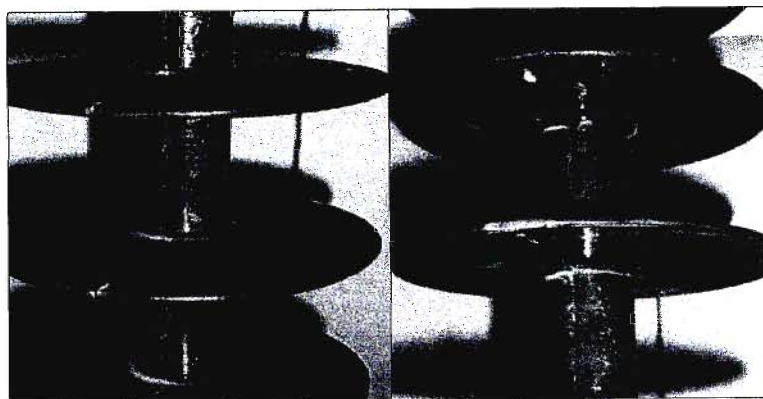


Figure 8.13: Wetting on the EPDM insulators in the weather chamber

creased pollution severity, the surface resistance of the wet insulators is also reduced for the tests performed in the weather chamber as opposed to those performed with the manual wetting.

During the weather chamber tests it was observed that the EPDM1 and EPDM2 insulators wet out fairly well however there was still a slight amount of beading present on the insulator sheath and sheds. *Figure 8.13* shows a picture of the pattern of surface condensation present on the EPDM insulators after 10 minutes in the weather chamber. On the left is a picture showing the wetting on the top side of the insulator sheds and on the right is a picture of the wetting on the underside of the sheds .

8.6.3 SiR1

The SiR1 insulators were tested using a light, medium and heavy pollution layer. The insulators were dipped in the pollution slurry and were then tested. The insulators were allowed to partially dry for 20 minutes before testing as it was found that this aided with the wetting of the surface. The insulators were applied with 10kV as the voltage source for the heavy wetting with the spray bottle and light pollution layer weather chamber tests. As the pollution layer severity increased for the weather chamber tests, the applied voltage was decreases so as to reduce the chance of flashover. *Figure 8.14* shows the results of the spray bottle and weather chamber tests.

During the weather chamber tests it was noted that the SiR1 insulator did not wet out very well due to its hydrophobicity. *Figure 8.15* shows the condensation on the SiR1 insulator surface after 10 minutes in the weather chamber.

It was noticed during testing that the wettability of the hydrophobic SiR1 insulator was very poor even when contaminated with the pollution layer. This was particularly true for the case of the manual heavy wetting of the insulator using a spray bottle. This resulted in inconsistencies in the results for the manual wetting. However it is noted that the results from the weather chamber tests were more consistent with each other, even though a fair amount of beading was still present.

| Weather Chamber | | | | | | | | | | | | | | |
|------------------------------|---------|----------|-------|---------|------------------------------|--------|----------|-------|--------|-----------------------------|--------|---------|-------|--------|
| Light | | | | | Medium | | | | | Heavy | | | | |
| 10 degrees | | | | | 10 degrees | | | | | 10 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 11381 | 0.0026 | 5027000 | | | 9447 | 0.0122 | 768330 | 10497 | 0.0097 | 9556 | 0.0244 | 474890 | 13315 | 0.016 |
| 9224 | 0.0024 | 5567500 | | | 9557 | 0.0186 | 628090 | 13810 | 0.0125 | 10165 | 0.0264 | 382910 | 14033 | 0.0102 |
| 10112 | 0.002 | 6041900 | | | 8450 | 0.0158 | 535230 | 13036 | 0.0111 | 8948 | 0.018 | 552670 | 12650 | 0.0103 |
| 10112 | 0.002 | 7286300 | | | 9500 | 0.0211 | 511880 | 13534 | 0.0058 | 10002 | 0.0212 | 474730 | | |
| 9056 | 0.0022 | 6451300 | | | | | | | | | | | | |
| Average Resistance: 6074800 | | | | | Average Resistance: 608382.5 | | | | | Average Resistance: 471300 | | | | |
| 15 degrees | | | | | 15 degrees | | | | | 15 degrees | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 9779 | 0.002 | 5820700 | | | 8892 | 0.0174 | 411180 | 13149 | 0.0066 | 8344 | 0.0192 | 409180 | 10497 | 0.0117 |
| 9779 | 0.0021 | 7451200 | | | 9670 | 0.0186 | 507290 | 11932 | 0.0134 | 10218 | 0.0271 | 375330 | | |
| 9556 | 0.0022 | 4859000 | | | 8786 | 0.0199 | 472960 | 13424 | 0.0094 | 7403 | 0.0188 | 467780 | 10882 | 0.0119 |
| 9560 | 0.0024 | 5470200 | | | | | | | | | | | | |
| 11496 | 0.0033 | 4913700 | | | | | | | | | | | | |
| 11657 | 0.0029 | 5706400 | | | | | | | | | | | | |
| Average Resistance: 6703533 | | | | | Average Resistance: 463810 | | | | | Average Resistance: 417430 | | | | |
| Spray Bottle | | | | | | | | | | | | | | |
| Light | | | | | Medium | | | | | Heavy | | | | |
| 1 | | | 2 | | 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I | V | I | R | V | I |
| 13929 | 0.00085 | 32439000 | 13914 | 0.00018 | 5303 | 0.0006 | 18455000 | | | 3977 | 0.0022 | 2121900 | | |
| 14849 | 0.0014 | 19245000 | 13914 | 0.0012 | 7237 | 0.0005 | 15004000 | | | 5027 | 0.0025 | 4376300 | | |
| 13929 | 0.0032 | 8408100 | 14389 | 0.00034 | 5469 | 0.001 | 19531000 | | | 6406 | 0.0013 | 7016900 | | |
| 15770 | 0.0021 | 10656000 | 14849 | 0.00028 | | | | | | | | | | |
| 14151 | 0.0014 | 14912000 | 13691 | 0.00019 | | | | | | | | | | |
| Average Resistance: 17132020 | | | | | Average Resistance: 17663333 | | | | | Average Resistance: 4505033 | | | | |

Figure 8.14: Test results for the SiR1 insulator

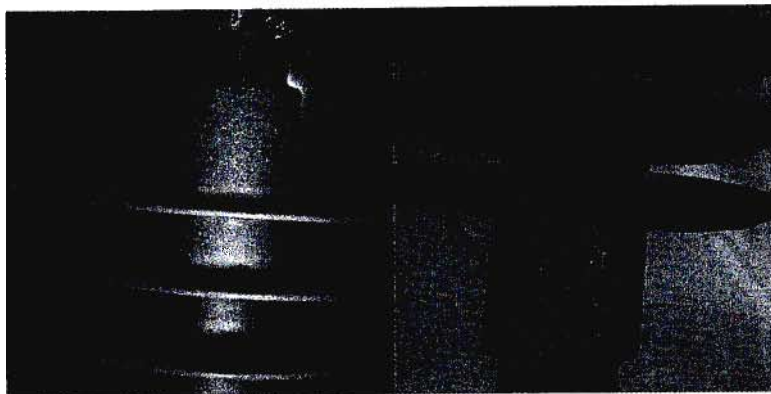


Figure 8.15: Wetting on the SiR1 insulator in the weather chamber

8.7 References

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Chapter 9

FINAL ANALYSIS OF RESULTS

9.1 Introduction

An experiment was set up to simulate weather conditions which were thought to result in the heavy wetting of outdoor insulator surfaces as a result of surface condensation. A finite element method program, *Maxwell*, was used to simulate the expected conditions to which the insulators would be exposed. This involved the modeling of the various insulators with a conductive water layer coating the surface of the insulators, and analyzing their response to an applied voltage.

A set of practical experiments were also setup to measure the leakage currents which flowed over the surfaces of the wet, polluted outdoor insulators, as a result of the surface condensation. This was done by performing tests in a weather chamber which was specifically designed to simulate the desired weather conditions.

Below follows an analysis of the results of the weather chamber tests and the relation of these results to those found with the *Maxwell* simulations as well as the implications of these findings.

9.2 Experimental Results

Two sets of practical experiments were performed. The first was a cold fog polluted insulator test where the insulator was polluted then wet heavily, using a hand held spray bottle. A voltage was then applied and the leakage currents were recorded. The second test was a steam fog test in a specialized weather chamber made to simulate specific weather conditions as highlighted in Chapter 4. Here the insulators were polluted, placed in the weather chamber and allowed to chill. They were then exposed to a steam fog and a voltage was applied and the resulting leakage currents were recorded. Here the differences between the results of the two tests are presented and analyzed.

One of the most obvious observations from the manual wetting and weather chamber results is that the surface condensation, which took place in the weather chamber, resulted in far heavier wetting than the manual heavy wetting with a spray bottle. This was concluded from both visual inspection and surface resistance results.

Table 9.1: Summary of experimental surface resistances for the Glass1 insulators

| | Light | Medium | Heavy |
|------------------------|-----------|-----------|-----------|
| Weather Chamber: 10 °C | 27kΩ/cm | 5.1kΩ/cm | 3.1kΩ/cm |
| Weather Chamber: 15 °C | 19kΩ/cm | 11.6kΩ/cm | 3.2kΩ/cm |
| Spray Bottle | 57.1kΩ/cm | 14.7kΩ/cm | 14.1kΩ/cm |

9.2.1 Glass1 Insulator

The results for the tests performed on the Glass1 insulators can be seen in section 8.6.1. *Table 9.1* shows a summary of these results. The values shown are the surface resistances per unit length, here the unit of length is 1cm.

It can be seen in *Table 9.1* that there is a large difference between the unit surface resistances measured for the heavy wetting using a hand held spray bottle and those wet by surface condensation in the weather chamber. The insulators wet in the weather chamber had much lower surface resistances than those wet using the spray bottle. Equation (17) shows the relationship between resistance (R), resistor length (L), conductivity (σ) and cross-sectional surface area (A) [1].

$$R = \frac{L}{\sigma \cdot A} \quad (17)$$

This shows that an increase in cross-sectional surface area will result in a decrease in the resistance of the pollution layer. A thicker layer of water condensing onto the surface would result in a larger cross-sectional area. Although having a larger amount of water condensing onto the polluted insulator surface would reduce the concentration of the salt dissolved in the pollution layer, thus reducing the conductivity, this effect is very slight and is negligible compared to the effect of the thicker water layer [2]. The thicker water layer on the surface of the insulator results in a lower resistance of the wet surface layer, thus explaining the trend seen in *Table 9.1*.

For the results of the tests performed in the weather chamber on the Glass1 insulators it can be seen that there is another trend that shows the surface resistance decreasing with increasing pollution severity. This too is explained by equation (17). As the pollution severity increases so will the conductivity of the wetted pollution layer. An increase in the conductivity level will result in a decrease in the surface resistance, as seen in *Table 9.1*.

This trend can also be seen with the light and medium pollution tests performed with manual heavy wetting, as expected. However the surface resistance result for the heavy pollution layer does not follow this trend, it was expected to have a lower surface resistance than those measured for the medium pollution tests. It is likely that this is due to irregular results in either the medium or heavy pollution tests. This could be due to the presence of the current limiting resistor in use in the test circuit. For the test performed with the manual wetting with a spray bottle the voltage was recorded before the current limiting resistor, hence the voltage drop across the resistor was not taken into account. Since the leakage currents measured for the heavily polluted Glass1 insulators were the highest currents measured using this circuit setup, it is likely that the voltage drop across the current limiting resistor was significant. As a result, false ap-

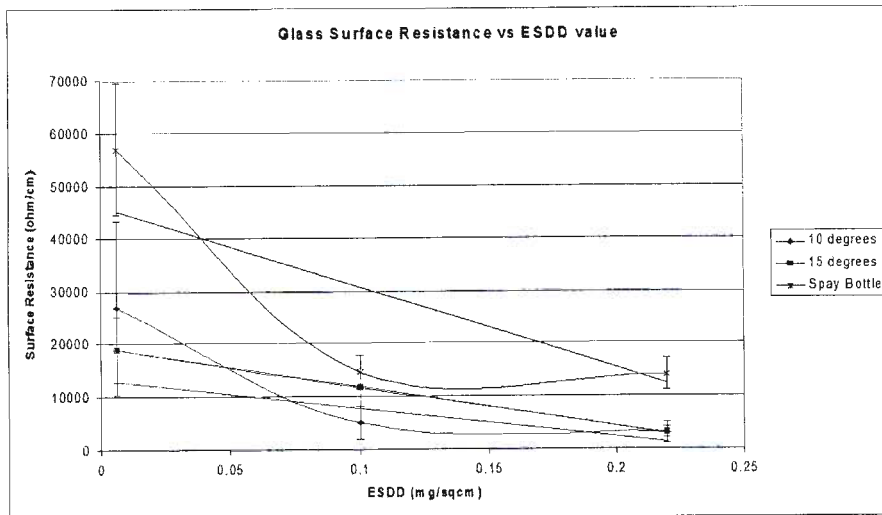


Figure 9.1: Glass1: Per Unit surface resistance vs ESDD values

plied voltage readings were recorded hence leading to an inaccurate calculation of the surface resistance.

Figure 9.1 shows a plot of the results in Table 9.1. The curves are shown to have error bars, these error bars show the percentage error in terms of the standard deviation.

The relationship between the ESDD level and the surface resistance should be linear [3]. Equation (17) shows that the relationship between the surface conductivity and resistance is linear. Therefore it can be speculated that the relationship between the ESDD level and the surface resistance should be linear. If one takes the error bars into account one should be able to draw a straight line through the curves for each test, thus better representing the relationship between the ESDD level and the measured surface resistance. As can be seen in Figure 9.1 this is true for the case of the weather chamber test results but not so for the test results for the manual wetting. This could be because of uneven wetting during the manual spraying thus resulting in inaccurate results. Inconsistencies in the measured data could also be attributed to inconsistent ESDD levels on the insulator surfaces.

The effects of Joule heating can not be ruled out. When a current flows through the wetted pollution layer the wetted layer warms up as a result of Joule heating [4]. If this is allowed to continue for too long the heating will result in the evaporation of the water layer and hence a reduction in the cross-sectional area of the conductive layer. This is the process which can lead to dry-band arcing [4]. It is therefore important to take the leakage current measurements as soon as the voltage is applied so as to minimize the effects of Joule heating on the wetted pollution layer. If the leakage current reading was not taken quickly enough it would have resulted in inaccurate surface resistance readings, as the pollution layer thickness would have reduced, hence increasing the surface resistance readings as a result of evaporation due to Joule heating.

Table 9.2: Summary of experimental surface resistances for the EPDM1 insulators

| | Light | Medium | Heavy |
|------------------------|------------|-----------|-----------|
| Weather Chamber: 10 °C | 26.8kΩ/cm | 5kΩ/cm | 0.97kΩ/cm |
| Weather Chamber: 15 °C | 28.6kΩ/cm | 3.5kΩ/cm | 0.74kΩ/cm |
| Spray Bottle | 146.8kΩ/cm | 12.4kΩ/cm | 9.6kΩ/cm |

Table 9.3: Summary of experimental surface resistances for the EPDM2 insulators

| | Light | Medium | Heavy |
|------------------------|------------|----------|-----------|
| Weather Chamber: 10 °C | 14.2kΩ/cm | 2.5kΩ/cm | 0.76kΩ/cm |
| Weather Chamber: 15 °C | 28.1kΩ/cm | 2.1kΩ/cm | 0.94kΩ/cm |
| Spray Bottle | 132.1kΩ/cm | 8.8kΩ/cm | 3.8kΩ/cm |

9.2.2 Polymer Insulators

The results for the tests performed on the polymer insulators can be seen in sections 8.6.2 and 8.6.3. *Tables 9.2, 9.3 and 9.4* shows a summary of the various test results for the EPDM1, EPDM2 and the SiR1 insulators respectively. The values indicated are in surface resistance per unit length.

EPDM1 Insulator

Table 9.2 shows the results of both the weather chamber tests and the tests using manual heavy wetting with a spray bottle. It can be seen that the weather chamber resulted in surface contamination layer resistances that were substantially lower than those found with the manual wetting. This is due to the thicker wetted contamination layer present on the surface of the insulator as a result of surface condensation. As seen from equation (17) above, a thicker contamination layer will result in a lower surface resistance.

The surface resistance also decreases for increased pollution layer severity, as is expected and predicted by equation (17). The surface resistances calculated for the manual wetting with a spray bottle also decrease with increasing pollution severity, as expected. Here the leakage currents are not as large as those measured for the heavy pollution layer on the Glass1 insulators, so the effect of the current limiting resistor is not as pronounced however they still may be present.

Figure 9.2 shows the plots of the results of *Table 9.2*, complete with error

Table 9.4: Summary of experimental surface resistances for the SiR1 insulators

| | Light | Medium | Heavy |
|------------------------|------------|------------|-----------|
| Weather Chamber: 10 °C | 101.2kΩ/cm | 10.1kΩ/cm | 7.9kΩ/cm |
| Weather Chamber: 15 °C | 95kΩ/cm | 7.7kΩ/cm | 6.9kΩ/cm |
| Spray Bottle | 285.5kΩ/cm | 294.4kΩ/cm | 75.1kΩ/cm |

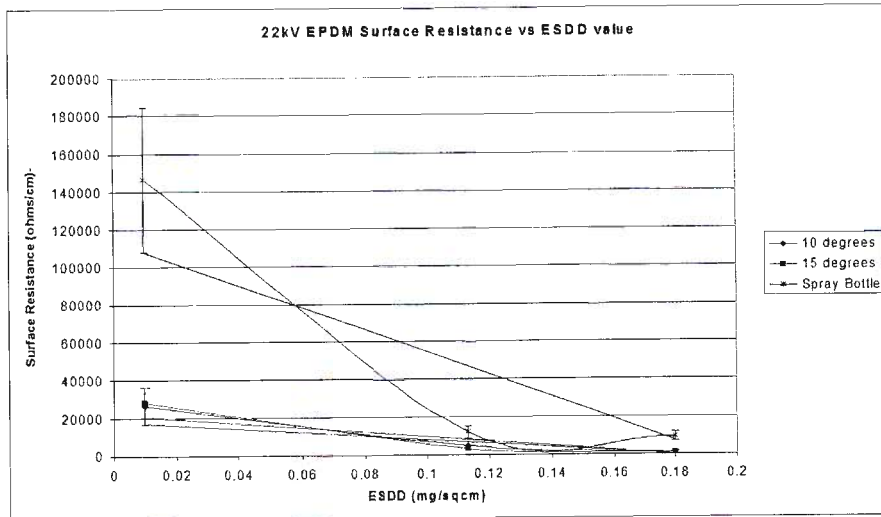


Figure 9.2: EPDM1: Per Unit surface resistance vs ESDD values

bars representing the percentage error in terms of the standard deviation.

A straight line can be drawn through the error bars for both the weather chamber test results. However, again this is not the case for the tests done with the manual wetting with the spray bottle. Inconsistencies in the measured data can be attributed to inconsistent ESDD levels on the insulator surfaces or uneven wetting of the insulator surface during the manual wetting testing. The effect of the current limiting resistor may also play a role in the results of the manual wetting tests. The test circuit with the current limiting resistor may have led to false voltage reading for test setups with higher leakage currents, resulting in surface resistance measurements appearing to be higher than they really are. Joule heating may also have resulted in the evaporation of the water on the insulator surface [4]. Giving the illusion of increasing the surface resistance and hence causing inconsistencies in the leakage current readings.

EPDM2 Insulator

The results for the testing of the EPDM2 insulator are of a similar form to the EPDM1 insulator. *Table 9.3* shows the results of the manual wetting and weather chamber tests. Once again it can be seen that there is a significant difference between the surface resistances found for the tests performed in the weather chamber and those performed using heavy manual wetting. Again showing that the surface condensation that took place in the weather chamber resulted in a thicker pollution layer than with manual wetting, and hence a lower surface conductivity, leading to higher leakage currents and hence increasing the likelihood of flashover taking place.

As the pollution layer severity increases, the surface resistance decreases, as expected. Inconsistencies in the measured data can be attributed to inconsistent ESDD levels on the insulator surfaces or human error.

Figure 9.3 shows the plot of the surface resistances measured versus the

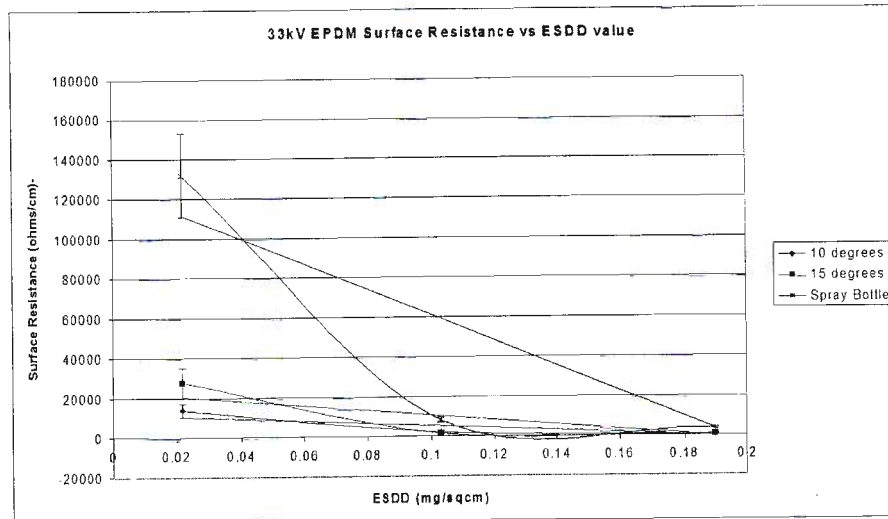


Figure 9.3: EPDM2: Per Unit surface resistance vs ESDD values

ESDD values for the EPDM2 insulator. The error bars representing the percentage error of the standard deviation are shown in the plot. The relationship between the surface resistance and the surface ESDD value should be linear. If a straight line is drawn through the error bars on the graphs the approximate relationship between the surface resistance and the ESDD level can be seen. This can be done quite effectively with the results from the weather chamber tests, however this is not the case for the manual wetting tests. As discussed above this could be due to a number of influences including uneven wetting during manual spraying, inconsistent ESDD levels, Joule heating or the effect of the current limiting resistor in test circuit one.

SiR1 Insulator

A summary of the results of the testing of the SiR1 insulator are shown in *Table 9.4*. They show the results from the weather chamber tests and the results from the testing with the manual heavy wetting by a hand held spray bottle. The surface resistances are reported in $k\Omega/cm$.

The testing of the SiR1 insulator proved to be more problematic than those performed on the other insulators. This was particularly relevant to the case of the manual wetting of the insulator with a hand held spray bottle. Due to the hydrophobic nature of the SiR1 insulator, the water sprayed onto the surface of the insulator beaded very easily and a continuous water layer was difficult to achieve. This resulted in inconsistencies in the results of the tests, specifically those performed with the manual wetting of the insulator, as can be seen in the *Excel* spreadsheet presented in *Figure 8.14* in section 8.6.3.

Again it can be seen that for the tests performed in the weather chamber the per unit surface resistance decreases with increasing pollution severity, as is expected. The results for the manual wetting show a very slight increase in surface resistance with the increase from a light pollution layer to a medium.

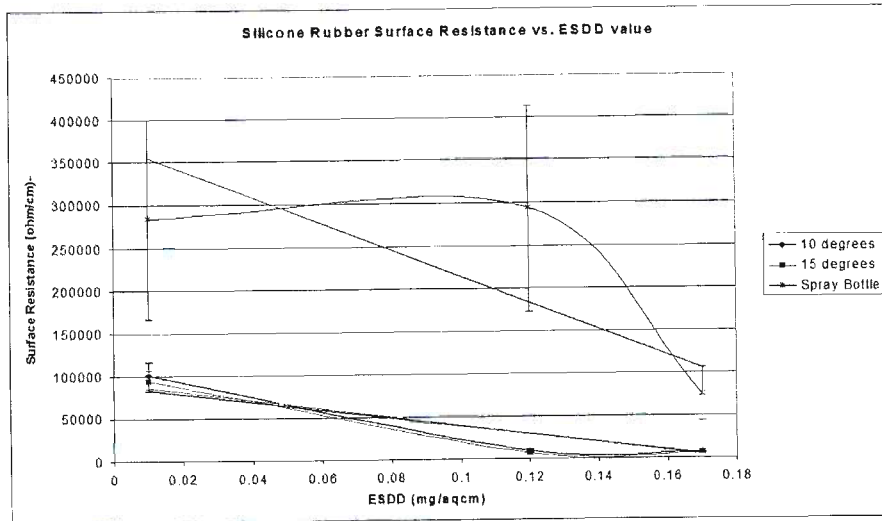


Figure 9.4: SiR1: Per Unit surface resistance vs ESDD values

This slight increase can be attributed to inaccurate leakage current measurements due to a discontinuous conduction layer on the hydrophobic surface. If the conduction layer is not continuous, dry regions exist between the conducting water layer regions. This could result in dry band arcing if the voltage is high enough [4]. This was true of the manual wetting tests. The dry bands would have a much higher surface resistance than the conducting water layer as the arc passes through air. This higher resistance will have the effect of increasing the surface resistance of the insulator. This effect is what resulted in the inconsistent readings in the manual wetting tests. However it can be seen that the heavily polluted SiR1 insulators had a lower surface resistance than the light and medium pollution layers, as would be expected. Inconsistencies in the measured data can also be attributed to inconsistent ESDD levels on the insulator surfaces or human error.

When the SiR1 insulator was tested in the weather chamber it was polluted and then allowed to dry for 20 minutes before it was tested. In the 20 minutes drying time the insulator surface did not dry out completely and some moisture was still present on the insulator surface. This aided in getting a continuous conduction layer on the silicone rubber surface, and hence more consistent surface resistance values.

Figure 9.4 shows the surface resistances versus the ESDD values for the SiR1 tests. In the figure the results of the weather chamber tests and the manual heavy wetting tests are plotted. The curves are plotted with error bars which represent the standard deviation error expressed as a percentage. Typically the relationship between the surface resistance and the ESDD value is linear. If one draws a line through the error bars of the above plots one can see the approximate relationship between the surface resistance and the ESDD value. Here a line can easily be drawn through the spray bottle curve, this is mostly due to the large errors present in these readings.

The lines drawn for the weather chamber tests do not fit within the error

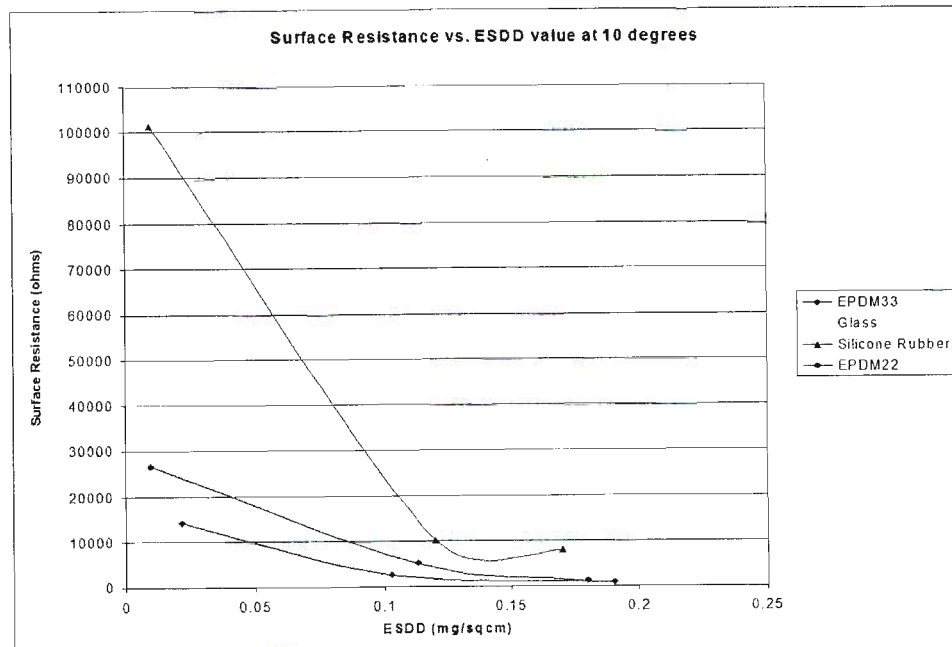


Figure 9.5: Per Unit surface resistance vs ESDD values at 10°C

bars as well as the line drawn for the manual wetting test results. This could be due to a number of factors including inconsistent ESDD values, dry band arcing, Joule heating or the runoff of excess water. The effect of the runoff of excess water will be discussed in the next section.

9.2.3 Comparison of Results for Different Insulator Types

From the results from *Tables 9.1 through 9.4* a comparison of the surface resistances can be made between the different insulator types. *Figure 9.5* shows a graph comparing the unit surface resistances of the different insulator types for the different pollution layer ESDD values. The results plotted were from the weather chamber tests conducted at 10°C.

From the graph it can be seen that the SiR1 is easily the best performer under these conditions. It displays the consistently highest unit surface resistance values at the different ESDD values. This is because of its hydrophobic properties. Because the SiR1 insulator is hydrophobic there is a good chance of dry regions forming on the insulator surface. This has the effect of raising the total surface resistance of the insulator surface, as the current passing through air would experience a higher resistance than if it passed through the conductive water layer. Although these plots should ideally be straight lines they are still a good indication of the insulator performance.

The EPDM2 insulator is the worst performer. It shows the lowest unit surface resistance. This is most likely due to its lack of hydrophobicity, therefore leading to the development of continuous water layers on the surface. The performance of the EPDM1 insulator and the Glass1 insulator is interchangeable.

The Glass1 insulator starts out as being the second worst performer and then it is taken over by the EPDM1 towards a heavier pollution layer. The Glass1 insulators are hydrophilic. The EPDM insulators were originally hydrophobic but were then sandblasted to reduce their hydrophobicity. After sand blasting the EPDM insulators were only slightly hydrophobic, classed as a 6 on the STRI guide [5]. It is possible that the EPDM insulators could have lost their last bit of hydrophobicity through the testing process. It has been shown that discharge activity on the EPDM surface can reduce its hydrophobicity [6]. This could also be the reason behind the interchange between the results of the Glass1 and the EPDM1 insulator.

Another factor which could have effected the outcome of the results is the orientation of the insulators during the weather chamber tests. The EPDM1 and EPDM2 insulators were orientated vertically so that the sheds ran parallel to the ground. This orientation did not allow for excess water to run off the insulator surface, possibly leading to a thicker water layer on the tops of the sheds. This can be seen in the pictures shown of the wetting on the insulators presented in section 8.6.2. This thicker layer would result in a lower surface resistance over the tops of the insulator sheds, thus having the effect of lowering the overall surface resistance.

The Glass1 insulators were also orientated vertically, so that the glass cap was horizontal. The top of the glass cap is slightly curved which can result in the slight runoff of excess water, thus reducing the water layer thickness and hence increasing effective surface resistance of the wet pollution layer. However on the underside of the glass cap there are three skirts. These skirts are pointing downwards and therefore water would collect on the tips of the skirts. This thicker water layer would reduce the surface resistance in this area. However if water were to drip off these skirts it would have the effect of reducing the total amount of water on the surface and hence increasing the surface resistance. So the surface resistance of the Glass1 insulator may change slightly depending on whether, and if so how much, water dripped off the skirts. This too could explain the interchangeability of the EPDM1 insulator and the Glass1 insulator.

The surface area to weight ratio of an insulator also has an effect on its performance in fog conditions. It has been shown that as the surface area to weight ratio decreases, condensation rate increases [2]. The Glass1 insulators have a lower surface area to weight ratio than the EPDM1 and EPDM2 insulators, resulting in more condensation taking place on the glass insulator surface. This could lead to excessive water condensation on the glass surface resulting in quite a lot of runoff. This would result in a washing effect [2], reducing the effective conductivity of the wet pollution layer and hence increasing the surface resistances measured. This too could be the reason for the EPDM insulators having the overall lowest surface resistance values.

The difference in unit surface resistance values between the EPDM1 and the EPDM2 insulators is approximately 60%. There is little reason why this should be the case as they would be expected to have the same values. The difference can therefore only be put down to an irregularity in the pollution layer (inconsistent ESDD values).

The orientation of the SiR1 insulator was not vertical. It was resting so that the rod was at about 70° to the horizontal. It was orientated like this for ease of testing. This orientation would have resulted in the sheds being tilted allowing for excess water to flow off the surface of the insulator. This would have the

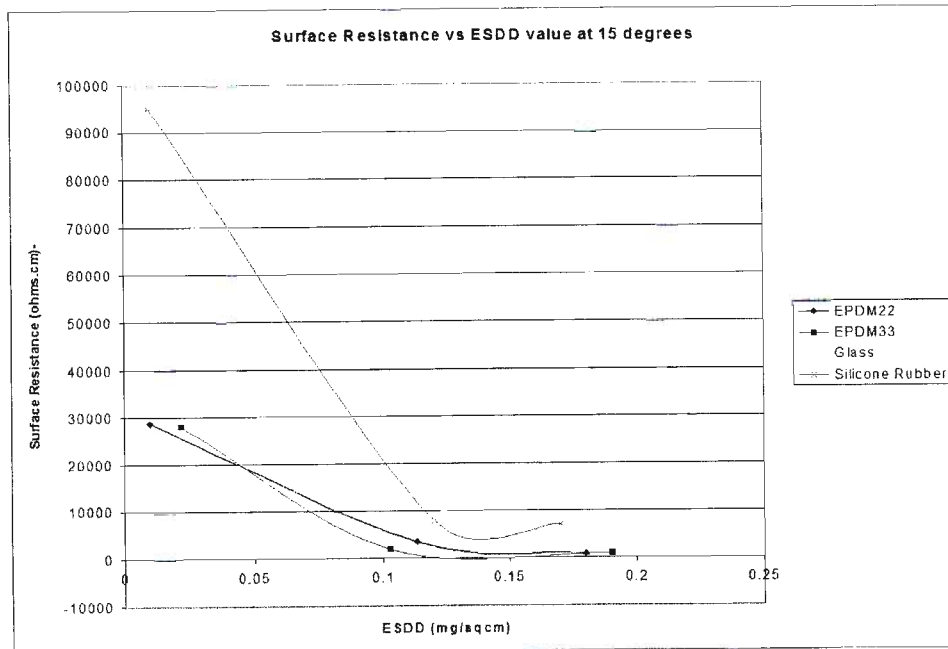


Figure 9.6: Per Unit surface resistance vs ESDD values at 15 °C

effect of lowering the effective thickness of the water layer and hence increasing the surface resistance. This, along with its hydrophobic properties, would have resulted in the significantly higher surface resistances measures during the weather chamber tests.

Figure 9.6 shows the plot of the surface resistances measured with the varying ESDD values for the weather chamber tests performed at 15 °C.

For the tests performed at 15 °C the EPDM results were more similar to each other however they still differed slightly. With these tests it should be noted that the SiR1 and Glass1 surface resistance results for the medium and heavy pollution cases were quite similar. This can most probably be attributed to inconsistencies in the pollution layer or excessive water runoff from the Glass1 insulator resulting in a higher than expected surface resistance under medium pollution conditions.

The effects of Joule heating could have also resulted in inaccuracies in the leakage current measurements [4]. If too much time was allowed to pass before the leakage current measurement was taken, Joule heating may have resulted in the evaporation of some of the water on the insulator surface therefore increasing the surface resistance of the water layer.

The weather chamber tests were performed at two different temperatures. This was done so that the effect of the surface temperature of the insulator, on the amount of water that condenses onto the surface could be examined as mentioned in sections 5.7 and 8.6. From the results of the weather chamber tests the effect of the different temperatures is inconclusive. The results showed equal variation in the surface resistances with the different weather chamber temperatures. Further and more extensive tests will have to be carried out to

Table 9.5: Surface resistances calculated

| Light | | | |
|--------|-------------------|-----------------------|-----------------------|
| | <i>Maxwell</i> | Weather Chamber 10 °C | Weather Chamber 15 °C |
| EPDM1 | 190k Ω /cm | 26.8k Ω /cm | 28.6k Ω /cm |
| EPDM2 | 170k Ω /cm | 14.2k Ω /cm | 28.1k Ω /cm |
| SiR1 | 100k Ω /cm | 101.2k Ω /cm | 95k Ω /cm |
| Glass1 | 110k Ω /cm | 27k Ω /cm | 19k Ω /cm |
| Medium | | | |
| | <i>Maxwell</i> | Weather Chamber 10 °C | Weather Chamber 15 °C |
| EPDM1 | 76k Ω /cm | 5k Ω /cm | 3.5k Ω /cm |
| EPDM2 | 67k Ω /cm | 2.5k Ω /cm | 2.1k Ω /cm |
| SiR1 | 41k Ω /cm | 10.1k Ω /cm | 7.7k Ω /cm |
| Glass1 | 43k Ω /cm | 5.1k Ω /cm | 11.6k Ω /cm |
| Heavy | | | |
| | <i>Maxwell</i> | Weather Chamber 10 °C | Weather Chamber 15 °C |
| EPDM1 | 41k Ω /cm | 0.97k Ω /cm | 0.74k Ω /cm |
| EPDM2 | 36k Ω /cm | 0.76k Ω /cm | 0.94k Ω /cm |
| SiR1 | 24k Ω /cm | 7.9k Ω /cm | 6.9k Ω /cm |
| Glass1 | 22k Ω /cm | 3.1k Ω /cm | 3.2k Ω /cm |

further investigate the effect of different surface temperatures.

9.3 Comparison of Experimental and *Maxwell* Results

The surface resistances predicted by the *Maxwell* simulations were quite dissimilar to those found though the weather chamber experiments. The results of the *Maxwell* simulations are presented in *Table 9.5* along with the results from the weather chamber tests.

As can be seen in *Table 9.5* there is a difference in surface resistances ranging from approximately 1 times to 40 times the data between the *Maxwell* and weather chamber results. On average the surface resistance data gathered from the weather chamber tests is significantly lower than the surface resistances calculated from the *Maxwell* simulations.

Those values calculated from the *Maxwell* simulations were calculated for a light pollution layer, with the surface conductivity being 60 $\mu S/cm$. The corresponding results from the weather chamber tests were performed with a very light pollution layer, with an ESDD value of approximately 0.012mg/cm². Using data outlined in [7] a surface conductivity level of 60 $\mu S/cm$ would correspond to a ESDD of approximately 0.048mg/cm², which is higher than those values used for the light pollution layer in the weather chamber tests. Due to the differences in ESDD values used in the *Maxwell* simulations and the weather chamber test the results were plotted to allow ease of analysis.

Figures 9.7 through to *9.10* show the results of the *Maxwell* and the weather chamber tests.

From *figures 9.7* through to *9.10* it can be seen that the surface resistances predicted by the *Maxwell* simulations are much higher than those found through the weather chamber tests. This is particularly true for the Glass1, EPDM1 and

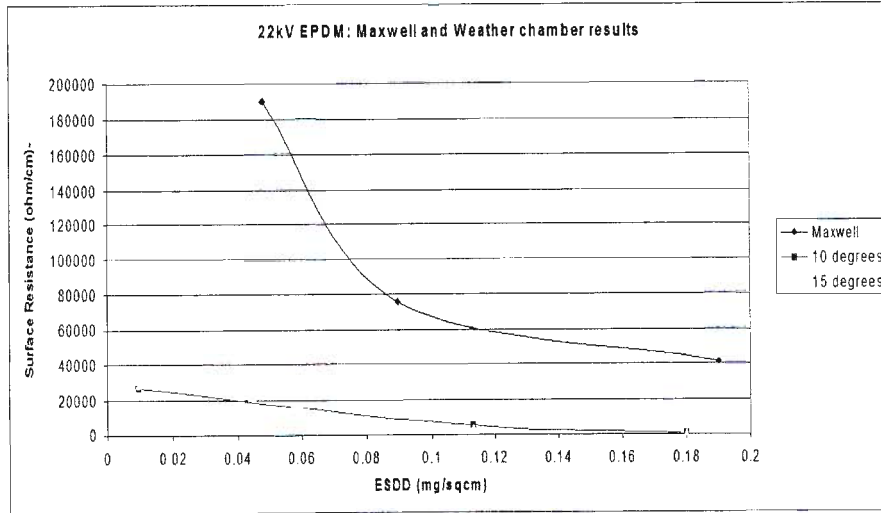


Figure 9.7: EPDM1 *Maxwell* and Weather chamber results

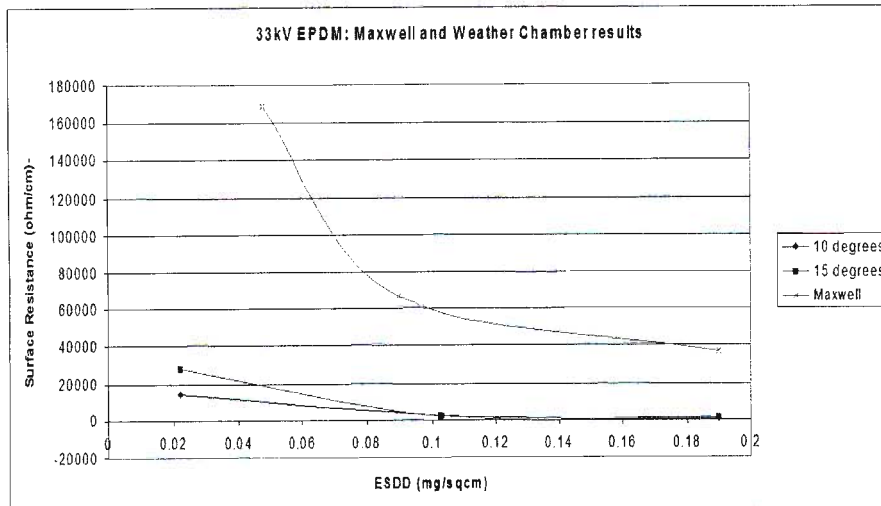


Figure 9.8: EPDM2 *Maxwell* and Weather chamber results

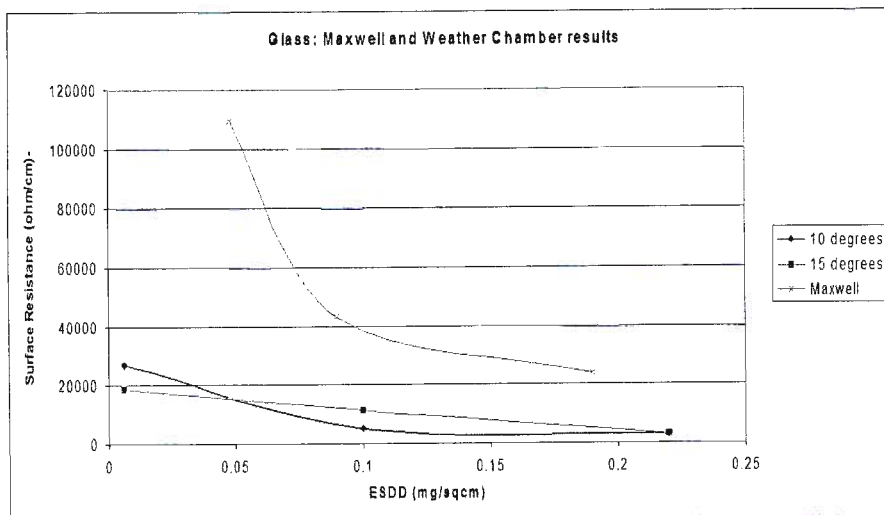


Figure 9.9: Glass1 *Maxwell* and Weather chamber results

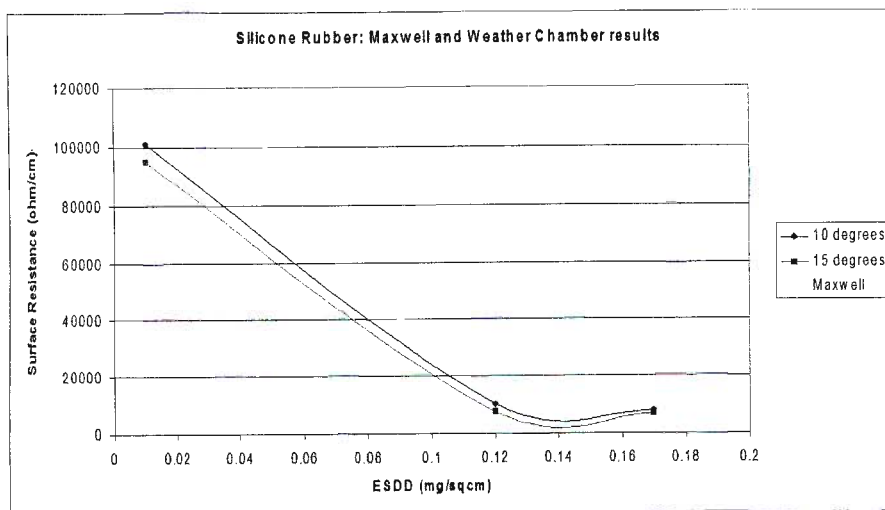


Figure 9.10: SiR1 *Maxwell* and Weather chamber results

EPDM2 insulators. A possible explanation for these results could be errors, as mentioned in section 4.7, in the heat and surface condensation calculations introduced in Chapters 3 and 4, which lead to an inaccurate surface condensation rate being calculated. The surface condensation rate calculated was much lower than what was experienced by the insulators in the weather chamber, leading to a much thicker water layer being present on the test insulators than those simulated in the *Maxwell* simulations. This in turn would lead to a much lower surface resistance for the test insulators than the simulated insulators.

The results of the SiR1 weather chamber tests compare more similarly to those found in the *Maxwell* simulations. Relating to the condensation rate mentioned above, the similarity could be due to a combination of the the SiR1 insulator's hydrophobicity and the orientation of the the insulator during the weather chamber tests. Should the condensation rate in the weather chamber have been higher than expected more water would have condensed on to the silicone rubber surface, but because of it's hydrophobicity and orientation the excess water ran off the insulator easily, reducing the overall conductive layer thickness and hence raising the surface resistance to a level which is closer to the results found in the *Maxwell* simulations. However it should be noted that although the SiR1 results were most similar out of all the insulators tested and simulated, there was still a significant different between the simulated and weather chamber results for the SiR1 insulator.

The insulators that were modeled in the *Maxwell* simulations were constructed to have a completely uniform conductive layer covering the entire surface of the insulating material. Only the glass insulator had a slightly uneven conductive layer on its surface. In the practical experiments, the water that condensed onto the polluted insulator surfaces was not in a uniform pattern. Due to the effects of gravity and insulator orientation, some sections of the insulator experienced a thicker conductive water layer than other sections. Although this would not have much of an effect on the total amount of water which condenses onto the surface it would result in some sections having a lower surface resistance than others.

The main reason for the discrepancy between the *Maxwell* simulation results and the weather chamber results is due to the condensation rate. It was shown that given high humidity levels and cool insulator surface temperatures, surface condensation was likely on the surface of the insulators [2]. The greater the difference between the insulator surface temperature and the steam fog temperature the greater the condensation rate will be [2]. This resulted in the differences in the amount of water present on the insulator surfaces during the weather chamber tests and the amount found through the condensation rate equations. The temperature of the humid particles used in the equations was only about a maximum of 5 °C warmer than the insulator surface temperature. In the weather chamber a steam fog was used, this means that the water particles were significantly, in the order of 70 °C, warmer than the insulator surface leading to a much higher condensation rate. Thus resulting in far heavier condensation in the weather chamber, than what was predicted by the condensation rate equations in section 4.6.

When the water vapor condenses onto the surface of the cooled insulators the temperature of the insulator surface will gradually warm up, due to the latent heat of condensation, when the temperature of the insulator surface is equal to the temperature of the fog, condensation will cease.

Table 9.6: Leakage currents of polluted insulators exposed to surface condensation

| Insulator | Rated Voltage | Pollution Level | Total Surface Resistance | Leakage Current |
|-----------|---------------|-----------------|--------------------------|-----------------|
| Glass1 | 10kV | Light | 782k Ω | 12.8mA |
| | | Medium | 149k Ω | 66.8mA |
| | | Heavy | 91k Ω | 109mA |
| EPDM1 | 22kV | Light | 1.3M Ω | 17mA |
| | | Medium | 239k Ω | 91.8mA |
| | | Heavy | 46k Ω | 474mA |
| EPDM2 | 33kV | Light | 1.3M Ω | 25.4mA |
| | | Medium | 234k Ω | 141mA |
| | | Heavy | 70K Ω | 473mA |
| SiR1 | 22kV | Light | 6.1M Ω | 3.6mA |
| | | Medium | 608k Ω | 36mA |
| | | Heavy | 471k Ω | 47mA |

9.4 Implications of findings

The findings above are significant. They show that surface condensation can lead to a significant amount of water condensing onto the surface of outdoor insulators. Should these outdoor insulators be polluted with a salt contamination, as they often are in coastal environments [6], this condensed water will dissolve the salt on the insulator surface and result in a conductive layer on the insulator surface hence leading to high leakage currents and hence discharge activity.

Table 9.6 shows the insulators that were tested, their rated voltage, the average surface resistance and the leakage current which results from these conditions. The results shown are for the tests performed in the weather chamber at 10 °C.

Table 9.6 shows that the leakage currents that would be present on the surface of the insulators under test, should they have been tested at their rated voltage, would be very high. This is particularly true for the EPDM insulators.

When a leakage current flows through a wet conducting contamination layer Joule heating takes place [4]. The greater the current the greater the amount of Joule heating takes place. If the amount of Joule heating is sufficient the water layer evaporates and dry regions, or dry bands, develop [4]. These dry bands usually occur in areas where the current density is the the highest. This would be at points where the cross-sectional surface area of the contamination layer is the lowest, thus making the rod's the part of the polymeric insulators the most susceptible to dry band formation [2]. These dry bands are then exposed to most of the voltage and so the voltage gradient across the dry band is intensified resulting in the flash over of the dry band. Dry band breakdown usually occurs at about 250mA [8].

Given the above, heavily polluted EPDM insulators will readily experience dry band breakdown if subjected to these weather conditions in service. Figure 9.11 shows a plot of the leakage currents measured during the weather chamber test and their ESDD values.

The Glass1 insulators experienced a leakage current of 109mA with a heavy

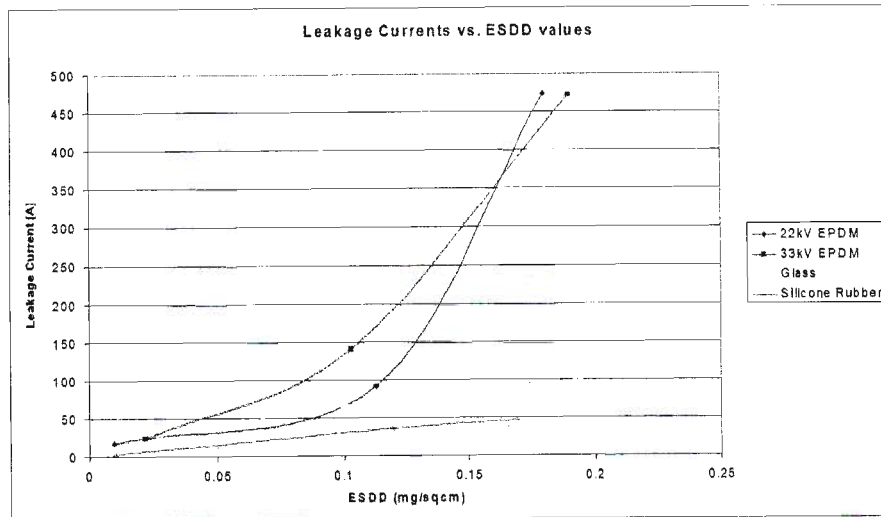


Figure 9.11: Weather chamber leakage current verses ESDD values

pollution layer. The SiR1 insulator experienced a leakage current of 47mA with a heavy pollution layer. With a very heavy pollution layer it can be speculated that the leakage current on the Glass1 insulator will exceed 250mA and dry band breakdown would occur. It has been observed that salt pollution in a marine environment often exceeds $0.3mg/cm^2$, this is classed as a very heavy pollution level [9]. It is therefore very likely that the insulators in the South African coastal sites will experience very heavy contamination, leading to low surface resistance values and high leakage currents, increasing the chance of failure. For the SiR1 insulator an extremely heavy pollution layer would have to be present on the insulator surface to allow a leakage current of greater than 250mA to flow.

This data ties in with the findings mentioned in reference [1] in Chapter 2 section 1 [6]. The paper covered the experiences of the Florida Power and Light (FPL) transmission system. During 1991 they experienced a large number of contamination outages as a result of the weather conditions which are under investigation in this dissertation. Their findings were that the EPDM insulators performed the worst when exposed to these conditions [6]. This is the same result as was found by the weather chamber tests. It was also found that the EPDM insulators performed worse than their porcelain insulators [6]. Porcelain insulators have similar properties to glass and can therefore be likened to glass insulators. Given this, this too agrees with the results of the tests carried out in the weather chamber. In [6] it was also found that the silicone rubber insulators performed the best, there were no outages or flashovers on the silicone rubber lines. This too agrees with the weather chamber results, which show the silicone rubber insulators to be the best performers and little chance of them experiencing dry band breakdown even at very heavy contamination levels.

Generally speaking the performance of EPDM insulators is expected to be better than glass or porcelain insulators. However this is not the case found through the weather chamber tests. The EPDM insulators performed far more

poorly than the glass insulators. This could be due to the insulator shape and orientation. Glass insulators are more likely to experience excess water runoff than EPDM insulators if orientated vertically. This runoff of excess water would help increase the surface resistance of the insulator and hence help reduce leakage currents.

When reviewing the condensation rate due to steam fog mentioned in literature reviewed on steam fog tests conducted at normal temperatures [2], it was noticed that when the insulator is cooled, as in the weather chamber tests, the condensation rate is much greater than steam fog tests performed at standard temperatures [2]. The literature shows the lowest surface resistance occurred only after 40-50 minutes in the steam fog [2]. During the weather chamber tests it was found that the leakage currents peaked after about 10 minutes of steam fog. This proves that a cooler insulator surface temperature will result in a greater surface condensation rate than what is experienced at standard temperatures.

In service outdoor high voltage insulators in a coastal environments are likely to experience the weather conditions which could lead to surface condensation on the insulator surfaces. Given the salt pollution from the coastal environment and the correct weather conditions severe leakage currents are likely to occur on the wet outdoor insulators. The tests performed in the weather chamber were steam fog tests, which means that the fog temperature was much higher than the fog temperatures experienced in natural weather conditions. This would lead to lower leakage currents developing on the wetted insulator surfaces than those found in the weather chamber tests. However the insulators will still experience more severe wetting than under normal fog conditions or manual wetting, leading to an increase in leakage currents and possible flashover.

9.5 References

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Chapter 10

CONCLUSION AND FUTURE WORK

10.1 Summary and Conclusion

The effects of specific weather conditions on outdoor high voltage insulators were investigated. The particular conditions to which the insulators were exposed were salt pollution, due to their being located in a coastal area, cold temperatures and severe humidity. The insulators that were under investigation were EPDM insulators, cap-and-pin type glass insulators and silicone rubber insulators. A new test method was proposed in order to test the performance of these insulators when exposed to these specific conditions. The test method involved the construction of a weather chamber to simulate the cold and humid conditions and the further monitoring of leakage currents when energized under these conditions.

An equation was constructed so that the surface temperature of the outdoor insulator could be calculated in response to the environmental conditions. This equation took both heat transfer through conductive heat transfer from the surrounding air, and radiative heat transfer into account. Once the equation was developed it was used to analyze weather data supplied by the South African Weather Service. This analysis confirmed that surface condensation did occur under the specified weather conditions. This led to the wetting of the insulator surface under these weather conditions. It was also shown that surface condensation resulted in more water condensing onto the insulator surface than would normally occur with normal dew formation. The surface condensation rate was calculated as well so that the data could be used in a computer simulation of the insulators' performance.

Once the weather data had been analyzed some of the data was used to simulate the insulators in a computer program. The program used was *Maxwell*. Here three dimensional representations of the four different insulators that would be tested were constructed. The insulators were first modeled with no pollution layer present and the voltage gradient and electric fields present with a 30kV applied voltage were plotted. A conductive pollution layer was then added to the surface of the insulators. A current was applied to the insulators and the resulting current densities were plotted. From this data the surface resistances of the contamination layers were calculated.

A weather chamber was then set up to simulate the weather conditions sometimes experienced in South African coastal environments. The weather chamber was made to chill the insulators to either 10 °C or 15 °C and then a heavy steam

fog was introduced into the chamber. The insulators were polluted by dipping them into a slurry. The pollution levels were classed as light, medium and heavy as specified by IEC 60815. A manual heavy wetting, with a spray bottle, test was also done for the purposes of comparison. The results of the weather chamber and manual wetting tests showed that the surface resistances resulting from the weather chamber were substantially lower than with the manual wetting tests. This went to show that surface condensation lead to more severe wetting than traditional methods. It was also found that the surface resistance decreased with increasing pollution severity, as would be expected.

When the weather chamber results were compared to the *Maxwell* simulation results it was seen that the predicted surface resistance results from the computer simulation were much higher than the results obtained in the weather chamber tests. This difference in results has been put down to the large difference in the steam fog temperature and the insulator surface temperature experienced in the weather chamber. The surface condensation rate used in the simulations was calculated with only a small difference in the fog temperature and the insulator surface temperature, therefore leading to a smaller condensation rate be calculated than that experienced in the weather chamber.

In general it was seen that the EPDM insulators performed the worst in the computer simulation, the manual wetting tests and the weather chamber tests. This agrees with past observations on the subject. The glass insulators' overall performance was second best in all three cases and the silicone rubber insulators performed the best. This too agrees with previous literature. The leakage currents which were present on the heavily polluted insulator surface was approximately 400mA for the EPDM insulators, 100mA for the glass insulator and 40mA for the silicone rubber insulator. Given this, the EPDM insulator would experience dry band arcing and probable flashover if exposed to the above environmental conditions and a heavy pollution layer. It is speculated that the glass insulator would also experience appreciable leakage currents and possible flashover if exposed to the above mentioned environmental conditions, with a very heavy pollution layer. It is unlikely that the silicone rubber insulator will experience leakage currents that are high enough to result in sever dry band arcing and eventual flashover.

It can therefore be concluded that outdoor insulators in coastal environments are exposed to conditions which could result in severe wetting which in turn would lead to substantial leakage currents flowing over the surface of the wet, polluted insulators, this is especially true for the EPDM type of outdoor insulators. South African coastal areas do experience weather conditions which will lead to surface condensation. This makes the possibility of flashover on EPDM or glass insulated high voltage power lines in coastal areas likely.

10.2 Future work

The work that was performed for this masters dissertation was not extensive as various limits were placed on the work. These limits were in the form of an insufficient amount of time allowed to perform testing and the availability of sufficient equipment. A certain amount of additional work needs to be performed in order to further test and validate the results displayed in this dissertation. This further work includes:

- Further weather chamber tests to examine the effect of the different insulator orientations on surface resistance.
- Perform a greater number of weather chamber tests at different temperatures to further investigate the effect of different insulator surface temperatures on the surface condensation rate, and hence the surface resistance of the wet polluted insulators.
- Future tests should be automated so that the desired voltage level can be switched onto the insulators instantaneously and not switched on and then raised to the desired voltage level. This will help reduce the amount of water that evaporates from the surface as a result of Joule heating. With this the leakage current and voltage readings should be taken as soon as the voltage is applied, also to reduce the effects of Joule heating.
- A standard steam fog test at room temperature should be run in conjunction with the weather chamber tests so that the extent of surface condensation at cold temperatures can be properly examined.
- It may be worth while to conduct the weather chamber tests with the insulators energized prior to steam injection. This would give a more realistic account of what leakage currents are experienced by outdoor insulators in service.
- A new weather chamber could be constructed with a built in steam injection system.
- Perform the weather chamber tests again but using a warm fog instead of a steam fog and compare results. Using a warm fog will result in conditions which are more similar to those experienced by in-service outdoor insulators.

Appendix A

MATLAB CODE: WEATHER ANALYSIS

This is the main *MatLab* function written. It is used to load and initialize data, call the ode function, perform analysis and plot relevant data.

%This block is used to clear all previous data and to initialize variables.

```
clear dummy = 0;
```

```
wind = 0;
```

```
global temp-insulator;
```

```
%data array of surface temperature of the insulator
```

```
temp-surroundings = 0; %data array of the environmental temperature to be used for T-infinity.
```

```
temp-insulator = 0;
```

```
temp-environment = 0; %data array of the environmental temperature
```

```
sun-radiation = 0; %data array of the solar radiation levels
```

```
T-infinity = 0; %variable to represent the temperature of the surrounding air, the temperature at infinity.
```

```
wind-velocity = 0; %data array of wind velocities
```

```
i = 0;
```

```
%a counter
```

```
k = 0; %another counter
```

```
IC = 0; %initial conditions. The initial temperature of the insulator surface.
```

```
%This block loads all relevant data files and prepares for calculations and performs comparisons.
```

```
temp-environment = load('CP01.txt'); %load temperature data from text file
```

```
temp-surroundings = load('CP01.txt') + 273; %load temperature data from text file
```

```
global sun-radiation; %define sun-radiation as global so that it can be used by the function.
```

```
sun-radiation = load('RadCP01.txt'); %load solar radiation data from text file.
```

```
sun-radiation = sun-radiation'; %transpose radiation data matrix so that it is in the correct format.
```

```
humidity = load('HumCP01.txt'); %load humidity data from text file
```

```
finish = length(temp-surroundings); %sets duration of analysis. One unit equals one hourly data point. This can be changed to analyze the full range or data or just a portion, to keep calculation time down.
```

global T-infinity; %Set T-infinity to global so that it can be used by the function.

T-infinity = temp-surroundings(2); %Set the temperature at infinity to be the second data point from the environmental temperature data array. It is the second point as this is the temperature the insulator has to reach from its current temperature which would be the first data point.

global wind-velocity; %Set wind-velocity to global so that it can be used by the function.

wind-velocity = load ('SpdCP01.txt') ; %load wind speed data from text file.

wind-velocity = wind-velocity'; %transpose wind speed data matrix so that it is in the correct format.

global i; %set counter i to be global.

i = 1;

m = 1;

global k; %set counter k to be global.

k = 1;

global IC ; %set counter IC to be global

IC =temp-surroundings(1); %Set initial conditions. Assume insulator surface temperature is at the environmental temperature for the first calculation. It will then tend to heat or cool towards the second environmental temperature data point.

%Loop through data

while i ; finish %Perform the calculation while the counter is less than the specified length of 'finish'

[T, Y] = ode45(@func, [0 3600], IC); %Calls function, func, so as to perform ode, Ordinary Differential Equation. Returns T (time vector) and Y (vector representing temperature change). @func calls the function func. on which the ode must be performed. The square brackets represent the time span for the intervals of integration. For this case it is set to go from 0 to 3600s (or an hour). IC is the initial conditions.

temp-insulator(k) = Y(end); %Set the surface temperature to equal to the the final value in the Y vector once the ode has been performed. This will represent the surface temperature change in one hour.

IC = temp-insulator(k); %Set the new IC to equal the new surface temperature

T-infinity = temp-surroundings(i+1); %Set the temperature at infinity to the next data point.

i = i+1; %increment counter

k = k+1; %increment counter

end %ends while loop

%plots data


```

plot(temp-environment), title('environment'); %plots environmental temperatures from the above data file
ylabel ('temperature')
xlabel('time')
hold on
plot (temp-insulator - 273,'Color',[1,0,0]), title('insulator');
ylabel ('temperature')
xlabel('time')

```

%This is code used to compare the data for further analysis of the weather data.

```

i = 1; %set counter.
j = 1; %set counter.
while i < (finish -2) if temp-surroundings(i) > temp-insulator(i) +1 && temp-insulator(i) > 289 && temp-insulator(i) < 303 && humidity(i) > 85;
dummy(j) = i; %get dummy vector of positions of the occurrence if the specified conditions are true.
j = j + 1; %increment counter
i = i + 1; %increment counter
else i = i + 1; %increment counter if the specified conditions are not true.
end
end
end

```

%This block is used to detect instances where the wind velocity data file where the data is equal to zero. These instances are displayed so that one can identify areas not to include in the analysis, as the wind velocity data was missing.

```

i = 1;
m = 1;
while i < (finish -2)
if wind-velocity(i) == 0;

wind(m) = i; %get dummy vector of positions of this occurrence.
m = m + 1;
i = i + 1;
else i = i + 1;
end
end
end

```

```
disp(dummy);
```

```

wind = wind
%displays instances of zero wind velocity.

```

The code below is the code written for the function func.m. This is where the ode is defined and calculated.

```

% This is the ode function. Here all variables are initialized, the ode function is defined. function dYdt = func(t, Y, IC) %input arguments.
Diameter = 0.024; %Diameter of the insulator (m).

```

```

radius =Diameter/2; %Radius
length = 0.01; %The length of the insulator
SurfaceArea = 2*pi*radius*length + 8*2*(pi*(0.033 + radius)^2 - pi*(radius)^2);
%surface area of cylinder + surface area of 8 sheds, 2sides (shed area - cylinder
area)

Volume = pi*radius*radius*length + 8*(0.002*(pi*(0.033 + radius)^2 - pi*(radius)^2));
%volume of cylinder and sheds.
density = 1500; %Density of insulator surface
SpecificHeat = 1250; %Specific heat of insulator surface
emissivity = 0.9; % Emissivity of insulator surface
absorptivity = 0.53; % Absorptivity of insulator surface
Boltz = 5.669e-8; %Boltzmanns constant

x = 0; %Variable for solar radiation
Re = 0; %Reynolds Number
A = 0; %Variable to be used in calculation
B = 0; %Variable to be used in calculation
C = 0; %Variable to be used in calculation
Nu = 0; %Nusselt Number
h = 0; %Heat convection coefficient

KF = 24.54E-3; %Thermal Conductivity
Pr = 0.713; %Prandtl Number
global i; %Global counters from weather.m
global k;
global wind-velocity; %Global wind velocity from weather.m
global T-infinity; %Global temperature at infinity from weather.m
global sun-radiation; %Global solar radiation from weather.m
global temp-insulator %Global insulator temperature from weather.m

%This if loop evaluates the radiation situation. If solar radiation is not
present or very little (first condition) then the amount of heat lost due to the
insulator radiating heat out is calculated. If radiation is present (second condi-
tion) then the data read in from the text file is divided and multiplied to get it
into the correct units for the calculation.

if (i==1) %If the loop is on its first pass set initial insulator temperature to
be 293K
IC = 293;
else
IC = temp-insulator(end); %else the surface temperature equals last temperature
calculated
end x = sun-radiation;
if (x(i) <= 0.5) %If there is very little or no radiation then calculate radiation
lost to environment.
z = Boltz*(IC^4 - T-infinity^4);
radiation = z; %store this value in radiation variable
term = emissivity*radiation; %Used in ode equation
else %If there is radiation then calculate solar radiation in correct units

```

```

y = (x(i)/278);
z = Boltz*(IC^4 - T-infinity^4);
radiation = -y + z; %Store this value in radiation variable
term = absorptivity*radiation; %Used in ode equation
end

kv = 13.93e-6; %The kinematic viscosity for air
if (wind-velocity(i) == 0)
Re = (0.01*Diameter)/(kv);
else
Re = (wind-velocity(i)*Diameter)/(kv); %Calculates Reynolds Number
end

%This section calculates the heat convection coefficient using the equation
outlined in equations (3, 4 and 5) of the heat analysis paper.
A = 0.62*Re^0.5*Pr^(1/3);
B = 1 + (Re/282000)^(5/8);
C = (1 + (0.4/Pr)^(2/3))^0.25;
Nu = 0.3 + [(A*(B^(4/5)))/C];
h = Nu*(KF/Diameter);
% The differential equation used to determine the change in heat over time.
dYdt = -(h*(Y - T-infinity) + term)*SurfaceArea)/(density*Volume*SpecificHeat);

```

Appendix B

ESDD MEASUREMENTS

| Light ESDD Measurements | | | | | | | | | |
|-------------------------|--------------------|--------|-------------|-----------|--------------------|--------|-------------|---------|---------|
| EPDM 22kV | | | | EPDM 33kV | | | | | |
| measured | deionized | result | ESDD | measured | deionized | result | ESDD | | |
| 8 | 4.1 | 3.9 | 0.0065 | 12 | 4.3 | 7.7 | 0.0131 | | |
| 9 | 4.1 | 4.9 | 0.0082 | 21 | 3.7 | 17.3 | 0.0301 | | |
| 10 | 5.2 | 4.8 | 0.008 | 13 | 4.1 | 8.9 | 0.0152 | | |
| 11 | 4.8 | 6.2 | 0.0105 | 12 | 3.7 | 8.3 | 0.0141 | | |
| 10 | 5.8 | 4.2 | 0.007 | 31 | 3.7 | 27.3 | 0.0482 | | |
| 11 | 4.4 | 6.6 | 0.0112 | 29 | 3.9 | 25.1 | 0.0442 | | |
| 12 | 4.9 | 7.1 | 0.012 | 29 | 5.1 | 23.9 | 0.042 | | |
| 10 | 4.7 | 5.3 | 0.0089 | 14 | 4.9 | 9.1 | 0.0155 | | |
| 13 | 5.9 | 7.1 | 0.012 | 11 | 4.3 | 6.7 | 0.0113 | | |
| 13 | 5.5 | 7.5 | 0.0127 | 13 | 5.8 | 7.2 | 0.0122 | | |
| | Average | | 0.0097 | 11 | 5.2 | 5.8 | 0.0098 | | |
| | Standard Deviation | | 0.002255364 | 15 | 5.4 | 9.6 | 0.0164 | | |
| | Variance | | 5.08667E-06 | 12 | 5 | 7 | 0.0119 | | |
| | | | | | Average | | 0.021846154 | | |
| | | | | | Standard Deviation | | 0.014045854 | | |
| | | | | | Variance | | 0.000197286 | | |
| Glass | | | | | | | | | |
| Top | | | | Undereath | | | | Av ESDD | |
| measured | deionized | result | ESDD | measured | deionized | result | ESDD | | |
| 14 | 2.8 | 11.2 | 0.0048 | 27 | 2.5 | 24.5 | 0.0052 | | 0.0055 |
| 16 | 3.2 | 12.8 | 0.0055 | 30 | 3.3 | 26.7 | 0.0068 | | 0.00615 |
| 12 | 2.9 | 9.1 | 0.0039 | 18 | 2.5 | 15.5 | 0.0039 | | 0.0039 |
| 17 | 2.9 | 14.1 | 0.0061 | 20 | 2.8 | 17.2 | 0.0043 | | 0.0052 |
| 15 | 3.3 | 11.7 | 0.005 | 25 | 2.6 | 22.4 | 0.0057 | | 0.00535 |
| 16 | 3 | 13 | 0.0056 | 30 | 2.7 | 27.3 | 0.007 | | 0.0063 |
| 19 | 3 | 16 | 0.0069 | 38 | 2.8 | 35.2 | 0.009 | | 0.00795 |
| 17 | 3.8 | 13.2 | 0.0057 | 28 | 3.3 | 24.7 | 0.0063 | | 0.006 |
| 22 | 2.3 | 19.7 | 0.0085 | 51 | 5 | 46 | 0.0119 | | 0.0102 |
| 20 | 3.2 | 16.8 | 0.0072 | 26 | 3 | 23 | 0.0058 | | 0.0065 |
| 19 | 3.1 | 15.9 | 0.0068 | 27 | 3.1 | 23.9 | 0.0061 | | 0.00645 |
| 17 | 3 | 14 | 0.006 | 20 | 3.1 | 16.9 | 0.0042 | | 0.0051 |
| | Average | | 0.006216667 | | | | | | |
| | Standard Deviation | | 0.001594783 | | | | | | |
| | Variance | | 2.54333E-06 | | | | | | |
| Silicone Rubber | | | | | | | | | |
| measured | deionized | result | ESDD | | | | | | |
| 11 | 4.7 | 6.3 | 0.011 | | | | | | |
| 10 | 4.6 | 5.4 | 0.0094 | | | | | | |
| 13 | 6.2 | 6.8 | 0.0119 | | | | | | |
| 11 | 6.3 | 2.7 | 0.0046 | | | | | | |
| 11 | 5.2 | 5.8 | 0.0101 | | | | | | |
| 11 | 6.2 | 5.8 | 0.0101 | | | | | | |
| 13 | 7.2 | 5.8 | 0.0101 | | | | | | |
| 12 | 6.7 | 5.3 | 0.0092 | | | | | | |
| | Average | | 0.00955 | | | | | | |
| | Standard Deviation | | 0.003252051 | | | | | | |
| | Variance | | 1.05758E-05 | | | | | | |

Figure B.1: ESDD measurements for light pollution layer

| Medium ESDD Measurements | | | | | | | | |
|--------------------------|-----------|--------|-------------|---------------------|-----------|--------|-------------|---------|
| EPDM 22kV | | | | EPDM 33kV | | | | |
| measured | deionized | result | ESDD | measured | deionized | result | ESDD | |
| 250 | 192 | 58 | 0.105 | 240 | 192 | 48 | 0.086 | |
| 254 | 193 | 61 | 0.11 | 252 | 193 | 59 | 0.107 | |
| 294 | 230 | 64 | 0.116 | 288 | 227 | 61 | 0.11 | |
| 288 | 223 | 65 | 0.118 | 283 | 223 | 60 | 0.109 | |
| 301 | 238 | 63 | 0.114 | 280 | 224 | 56 | 0.101 | |
| 299 | 236 | 63 | 0.114 | 270 | 223 | 47 | 0.084 | |
| Average | | | 0.112833333 | Average | | | 0.1026 | |
| Standard Deviantion | | | 0.005909033 | Standard Deviantion | | | 0.009914636 | |
| Variance | | | 3.49167E-05 | Variance | | | 0.0000983 | |
| Glass | | | | | | | | |
| Top | | | | Underneath | | | | Av ESDD |
| measured | deionized | result | ESDD | measured | deionized | result | ESDD | |
| 420 | 193 | 227 | 0.106 | 540 | 201 | 339 | 0.093 | 0.0995 |
| 397 | 191 | 206 | 0.096 | 625 | 192 | 433 | 0.12 | 0.108 |
| 465 | 192 | 273 | 0.128 | 500 | 192 | 308 | 0.084 | 0.106 |
| 397 | 192 | 205 | 0.0953 | 442 | 192 | 250 | 0.068 | 0.08165 |
| 427 | 192 | 235 | 0.11 | 579 | 192 | 387 | 0.107 | 0.1085 |
| 411 | 224 | 187 | 0.0867 | 626 | 226 | 400 | 0.111 | 0.09885 |
| 386 | 223 | 163 | 0.0753 | 653 | 223 | 430 | 0.12 | 0.09765 |
| Average | | | 0.100021429 | Average | | | 0.100021429 | |
| Standard Deviantion | | | 0.009274196 | Standard Deviantion | | | 0.009274196 | |
| Variance | | | 8.60107E-05 | Variance | | | 8.60107E-05 | |
| Silicone Rubber | | | | | | | | |
| measured | deionized | result | ESDD | | | | | |
| 260 | 192 | 68 | 0.127 | | | | | |
| 240 | 192 | 48 | 0.089 | | | | | |
| 296 | 237 | 59 | 0.11 | | | | | |
| 298 | 235 | 63 | 0.118 | | | | | |
| 323 | 245 | 78 | 0.147 | | | | | |
| 302 | 237 | 65 | 0.121 | | | | | |
| Average | | | 0.118666667 | | | | | |
| Standard Deviantion | | | 0.016227549 | | | | | |
| Variance | | | 0.000263333 | | | | | |

Figure B.2: ESDD measurements for medium pollution layers

| Heavy ESDD Measurements | | | | | | | | | |
|-------------------------|-----------|--------|-------------|--|---------------------|-----------|--------|-------------|---------|
| EPDM 22kV | | | | | EPDM 33kV | | | | |
| measured | deionized | result | ESDD | | measured | deionized | result | ESDD | |
| 349 | 241 | 108 | 0.199 | | 366 | 247 | 119 | 0.2196 | |
| 292 | 237 | 55 | 0.0992 | | 365 | 240 | 125 | 0.231 | |
| 330 | 237 | 93 | 0.1704 | | 337 | 237 | 100 | 0.184 | |
| 339 | 235 | 104 | 0.191 | | 326 | 236 | 90 | 0.165 | |
| 333 | 236 | 97 | 0.178 | | 346 | 235 | 111 | 0.204 | |
| 349 | 236 | 113 | 0.208 | | 337 | 235 | 102 | 0.187 | |
| 384 | 269 | 115 | 0.212 | | 315 | 222 | 93 | 0.17 | |
| 342 | 222 | 120 | 0.222 | | 300 | 219 | 81 | 0.148 | |
| Average | | | 0.18495 | | Average | | | 0.188575 | |
| Standard Deviantion | | | 0.038698062 | | Standard Deviantion | | | 0.028210725 | |
| Variance | | | 0.00149754 | | Variance | | | 0.000795845 | |
| Glass | | | | | | | | | |
| Top | | | | | Underneath | | | | |
| measured | deionized | result | ESDD | | measured | deionized | result | ESDD | Av ESDD |
| 715 | 236 | 479 | 0.229 | | 1002 | 243 | 759 | 0.214 | 0.2215 |
| 809 | 238 | 571 | 0.274 | | 927 | 238 | 689 | 0.194 | 0.234 |
| 643 | 236 | 407 | 0.193 | | 977 | 240 | 737 | 0.207 | 0.2 |
| 709 | 236 | 473 | 0.226 | | 991 | 236 | 755 | 0.213 | 0.2195 |
| 769 | 237 | 532 | 0.254 | | 978 | 235 | 743 | 0.209 | 0.2315 |
| Average | | | 0.2213 | | | | | | |
| Standard Deviantion | | | 0.01343782 | | | | | | |
| Variance | | | 0.000180575 | | | | | | |
| SIR | | | | | | | | | |
| measured | deionized | result | ESDD | | | | | | |
| 607 | 501 | 106 | 0.201 | | | | | | |
| 316 | 240 | 76 | 0.143 | | | | | | |
| 323 | 244 | 79 | 0.1485 | | | | | | |
| 340 | 241 | 99 | 0.1873 | | | | | | |
| Average | | | 0.16995 | | | | | | |
| Standard Deviantion | | | 0.028586302 | | | | | | |
| Variance | | | 0.000817177 | | | | | | |

Figure B.3: ESDD measurements for heavy pollution layer

Appendix C

LEAKAGE CURRENTS WITH MANUAL WETTING

| Glass | | | | | EPDM22 | | | | |
|------------------------------|--------|----------|-------|----------|------------------------------|---------|----------|-------|----------|
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 10951 | 0.0062 | 2037800 | 11230 | 2037800 | 14062 | 0.0049 | 4173200 | 14389 | 0.0012 |
| 9838 | 0.0081 | 1428100 | 10953 | 1365000 | 12429 | 0.0038 | 10177000 | 12993 | 0.00059 |
| 10201 | 0.0117 | 903430 | 11137 | 42020.8 | 14523 | 0.0035 | 6065800 | 14849 | 0.0012 |
| 13929 | 0.0103 | 1691400 | 13691 | 1516200 | 14003 | 0.0029 | 8137600 | 15681 | 0.0013 |
| 15087 | 0.0112 | 1585100 | | 1423800 | 14849 | 0.0024 | 10452000 | 14300 | 0.0012 |
| 13914 | 0.0103 | 2299900 | 15592 | 1251600 | 8954 | 0.0019 | 6372800 | 8065 | 0.000043 |
| | | | | | 9236 | 0.0022 | 5268800 | 9473 | 0.000046 |
| | | | | | 9845 | 0.002 | 5722000 | 10112 | 0.00094 |
| Average Resistance: 1657622 | | | | | Average Resistance: 7046150 | | | | |
| EPDM33 | | | | | Silicone Rubber | | | | |
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 18086 | 0.0024 | 11311000 | 18235 | 0.000046 | 13929 | 0.00085 | 32439000 | 13914 | 0.00018 |
| 18562 | 0.0024 | 12188000 | 18472 | 0.00067 | 14849 | 0.0014 | 19245000 | 13914 | 0.0012 |
| 19022 | 0.0019 | 13067000 | 19066 | 0.00074 | 13929 | 0.0032 | 8408100 | 14389 | 0.00034 |
| 20418 | 0.0018 | 11784000 | 20418 | 0.00068 | 15770 | 0.0021 | 10656000 | 14849 | 0.00028 |
| | | | | | 14151 | 0.0014 | 14912000 | 13691 | 0.00019 |
| Average Resistance: 12087500 | | | | | Average Resistance: 17132020 | | | | |

Figure C.1: Leakage Currents for light pollution with manual wetting

| Glass | | | | | EPDM22 | | | | |
|------------------------------|--------|--------|-------|--------|------------------------------|--------|--------|-------|--------|
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 9280 | 0.0247 | 491990 | 10680 | 0.0007 | 16007 | 0.018 | | 15770 | 0.0161 |
| 9960 | 0.0264 | 382820 | 10201 | 0.0265 | 13929 | 0.0165 | | 14389 | 0.0187 |
| 9964 | 0.0216 | 501620 | 13453 | 0.0203 | 15310 | 0.0157 | | 16468 | 0.0122 |
| 9518 | 0.0304 | 321240 | 9964 | 0.02 | 12533 | 0.0255 | 563820 | 15785 | 0.0141 |
| 10439 | 0.0267 | 428290 | 12770 | 0.0205 | 13927 | 0.0226 | 624070 | 19720 | 0.0187 |
| Average Resistance: 425192 | | | | | Average Resistance: 593945 | | | | |
| EPDM33 | | | | | Silicone Rubber | | | | |
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 17626 | 0.0261 | 727900 | 20418 | 0.02 | 8360 | 0.0257 | 315270 | 13216 | 0.0392 |
| 18324 | 0.0255 | 855070 | 20878 | 0.0205 | 14374 | 0.048 | 305920 | 15324 | 0.0421 |
| 17166 | 0.0193 | 821690 | 18086 | 0.015 | 6726 | 0.0215 | 323630 | 11375 | 0.0257 |
| | | | | | 8820 | 0.029 | 292730 | 13231 | 0.0431 |
| Average Resistance: 801553.3 | | | | | Average Resistance: 309387.5 | | | | |

Figure C.2: Leakage Currents for medium pollution with manual wetting

| Glass | | | | | EPDM22 | | | | |
|------------------------------|--------|--------|-------|--------|------------------------------|--------|--------|-------|--------|
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 11137 | 0.028 | 493000 | 12295 | 0.027 | 7200 | 0.0077 | 666720 | 12072 | 0.022 |
| 10439 | 0.0183 | 711000 | 12755 | 0.0115 | 13453 | 0.041 | 321520 | 13453 | 0.031 |
| 9756 | 0.0316 | 352840 | 10201 | 0.0256 | 11612 | 0.0182 | 398580 | 14152 | 0.0239 |
| 9756 | 0.0315 | 361880 | 14151 | 0.0267 | | | | | |
| 11597 | 0.0354 | 367050 | 11835 | 0.0211 | | | | | |
| 12072 | 0.027 | 528760 | 14612 | 0.0159 | | | | | |
| Average Resistance: 469088.3 | | | | | Average Resistance: 462273.3 | | | | |
| EPDM33 | | | | | Silicone Rubber | | | | |
| 1 | | | 2 | | 1 | | | 2 | |
| V | I | R | V | I | V | I | R | V | I |
| 6504 | 0.0089 | 393080 | 15785 | 0.0271 | 8122 | 0.0259 | 313810 | 12755 | 0.0378 |
| 6727 | 0.0145 | 217660 | 21338 | 0.0262 | 12770 | 0.0414 | 288090 | 13676 | 0.0385 |
| 14374 | 0.031 | 444710 | 14389 | 0.022 | 12058 | 0.0401 | 287630 | 10899 | 0.0276 |
| | | | | | 11835 | 0.0406 | 280520 | 18324 | 0.0403 |
| Average Resistance: 351816.7 | | | | | Average Resistance: 292512.5 | | | | |

Figure C.3: Leakage Currents for heavy pollution with manual wetting

Appendix D

MATLAB CODE: LEAKAGE CURRENTS

%MatLab program written to analyze and display data from tests using test circuit one. These were used for the testing of the various polluted insulators wet by hand.

```
% 10 cycles at 50hz
%2000 sampled points
%sampling frequency = 10000Hz
% first block initialized certain variables.
f1c = 0;
x = 0;
y = 0;
lc = 0;
fs = 10000;
fo = 500;
a=1:2000; %sets the range of a
    time1 = data1(a,1); %The time is the range 'a' of column 1
    voltage1 = data1(a,2); %The voltage is the range 'a' of column 2

    %removes the offset from the voltage signal
    av1 = mean(voltage1);
    voltage1 = voltage1 - av1;
    lc1 = data1(a,3); %The leakage current's the range 'a' of column 3
    [y,x] = butter(7,fo/(fs/2)); %Finds the coefficients of a seventh order butter-
worth filter, with cutoff frequency of 400HZ based on 2000hz sampling frequency.
    f1c1 = filter(y,x,lc1); %Implements the filter function, and hence filters the leak-
age current.

    maxI1 = max(f1c1); %calculates the peak-to-peak value.
    minI1 = min(f1c1);
    p2pI1 = maxI1 - minI1;
    X =(p2pI1/(2 * sqrt(2))); %calculates and displays the RMS current.
    rmsI1 = X/100 %Value is divided by 100, as it indicates the current flowing
through the 100ohm resistor.
    maxV1 = max(voltage1); %calculates the peak-to-peak value.
    minV1 = min(voltage1);
    p2pV1 = maxV1 - minV1;
    rmsV1 = 42000*(p2pV1/(2* sqrt(2))) %Calculates and displays the RMS
```

```

Voltage. Multiplies by 42000 as this is the scaling factor.
voltage1 = voltage1* 42000; %Multiply by scaling factor for further use.
%This code is the same as above but is used to analyze a second set of data.
time2 = data2(a,1);
voltage2 = data2(a,2);
av2 = mean(voltage2);
voltage2 = voltage2 - av2;
lc2 = data2(a,3);
[y,x] = butter(7,fo/(fs/2));
flc2 = filter(y,x,lc2);
maxI2 = max(flc2);
minI2 = min(flc2);
p2pI2 = maxI2 - minI2;
Y =(p2pI2/(2* sqrt(2)));
rmsI2 = Y/100
maxV2 = max(voltage2);
minV2 = min(voltage2);
p2pV2 = maxV2 - minV2;
rmsV2 = 42000*(p2pV2/(2* sqrt(2)))
voltage2 = voltage2* 42000;
%This block plots the voltage and leakage current signals recorded.
subplot(221) plot(time1, voltage1)
xlabel('time (s)');
ylabel('voltage (V)');
subplot (223);
plot(time1, flc1)
xlabel('time (s)');
ylabel('leakage current (A)');
subplot(222) plot(time2, voltage2)
xlabel('time (s)');
ylabel('voltage (V)');
subplot (224); plot(time2, flc2)
xlabel('time (s)');
ylabel('leakage current (A)');
[C1,i1] = max(voltage1); %Finds the indices of the maximum value of voltage1 and stores it in vector i1.
[C2,i2] = max(voltage2); %Finds the indices of the maximum value of voltage2 and stores it in vector i2.
volt1 = voltage1(i1); %Sets the voltage value. It then finds the corresponding leakage current value at i1 and sets the value of current1.
current1 = flc1(i1)/100;

R1 = volt1/current1 %Calculates and displays the resistance.

volt2 = voltage2(i2); %Sets the voltage value. It then finds the corresponding leakage current value at i2 and sets the value of current2.
current2 = flc2(i2)/100;

R2 = volt2/current2 %Calculates and displays the resistance.

```