INVESTIGATIONS OF ZnO MICROVARISTOR FOR STRESS CONTROL ON POLYMERIC OUTDOOR INSULATORS

A thesis submitted to Cardiff University in candidature for the degree of Doctor of Philosophy

By

RAHISHAM ABD RAHMAN
M.Eng (Hons)

School of Engineering, Cardiff University
August 2012
This thesis is concerned with the investigation of the efficacy of Zinc Oxide microvaristor compound for stress control on polymeric outdoor insulators. The preliminary work has involved a comprehensive literature survey, followed by extensive computational modelling and simulation studies as well as laboratory works covering experimental investigations and fabrication of insulator prototypes.

The literature survey reviewed stress-induced degradations as the cause of ageing and insulation failures, the determination of electric field distributions, considerations for outdoor insulator modelling, and field-optimisation techniques for achieving stress relief.

An 11 kV polymeric insulator has been modelled and simulated under dry-clean and wet-polluted surface conditions in order to obtain electric field distribution along the insulator creepage path. The critical high field regions on polymeric surfaces were identified. In addition, clean fog solid layer tests were carried out to experimentally examine dry band formation and electric discharges. Experimental investigations confirmed the results previously achieved from theoretical simulations.

A non-linear pollution model has been developed for simulating polluted outdoor insulators. The field-dependent conductivity was derived from layer conductance measurements in a non-standard low voltage test. The proposed model was used to simulate insulators under fog and light rain conditions which respectively represent a uniform and non-uniform wetting action in practice. It was demonstrated that the non-linear pollution model yields a more detailed and realistic field distribution compared with results obtained with models using constant/linear conductivity.

Short-length microvaristor coating, having a cone-shaped structure, was introduced at both insulator ends for controlling high field, particularly near the high voltage and ground terminals. The performance of field grading was evaluated through a number of simulation scenarios. The introduction of microvaristor material with an appropriate switching characteristic has led to a substantial improvement in the electric field and heat distributions along the insulator profile.

The prototype of an 11kV insulator with microvaristor grading material was fabricated in-house for preliminary tests. Lightning impulse (1.2/50 μs) flashover tests were carried out using the ‘up and down’ method, and the flashover voltage was estimated by the 50% probability breakdown, U_{50}. The results of the lightning impulse test have indicated a considerable increase in the flashover voltage up to 21% when using microvaristor-graded insulator. Favourable field distributions obtained in the simulation study have indicated a strong correlation with the experimental results.
INVESTIGATIONS OF ZnO MICROVARISTOR FOR STRESS CONTROL ON POLYMERIC OUTDOOR INSULATORS

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND 1-1

1.2. EFFECTS OF POLLUTION AND FIELD STRESS 1-3

1.3. CONTROL OF ELECTRIC FIELD 1-4

1.4. DIRECTION OF RESEARCH AND OBJECTIVES 1-5

1.5. CONTRIBUTION OF THE PRESENT WORK 1-6

1.6. ORGANISATION OF THESIS 1-7
CHAPTER 2: DESIGN AND PERFORMANCE OF POLYMERIC OUTDOOR INSULATORS: A REVIEW

2.1. INTRODUCTION

2.2. POLYMERIC OUTDOOR INSULATORS

2.2.1. Benefits and Limitations of Polymeric Insulators

2.2.2. Design and Structural Shape

2.2.3. Polymeric Insulation Housing

2.3. STRESS INDUCED DEGRADATIONS

2.3.1. Electrical Stress

2.3.1.1. Corona

2.3.1.2. Droplet Induced Discharge

2.3.1.3. Dry Band Discharge

2.3.1.4. Insulator Flashover

2.3.2. Environmental Stress

2.3.2.1. Pollutions

2.3.2.2. Ultra-violet Radiation

2.3.3. Mechanical Stress

2.4. DETERMINATION OF ELECTRIC FIELD DISTRIBUTION

2.4.1. Experimental Measurements

2.4.1.1. Electrostatic Probe

2.4.1.2. Spherical Dipole

2.4.1.3. Optical Sensors

2.4.2. Numerical Computation

2.4.2.1. Finite Element Method

2.4.2.2. Boundary Element Method

2.5. MODELLING OF POLYMERIC OUTDOOR INSULATOR

2.5.1. General Consideration

2.5.1.1. 2D vs. 3D Insulator Model

2.5.1.2. Regions of Interest

2.5.2. Hardware Structure and Arrangement
2.5.3. Hostile Surface Conditions
   2.5.3.1. Pollution Layer
   2.5.3.2. Water Droplet

2.6. FIELD OPTIMISATION TECHNIQUES
   2.6.1. Grading Ring
   2.6.2. End-fitting Design
   2.6.3. Weather Shed Insulation Profile
   2.6.4. Combined Insulator Assembly
   2.6.5. Insulation Jacket for Line Conductor

2.7. FIELD GRADING MATERIAL
   2.7.1. Capacitive Grading
   2.7.2. Resistive Grading

2.8. ZINC OXIDE MICROVARIStORS
   2.8.1. Fabrication of Microvaristor Filled Elastomers
   2.8.2. ZnO Microvaristors for Outdoor Polymeric Insulators

2.9. CONCLUSION

CHAPTER 3: INVESTIGATIONS OF ELECTRIC FIELD DISTRIBUTION OVER THE SURFACE OF POLYMERIC INSULATORS

3.1. INTRODUCTION

3.2. INSULATOR UNDER INVESTIGATION.

3.3. FINITE ELEMENT MODELLING
   3.3.1. Simulated Insulator Model
   3.3.2. Material Properties
   3.3.3. Boundary Conditions
   3.3.4. Meshing
   3.3.5. Solver Settings

viii
3.4. SIMULATION RESULTS AND ANALYSIS

3.4.1. Equipotentials and Voltage Distribution 3-10
3.4.2. Electric Field Distribution 3-13

3.5. EXPERIMENTAL INVESTIGATIONS

3.5.1. Fog Chamber Test Facilities 3-16
3.5.2. Circuit Arrangement 3-17
3.5.3. Preparation of Artificial Contaminant 3-18
3.5.4. Low Voltage Test 3-19
3.5.5. High Voltage Test 3-21

3.6. OBSERVATIONS AND DISCUSSION 3-21

3.7. CONCLUSION 3-26

CHAPTER 4: A NEW DYNAMIC SIMULATION MODEL FOR POLLUTED INSULATOR

4.1. INTRODUCTION 4-1

4.2. FIELD-DEPENDENT CONDUCTIVITY OF POLLUTION LAYER 4-2

4.3. LAYER CONDUCTANCE TEST 4-4
4.3.1. Non-Standard Wetting Action 4-4
4.3.2. Non-Standard Test Procedures 4-5

4.4. DEVELOPMENT OF NON-LINEAR POLLUTION MODEL 4-6
4.4.1. Experimental Results and Analysis 4-6
4.4.2. Proposal for the Derivation of Field Dependent Conductivity of the Pollution Layer 4-9

4.5. CLASSIFICATION OF POLLUTION MODEL 4-15
4.5.1. Model Under Fog Condition (Uniform Wetting) 4-15
4.5.2. Model under Light Rain Condition (Non-Uniform Wetting) 4-16
4.6. COMPUTATION OF ELECTRIC FIELD USING THE PROPOSED NON-LINEAR POLLUTION MODEL

4.6.1. FEM Modelling

4.6.2. Simulation Results and Analysis

4.7. CONCLUSION

CHAPTER 5: PROPOSAL FOR STRESS CONTROL ON INSULATOR SURFACE USING ZNO MICROVARISTOR COMPOUNDS

5.1. INTRODUCTION

5.2. PROPOSAL FOR MICROVARISTOR-GRADED INSULATOR

5.2.1. Microvaristor Characteristics

5.2.2. Options for New Insulator Design

5.3. OPTIMISATION OF MICROVARISTOR CHARACTERISTICS

5.3.1. Consideration for Field Switching Threshold

5.3.2. Effect of Microvaristor Characteristics on Field Distribution

5.4. EVALUATION OF MICROVARISTOR PERFORMANCE

5.4.1. Field Control Under Dry-Clean and Wet-Polluted Conditions

5.4.2. Power Dissipation and Heating Assessment

5.4.2.1. Power Dissipation in the Pollution Layer

5.4.2.2. Heat Assessment in Microvaristor

5.5. CONCLUSION

CHAPTER 6: DEVELOPMENT OF A MICROVARISTOR-GRADED INSULATOR PROTOTYPE AND LABORATORY CHARACTERISATION UNDER IMPULSE CONDITIONS

6.1. INTRODUCTION
6.2. Microvaristor Grading Material

6.3. Characterisation of Microvaristor Compound
   6.3.1. Test Electrodes Cell and Sample
   6.3.2. Experimental Setup and Test Procedures
   6.3.3. Experimental Results and Analysis
   6.3.4. Determination of Field Switching Threshold

6.4. Fabrication of Microvaristor-Graded Insulator Prototype
   6.4.1. New Insulator Design
   6.4.2. Preparation of Microvaristor Grading Coating
   6.4.3. Moulding of Weather Shed Insulation Housing

6.5. Lightning Flashover Tests $U_{50}$ on Prototype Graded and Non-Graded Insulators
   6.5.1. Experimental Setup
   6.5.2. Test Procedures

6.6. Experiment Results and Discussions

6.7. Computer Modelling and Simulation Studies
   6.7.1. Equipotential and Electric Field Distribution
   6.7.2. Grading Effect during Impulse Rise Time

6.8. Conclusion

CHAPTER 7: General Conclusions and Future Works

7.1. General Conclusions

7.2. Future Works

Appendix A

References
LIST OF FIGURES

Figure 2.1: Typical polymeric insulator components [30] .................................................. 2-5
Figure 2.2: An approach to the selection and design of insulator profiles [33] ............... 2-6
Figure 2.3: Field enhancement at the triple junction of water droplet [53] ................. 2-11
Figure 2.4: Degradation trace on polymeric insulator surface [54] ......................... 2-12
Figure 2.5: Behaviour of water droplet under different A.C. energisation [57] .... 2-13
Figure 2.6: Illustration of flashover mechanism on polymeric insulator [55] ........ 2-14
Figure 2.7: Experimental setup for electrostatic probe [68] ........................................ 2-18
Figure 2.8: Arrangement of spherical dipole on ceramic disc insulator [70] ......... 2-19
Figure 2.9: General principle of electro-optic effect using Pockels sensor [72] ...... 2-20
Figure 2.10: Field distribution for different types of polymeric insulators [46] .... 2-26
Figure 2.11: (a) Photographs of water droplets on the insulator surface, and (b) the corresponding droplet models used in the numerical simulations [102] .............. 2-29
Figure 2.12: Comparison of maximum electric field for system with and without corona ring at high voltage end [46] .......................................................... 2-30
Figure 2.13: Typical end fitting designs for polymeric insulators [93] ..................... 2-32
Figure 2.14: Electric field distribution on polymeric surface near the high voltage terminal [87] .................................................................................. 2-33
Figure 2.15: Field control at live end using combined insulator assembly [106] .. 2-34
Figure 2.16: High field control using insulation coating for live conductor [108] .................................................................................................................. 2-35
Figure 2.17: Effect of permittivity coating on polymeric surface [68] ..................... 2-37
Figure 2.18: Cone-shaped stress grading in cable application [109] ....................... 2-38
Figure 2.19: Equipotential lines around high field region: (a) with no stress grading, and (b) with a resistive silicone rubber coating [110] ............... 2-39
Figure 2.20: Electrical characteristic of microvaristors with different switching filled composite as a function of electric field [113] ........................................... 2-40
Figure 2.21: Microvaristor particle viewed using SEM [118] ............................... 2-41
Figure 3.1: An 11kV polymeric insulator under consideration: (a) practical insulator, and (b) cross-sectional profile and dimensions .................. 3-4
Figure 3.2: General procedures for FEM simulations ............................................ 3-5
LIST OF TABLES

Table 2.1: Summary of common fillers in high voltage insulation material [39] ........2-8
Table 3.1: Material properties used for insulator modelling ........................................3-7
Table 4.1: Measurement of initial conductance prior to the test investigating drying effect on conductance (test voltage 250 V rms) .....................................................4-8
Table 5.1: Peak magnitude of tangential field on the surface of dry-clean insulator .................................................................5-11
Table 5.2: Peak magnitude of tangential electric field on polymeric surface near both insulator terminals .................................................................5-15
Table 5.3: Summary of thermal heating performance on polluted insulator ...........5-19
Table 6.1: The computed 50% breakdown voltage, $U_{50}$ ........................................6-17
Table 6.2: Stress grading performance under impulse energisation at 160 kV ....6-22
CHAPTER 1:

INTRODUCTION

1.1. BACKGROUND

Developments of the modern world depend significantly upon a continuous electric power supply. With growing demand, utilities must provide secure and reliable power delivery while maximising the performance of the power distribution system from both technical and economic standpoints. Interruptions or failures within the power systems may result not only in damage to valuable high-voltage equipment, but can also lead to considerable loss of revenue, particularly for industrial consumers.

Outdoor insulators are among the key components in the electric power transmission network, essentially required for two primary purposes: i) to isolate the transmission tower from the high-voltage source, and ii) to provide a load-bearing platform capable of supporting heavy overhead conductors well above the ground [1]. While in use, line insulators must withstand a wide range of voltage magnitude under normal operating conditions, as well as surge transients imposed by lightning strikes and switching operations.
Ceramic insulation systems, such as glass and porcelain insulators, have been in use for more than 100 years [2]. They have undergone substantial modifications and refinement to guarantee the present satisfactory performance from the disc string design currently used worldwide. Ceramic insulators have demonstrated a proven track record in various aspects of the insulation performance, particularly ageing and lifespan. In addition to high mechanical strength, they provide excellent resistance to material degradation caused by electrical stress and discharge activities [3]. Nevertheless, their electrical performance is greatly affected by pollution and humidity [4]. The insulator surface exhibits hydrophilic properties, which means that water can easily form a continuous conductive film along the creepage path. Flow of high-magnitude leakage current under adverse weather conditions could lead to complete flashover and power outage.

In recent decades, composite polymeric insulators have started to gain wide acceptance among power utilities worldwide as replacements for the traditional ceramic insulators [5], [6]. Composite polymeric insulators offer many advantages such as: lightweight, ease of handling, low operation and maintenance costs, improved mechanical strength, anti-vandalism properties, and more importantly, excellent electrical performance under moderately to heavily polluted environments [7], [8]. Polymeric material, such as silicone rubber, demonstrates a strong hydrophobic (water-repellent) property by which water on the polymeric surface tends to form discrete droplets, which have small contact areas on the insulator surface. This unique property helps to minimise the leakage current and the probability of dry band formation.
1.2. Effects of Pollution and Field Stress

In practice, outdoor insulators are constantly exposed to various environmental contaminants, including natural and agricultural substances and industrial emissions, during their period of service. Insulators near coastal regions, for example, encounter sea salts whereas those in urban areas are subjected to ash, dust, and chemical particles. These airborne particles tend to deposit and accumulate on the insulator surface, although the open profile of polymeric insulation housing normally allows for natural cleaning by rain and wind flow. The contaminants form a layer that may become conductive when exposed to wet atmospheric conditions such as fog, mist and drizzle. The presence of pollutants covering the insulator surface could also reduce the hydrophobicity of the polymeric material, thereby promoting the formation of a continuous conductive film. The resulting leakage current under system voltage generates resistive heating that evaporates water from the wet surfaces, risking the formation of dry bands [9]. In addition, the general shape of polymeric insulators causes non-uniform current density that promotes uneven surface drying, establishing dry patches on the insulator surface. Potential gradients across the electrode-like filament, coupled with the high electric field, trigger electrical discharges. In favourable conditions, the discharges may elongate over many dry bands and, consequently, may lead to complete flashover [10].

One of the main factors contributing to the development of discharges on insulator surfaces is the electric field distribution on the insulator surface, which in turn controls the current density. The usually non-uniform field profile along the surface has peak regions in which dry bands are formed. Of great concern to many researchers is the electrical stress in the region near the high voltage and the ground terminals. High electric fields trigger corona and discharge activities that contribute considerably to
premature degradation through surface tracking and erosion. Under extreme conditions, intense electric arcs could puncture the polymeric housing and, more seriously, cause insulation failure from severe deterioration [11], [12].

In addition to the primary problems of pollution flashover and material degradation, corona and electric discharges can also result in secondary problems such as audible noise and electromagnetic interferences. Electric discharges produce constant buzzing sounds, and the established high-frequency wave could cause disturbances in radio and television, as well as in other communication signals [13].

1.3. CONTROL OF ELECTRIC FIELD

Considering the above-mentioned problems, electric field control is highly desirable to alleviate the effect of electrical discharges on polymeric outdoor insulators. Several grading techniques have been introduced to regulate the high field over the insulator surface. The grading ring is the most common device used for high-voltage insulators to control excessive stress near the high-voltage and ground terminals [14], [15]. The presence of the ring structure redistributes the concentrated field lines over wider regions, reducing high field strength at both insulator ends. Field optimisation can also be achieved through an appropriate end-fitting design and the shape of insulation housing. Smooth and rounded edges prevent field enhancement on critical regions along the creepage path.

The use of field grading compound is another popular method for controlling high electric field on polymeric insulation systems. This can be realised by using a material that has a high dielectric constant for capacitive grading or a compound with conductive fillers for resistive grading. In recent years, the potential for non-linear grading compounds to achieve stress relief for polymeric insulators has been explored.
Preliminary research results from both simulation [16] and experimental [17] studies have offered promising results, creating interest in further investigations.

1.4. DIRECTION OF RESEARCH AND OBJECTIVES

The focus of the present research is to contribute an alternative approach to the existing technique for optimising field distribution on polymeric outdoor insulators. Non-linear compounds composed of semi-conductive microvaristor particles have been introduced as a field grading material to control high electric fields at both insulator ends. The non-linear electrical properties of the grading compound are expected to provide a better and more uniform field distribution along the polymeric surface, thereby minimising the probability of dry band formation and the risk of surface discharges.

Determination of electric field over the insulator surface is important for predicting high stress regions on the insulator surface. Field distribution was computed through numerical simulation based on the finite element method. A polluted insulator with non-linear, field-dependent conductivity was modelled and simulated to provide better insight into realistic electric distributions. The specific objectives of this research are outlined below:

i) To review current knowledge related to the study undertaken, which includes stress-ageing phenomena, determination of electric field, insulator modelling, and field optimisation techniques.

ii) To evaluate field distribution along the leakage path and observe the consequent electric discharge on the surface of polymeric insulation housing.
iii) To propose a new pollution model with dynamic non-linear electrical properties for more realistic and accurate field modelling.

iv) To investigate the potential use of non-linear grading compound for controlling high field at the end fitting regions.

v) To examine the effectiveness of field grading material under impulse and transient overvoltage conditions in the high voltage laboratory.

1.5. CONTRIBUTION OF THE PRESENT WORK

The major achievements and contributions of this research investigation can be summarised as follows:

i) Electric stress on polymeric insulators was investigated by means of computer simulations and experiments. Good correlation was achieved between simulated field distributions and practical observations on discharge activities. Small discrepancies due to test arrangement and conditions were addressed and explained.

ii) The reduction in pollution conductivity due to surface heating and evaporation was quantified through experimental measurements. This led to the derivation of a new non-linear pollution model, which was used in the finite element simulations of polluted insulators. A more detailed and realistic field distribution obtained from the proposed model will result in a better dry band prediction.

iii) The potential was explored for the use of non-linear grading materials as a stress control solution for polymeric outdoor insulators. Comparative field
studies have demonstrated that microvaristors, with an appropriate geometrical design and switching property, could effectively minimise field stress on the critical region near metal electrodes.

iv) Results from preliminary tests with lightning impulse voltage on the prototype of an 11kV insulator equipped with microvaristor grading material were encouraging. The effectiveness of the non-linear grading scheme was confirmed with a considerable increase in the breakdown threshold. Field simulations provide better understanding of the response under impulse energisation that leads to such improvement.

1.6. ORGANISATION OF THESIS

This thesis is divided into seven chapters:

CHAPTER 2 provides an extensive review of published literature pertaining to the study undertaken. General insights into polymeric insulators including key advantages, structural design, and factors contributing to the ageing process are presented. Practical measurements and a simulation approach for determining accurate field distribution around the insulator are discussed. The present techniques for controlling high electric field on insulator surfaces are reviewed, and the possibilities of different field grading material are considered.

CHAPTER 3 presents the investigation of electric stress on polymeric insulators by means of computer simulations and laboratory test programmes. A commercial finite element package is employed for insulator modelling to determine electric potential and field distribution along the creepage path under dry-clean and wet-polluted surface conditions. The simulation results are discussed in this chapter. To examine visually the
effect of high electric field, an artificial pollution test based on the solid layer method is
carried out on a practical insulator. Observations of discharge activities through video
and thermal recording are analysed and correlated with the results from simulation
studies.

CHAPTER 4 proposes the use of a non-linear pollution model, characterised by
field-dependent conductivity, to achieve a better and more realistic field simulation. The
field-conductance relationship is developed from experimental measurements in a non-
standard low-voltage layer conductance test. Laboratory test procedures and the
derivation of the non-linear electrical property are described. The proposed pollution
model is simulated under two wet atmospheric conditions: fog and a light rain, which
respectively represent uniform and non-uniform wetting action. The simulation results
are evaluated and discussed in this chapter.

CHAPTER 5 presents an approach to achieving stress relief in the high field
region near terminals through the use of non-linear microvaristor coating. The principle
of a field-controlled solution that leads to near-uniform field distributions is described
in this chapter. A case study is carried out for a typical 11 kV polymeric insulator to
highlight the merits and effectiveness of the non-linear grading scheme. Analysis of
field distribution is quantified under dry-clean and wet-polluted conditions for both
standard non-graded and microvaristor-graded insulators. In addition, dissipated power
is computed to examine surface heating and losses in the grading regions and for the
complete insulator.

CHAPTER 6 evaluates the performance of polymeric insulators equipped with
microvaristor grading material under impulse conditions through experimental work and
computational modelling. A commercial microvaristor compound is tested to determine
its non-linear electrical properties. A graded insulator prototype is designed and moulded using in-house vacuum-casting facilities, which is then subjected to $U_{50}$ breakdown test procedures. The experimental results for both graded and non-graded insulators are compared and discussed in this chapter. For a better understanding, numerical simulations are performed to facilitate the interpretation of field response under impulse energisation.

CHAPTER 7 presents general conclusions based on the findings in this study, and outlines some recommendations for future investigation.
CHAPTER 2:

DESIGN AND PERFORMANCE OF POLYMERIC

OUTDOOR INSULATORS: A REVIEW

2.1. INTRODUCTION

Polymeric insulators for outdoor applications have been commercially produced for more than four decades, and the demand is increasing rapidly due to their encouraging performance under diverse conditions. Massive deployment of polymeric insulators throughout the power industries has resulted in large-scale research investigations aimed at enhancing in-service operation that could last for at least thirty to forty years, just as was the case of their ceramic counterparts.

This chapter presents a comprehensive review of the studies related to the research programme concerning electric stress control on polymeric outdoor insulators. Factors contributing to polymeric ageing and associated problems are discussed to understand better the need for an improved stress grading scheme. Equally important is the determination of electric field, which needs to consider various modelling criteria for realistic computer simulations. This is particularly important in predicting high field regions that are susceptible to dry band formation and electric discharges. As an
CHAPTER 2:

DESIGN AND PERFORMANCE OF POLYMERIC

OUTDOOR INSULATORS: A REVIEW

2.1. INTRODUCTION

Polymeric insulators for outdoor applications have been commercially produced for more than four decades, and the demand is increasing rapidly due to their encouraging performance under diverse conditions. Massive deployment of polymeric insulators throughout the power industries has resulted in large-scale research investigations aimed at enhancing in-service operation that could last for at least thirty to forty years, just as was the case of their ceramic counterparts.

This chapter presents a comprehensive review of the studies related to the research programme concerning electric stress control on polymeric outdoor insulators. Factors contributing to polymeric ageing and associated problems are discussed to understand better the need for an improved stress grading scheme. Equally important is the determination of electric field, which needs to consider various modelling criteria for realistic computer simulations. This is particularly important in predicting high field regions that are susceptible to dry band formation and electric discharges. As an
approach to field control, the possible use of field grading material, especially non-linear composite, is emphasised in addition to the present field optimisation techniques which are also reviewed in this chapter.

2.2. POLYMERIC OUTDOOR INSULATORS

The chronology and development of composite insulators from the time when these were first introduced for indoor application in the 1940s is briefly presented in [18] and [19]. Polymeric insulators for commercial use on the transmission network were available only from the 1970s, after undergoing a process of evolution and refinement. In the early stages of their introduction, the practical performance of these insulators was far less than satisfactory, with a number of problems and failures. However, with continuous advancement in both material formulation and fabrication technology, the reliability of polymeric insulators has improved considerably [20],[21].

2.2.1. Benefits and Limitations of Polymeric Insulators

Polymeric outdoor insulators made of polymeric material, especially silicone rubber, exhibit excellent electrical performances under moderate to heavily polluted environments [22], [23]. In a wet atmosphere, water tends to bead up on the polymeric surface, thus reducing the leakage current and the probability of dry band formation, which consequently results in reduced flashover voltages. The strong water-repellent property is attributed to the diffusion of low molecular weight (LMW) silicone chains from the bulk material to the surface, forming a lattice type thin layer consisting of methyl groups (CH$_3$) [24]. Interestingly, this property can also be transferred to an overlying pollution layer [25] enabling improved pollution performance for insulation systems in highly contaminated regions such as coastal and industrial areas. Even though silicone housing can temporarily lose its hydrophobicity under severe
Chapter 2 – Design and Performance of Polymeric Outdoor Insulator: A Review

conditions, the materials have been reported [26], [27] to be able to regain hydrophobicity after a sufficient resting period with the absence of discharge activity.

Polymeric insulators offer significant weight reduction compared to the corresponding ceramic insulation systems [28]. There is less need for strong heavy support and cranes for installation, which results in easier handling and substantial savings in overall installation, operation and maintenance costs. In addition, voltage up-rating and compact transmission tower design for Ultra-High Voltage (UHV) distribution networks can be practically realised with polymeric insulators. Considering these benefits, it is not surprising that being ‘lightweight’ was among the main reasons for power utilities to switch to polymeric insulators, according to a survey conducted by Non-Ceramic Insulators Technical Committee, Japan [6].

Polymeric insulators have a high mechanical strength to weight ratio that allows for longer spans and less expensive tower structures. They provide improved mechanical strength under bending, deflection and compression stress. It has been reported [29] that polymeric insulators passed mechanical tests under extreme conditions without any permanent damage. Insulation housing with elastic properties also helps to prevent the risk of breakage during transportation or vandalism from gunshots that could lead to cascading failure as was experienced with ceramic insulators. In addition, complex weather shed designs are feasible and easily moulded using polymeric composite material.

Despite the abovementioned advantages, polymeric outdoor insulators however suffer from a problem of material deterioration, known as ageing. This is primarily due to concurrent stresses; environmental, electrical and mechanical stresses encountered in diverse range of service conditions. Polymeric materials which are organic in nature
have weaker bonds, and hence susceptible to chemical change and compound degradations. Ageing of weathersheds housing will reduce insulation performance and cause other fatal consequences such as flashover and power outage.

Other than the ageing problem, fabrication of polymeric insulation housing for outdoor applications often required complex material formulations and design optimisation to suit specific environmental conditions. Appropriate amount and type of additives and weathersheds profiles need to be considered to inhibit degradation and ageing process, hence assuring good insulation performance throughout years of service. As the polymeric insulators have shorter service experience compared with the traditional glass porcelain system, long term ageing and outdoor performance remain unclear. As for now, accelerated weathering test is the best alternative to predict and evaluate the insulation performance over a longer period of time.

2.2.2. Design and Structural Shape

General construction design of polymeric insulators comprises three essential components: i) end-fitting terminals made of forged steel to support heavy load conductors on transmission towers, ii) fibre-reinforced core to provide essential mechanical strength and insulation between the two terminals, and iii) polymeric weather shed housing to protect the fibre core from various environmental impacts while providing sufficient leakage distance under wet surface conditions. Figure 2.1 shows the assembly of these three components where flanges are crimped to a fibre reinforced rod encapsulated within weather shed polymeric housing.

The insulation housing in modern design is moulded as one piece to avoid failure from multiple interfaces gluing between the polymeric sheath and the sheds, as experienced by early generation models [18]. Typical weather shed design with an
aerodynamic and open profile encourages natural cleaning of deposited pollutants by wind or rain, which is particularly useful for resisting the accumulation of pollution on the insulator surface.

![Typical polymeric insulator components](image)

**Figure 2.1: Typical polymeric insulator components [30]**

The selection of outdoor insulators is essentially governed by the minimum specific creepage distance, taking into account two important aspects: i) system requirements, and ii) environmental conditions, as recommended in IEC 60815 Standard [31]. In addition, Young et al. [32] have suggested two other criteria: i) the
resistance index, and ii) the distribution of current density, particularly for polymeric insulators that are subjected to variations in shape and weather shed design. Realising the importance of selecting appropriate outdoor insulators, CIGRE, through task force 33.04.01 [33], has outlined a structured approach, shown in Figure 2.2, which can be a guide in determining suitable insulator characteristics to be used in a given area.

Figure 2.2: An approach to the design and selection of insulator profiles [33]
2.2.3. Polymeric Insulation Housing

Ethylene-propylene-diene-monomer (EPDM) and silicone rubber (SiR) are the two most common polymeric compounds used for outdoor high voltage insulation system. Both materials have their characteristic strengths with regard to in-service performance. Polymeric housing made of EPDM materials offers good mechanical properties and high resistance to arc-induced degradation. Experimental findings published in [34] evidently indicate that EPDM composite has suffered the least impact in surface erosion test when compared with other polymeric compounds, including silicone rubber. On the other hand, silicone compound is generally preferred because of its excellent electrical performance in various polluted environments. This is attributed to the strong hydrophobic surface properties, contrasted with EPDM which starts to show hydrophilic effects on exposure to prolonged wetting and electrical activity [35]. In an attempt to overcome the shortfall in both materials, EPDM and silicone rubber have been blended together to take advantage of their mechanical and electrical properties. Experimental evidence in [36] shows substantial improvement in the overall performance when using the mixed compounds, i.e. EPDM + SiR.

Polymeric materials used for outdoor insulation housing are usually formulated with other elements called fillers, which help to minimise the stress effects and to establish protection schemes against damaging electrical activities. Fillers are categorised into two main classes based on their functionality: i) reinforcing fillers for mechanical strength, and ii) extending fillers for some desirable properties such as surface degradation [37]. Silica and carbon black are examples of reinforcing fillers that enhance physical, tensile and tear strength through molecular bonding with the silicone polymer. Extending fillers such as Alumina Trihydrate (ATH) and quartz impart tracking and erosion resistance, especially when the polymeric surface has poor
hydrophobic recovery [38]. The presence of both silica and ATH in compounds also improves thermal conductivity, which helps to remove heat from the intense dry band area. Barium Titanate, (BaTiO₃), on account of its excellent piezoelectric property, is the most popular element for increasing relative permittivity of insulator compounds [39]. In addition, the use of antimony (Sb) with doped tin oxide (SnO) fillers will increase the electrical conductivity of composite polymers, which is beneficial in reducing field stresses, thereby minimizing the effects of arcing and erosion damage. Table 2.1 provides a summary of the most commonly used fillers and their roles in protecting the insulation housing.

Table 2.1: Summary of common fillers in high voltage insulation material [39]

<table>
<thead>
<tr>
<th>Filler</th>
<th>Property change</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Al₂O₃·3H₂O</td>
<td>Thermal conductivity</td>
<td>• Resistance to dry band</td>
</tr>
<tr>
<td>• SiO₂</td>
<td></td>
<td>arcing, partial discharge and Corona</td>
</tr>
<tr>
<td>• BaTiO₂</td>
<td>Relative permittivity</td>
<td>• Electric field grading</td>
</tr>
<tr>
<td>• BaTiO₃ + Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• SiC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Varistor (ZnO)</td>
<td>Electrical conductivity</td>
<td>• Pollution performance</td>
</tr>
<tr>
<td>• Sb₂O₃ + SnO</td>
<td></td>
<td>• Electric field grading</td>
</tr>
</tbody>
</table>

It has been reported in [40], [41] and [42] that the effectiveness of fillers depends on the particle size and shape, as well as the volume concentration. For example, polymeric materials filled with fumed silica exhibit improved mechanical properties when compared to those with precipitated silica [40]. Thus, the selection of fillers with appropriate properties is a key component in formulating the weather shed insulation housing for optimum in-service performance.
2.3. Stress Induced Degradations

Polymeric insulators used for outdoor applications encounter a range of concurrent stresses while in service. These stresses can be grouped into three main categories, namely, electrical, mechanical and environmental stress [43]. The polymeric materials, due to their weak organic bonds, are vulnerable to chemical change on exposure to these stresses, which consequently lead to degradation and ageing of the polymeric insulator [44].

2.3.1. Electrical Stress

Electrical performance of high voltage insulators is governed by the distribution of electric fields around the insulator profile. Non-uniform and high fields could lead to electric discharges in the form of corona, dry band arcing and flashover.

2.3.1.1. Corona

Electric field distribution on polymeric insulators is generally more non-linear than the distribution on the equivalent disc string ceramic insulators. The magnitude of the electric field near the end fittings could be several times higher than the field in the middle. Traditional glass and porcelain systems have the advantage of a natural grading effect from their large capacitance [45] and also the intermediate metal parts along the string [46], which is not the case for polymeric insulators. The assembly and physical structure of polymeric insulators with low permittivity materials causes large potential gradients to occur at the high voltage and ground terminals. Such conditions develop a high field that places a constant stress on the polymeric surface in the nearby regions. The stress is considerably more for longer insulator strings with higher operating voltages.
It is now well known that the electric field is normally highest at regions near terminal fittings [47], [48]. Under dry surface conditions, when the electric field in these regions is sufficiently high to reach the air ionisation threshold, metallic induced corona is triggered. The corona normally exists as faint streamer discharges anchored at the metal electrodes. Two common by-products from corona activities are ozone and nitrogen oxide, which are converted into nitrous and nitric acid in the presence of moisture. [49] The acid attacks the insulation surface by destroying crosslinks in the polymeric compound, and the combined effect of chemical and thermal stress consequently results in the degradation of the insulation material and is believed to cause brittle damage to the core-conductor interface. However, Moreno et al. [50], through their experimental investigations, have rejected the possibility of thermal heating that leads to material degradation. The highest surface temperature recorded during the corona test was far less than the threshold level of 200-300°C required to initiate degradation.

2.3.1.2. Droplet Induced Discharge

Water droplets on the insulator surface, due to their high permittivity, cause local field enhancement around their extremities at the triple-point interface – water-air-dielectric [51], [52]. Figure 2.3 provides examples of equipotentials and field distribution profile indicating the high field region. If sufficiently high, field intensification could initiate random partial discharges over the insulator surface. It has been reported [53] that the corona onset level for water droplets ranges from 4 to 10 kV/cm, depending on various parameters such as droplet shape and volume, hydrophobicity and atmospheric conditions.
Figure 2.3: Field enhancement at the triple junction of water droplet [53]

Intense and continuous discharge activities can destroy hydrophobicity and gradually consume the insulation surface through tracking and erosion, as shown in Figure 2.4. In small scale experiments reported in [50], early signs of material degradations due to electric discharges were manifested as surface crazing (< 5 µm depth), cracking (> 50 µm depth) and discoloration. In some cases, the insulator may show the appearance of chalky white traces, attributed to the ATH fillers that diffused to the surface.
2.3.1.3. Dry Band Discharge

Despite the advantages of hydrophobicity, continuous conductive film on the insulator surface can still occur in several ways:

i) Corona and random surface discharges, as described in the previous section, could result in the loss of hydrophobicity, creating an increase in surface wettability, hence allowing the spread of water on hydrophilic regions.

ii) When the polymeric insulator is coated with pollution, deposited soluble elements such as salt and chemical fertilizer may dissolve in water to form an electrolyte layer covering the insulator surface. In other cases, water may diffuse through the LMW lattice to establish a conductive path beneath the pollution surface [55].

iii) Water droplets are subjected to deformation under voltage energisation [56]. Induced charges within the droplet experience a strong electromagnetic force that causes the hemispherical shaped droplet to flatten and extend in the
direction of the electric field, thus covering a wider surface area. Such deformation is more vigorous under A.C. energisation where droplets are subjected to vibration due to the change of voltage polarity, as observed in experimental investigation by Katada et al. [57] depicted in Figure 2.5.

![Figure 2.5: Behaviour of water droplet under different A.C. energisation](image)

Dry band discharges normally occur when water has the opportunity to wet the polymeric surface, thus allowing the flow of leakage current along the conductive path. The resulting resistive heating leads to surface water evaporation and drying of the wet insulator surface. Dry bands are likely to appear on the smallest circumferential region where the current density and dissipated power are greatest [58]. Large potential difference sustained between the electrode-like filaments combined with the highly non-uniform electric field can result in intense electric discharges to bridge the dry region.

2.3.1.4. Insulator Flashover

Active discharge activities from corona, water droplets and dry band arcing generate considerable thermal heating to cause further drying on the insulator surface. Electric discharges that are short at the beginning gradually elongate as the dry regions
widen. Under favourable conditions, successive discharges may extend over multiple dry bands and join with other electric discharges that can eventually lead to a complete flashover [55]. Figure 2.6 illustrates the development of flashover on the polymeric surface.

![Flashover Mechanism Diagram](image)

**Figure 2.6: Illustration of flashover mechanism on polymeric insulator [55]**

In the event of prolonged wetting and heavy rain, polymeric weather sheds can be bridged by the water stream [59]. The role of the creepage path along the insulator surface in limiting leakage current in this case is not effective. Water cascading
promotes inter-shed arcing, and can easily lead to insulator flashover even at lower pollution severity. In addition, the flashover can occur at much lower voltage levels than the rated value. Polymeric insulators with an alternating shed design can be a good practice to minimise the probability of water bridging the weather sheds.

2.3.2. Environmental Stress

2.3.2.1. Pollutions

Environmental pollution is one of the major threats to polymeric outdoor insulation systems. Depending on the location and the surrounding area, insulators encounter different types of pollutants: sand and soil elements in desert and mining areas, metallic and chemical substances in industrial and agricultural lands, and salt particles in coastal regions. Deposits of these airborne particles gradually form a solid pollution layer on the insulator surface, which has a significant effect on both short and long-term performance of the insulation system. Electric field distribution is highly distorted by a non-uniform pollution layer on the insulator surface [60]. This contributes to localised field enhancement which could trigger corona and random partial discharges over the polymeric surface. In the presence of moisture, soluble contaminants dissolve in water establishing a conductive pollution film that allows the flow of leakage current along the creepage distance, increasing the risk of damaging dry band discharges.

In some cases, the insulator may also be subject to conductive moisture sources such as salt water, industrial acid fog, chemical mist and fertilizers, crop spraying and acid rain. These electrolyte-type pollutants can cause instantaneous leakage current and trigger flashover voltage even without the accumulation of pollution on the insulator surface [61].
REFERENCES


