DYNAMIC NONLINEAR MODEL FOR POLLUTED OUTDOOR INSULATORS

R. Abd-Rahman*, A. Haddad and N. Harid
High Voltage Energy Systems Group, School of Engineering, Cardiff University, UK
*Email: <AbdrahmanR@cardiff.ac.uk >

Abstract: Despite the advantages of polymeric insulators over the conventional glass and porcelain outdoor insulators, concerns remain about their performance in contaminated environments. In-depth understanding of the problems associated with pollution such as flashover and ageing process requires better determination of electric field strength and its profile over the polymeric surface. This paper investigates the use of a new dynamic pollution model to compute the electric field distribution along the leakage path. The study is performed under wet weather conditions of fog and light rain, which in practice are classified based on wetting and drying action. Nonlinear field-dependent conductivity with simplified modelling assumptions is proposed to characterise the electrical properties of the pollution model. An 11kV polymeric insulator is considered in this study, and the modelling and computation is performed using a Finite Element Method (FEM) package. Comparative field studies show that the simulation using the proposed dynamic pollution model results in more detailed and realistic field profiles around insulators, and this may be useful to predict formation of dry bands and initiation of electrical discharges on the polymeric surface.

1 INTRODUCTION

Polymeric outdoor insulators are constantly exposed to various environmental contaminants ranging from natural, agricultural to industrial emissions during their period of service. Insulators near coastal regions for example encounter sea salt particles whereas those in the city or close to industrial area are exposed to ash, dust, and chemical emissions. These airborne particles accumulate on the insulator surface, forming a contaminant layer which becomes conductive when exposed to humid atmosphere such as fog and drizzle. The resulting leakage current under system voltage develops resistive heating that evaporates water from the insulator surface, risking the formation of dry bands [1] The voltage gradient across dry regions coupled with high electric field could easily trigger electrical discharges that lead to material degradation through tracking and erosion. Under favourable conditions, the electric discharge may elongate over many dry bands and subsequent arcing can result in complete flashover and line outages.

Many experimental and theoretical studies have been carried out to investigate the performance of polymeric outdoor insulators, with a large number focusing on the computation of electric field around the insulators [2-5]. The field distribution over the insulator surface provides a better understanding of pollution problems which includes premature degradation and polymeric ageing process. Moreover, prediction of dry band formation can be made more accurately.

The measurement of the electric field distribution in practice is rather difficult. The electrostatic probe [6] can be used but is occasionally subjected to errors, although this could be improved by using a more advanced and complex field detection system [7]. As an alternative, researchers have employed numerical techniques to obtain the electric field around the insulator. This could be achieved using well-know computation methods such as Finite Element Method (FEM) [8, 9], Charge Simulation Method (CSM) [10] and Boundary Element Method (BEM) [11]. Moreover, rapid growth in computer technology has facilitated development of advanced numerical packages that are able to deal with most complex modelling without compromising the processing time and accuracy of the results.

In the published literature, researchers usually assume a single conductivity for the pollution layer when dealing with insulator modelling. This is, however, not always the case in practice. The surface conductivity in fact will vary with the electric field strength, in particular the tangential component of the field. The conductivity decreases with time as moisture from the wet pollution layer starts to evaporate and dry out, mainly due to the effect of surface heating.

To date, no attempt has been made to consider a pollution layer with a nonlinear conductivity when modelling outdoor insulators. To address this point, this paper proposes the use of a pollution model that has a nonlinear field dependent conductivity to compute electric field distribution over the insulator surface. This will account for the drying effect due to electric field strength. The electric field is computed using the Finite Element Method (FEM) in the COMSOL Multiphysics package. A 2D geometrical model of an 11kV polymeric insulator, having a uniform pollution layer on its surface is modelled under wet weather conditions. Field-conductivity relationships with simplified assumptions are developed to characterise the electrical properties of the pollution layer under fog and light rain conditions. Field distributions obtained using the proposed dynamic model were analysed and compared with those obtained with a constant value of conductivity. The simulation results show that the nonlinear pollution model results in a more detailed and informative field profile, which may be useful to predict dry band formation more accurately. It should be emphasised that under normal conditions, polymeric insulators would rarely be subjected to uniform wetted surface situation due to their excellent hydrophobic surface properties when new or undegraded. Nevertheless, the following results would help to appreciate the non-linear effects due to electric field distribution and resulting heating effects.

2 COMPUTER MODELLING

2.1 Insulator profile and properties

The configuration and dimensions of the 11kV insulator under study are detailed in Figure 1.

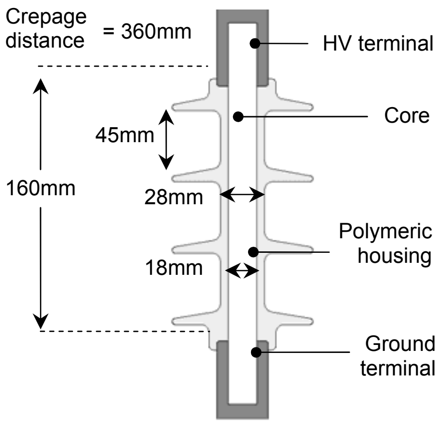


Figure 1: Insulator profile and dimensions

The polymeric insulator is composed of three main components; core, insulation housing and terminals. The polymeric housing, used as weather sheds and insulation material is made of a synthetic composite compound, Silicone Rubber (SiR), having a relative permittivity ε_r = 4.3. The creepage distance along the polymeric surface is approximately 360mm. A fibre reinforced plastic (FRP) rod with a relative permittivity ε_r = 7.1 is used as a core to provide essential mechanical support for overhead conductors on transmission towers. The high voltage (HV) and ground terminals are made of forged steel crimped to the FRP rod at a separation distance of 160mm.

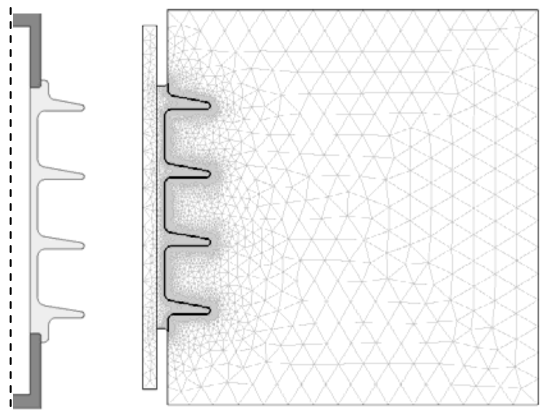
An AC voltage of 18kV peak was applied to the top terminal of the insulator, with the bottom terminal grounded. This voltage corresponds to the maximum phase to earth voltage defined under light polluted conditions for a typical 11kV system as described in the standards [12]. A uniform layer of pollution is applied on the insulator surface with a thickness of 0.5mm, and the conductivity is specified as a function of electric field $\sigma_p = f(E_s)$. The proposed field-conductivity relationship is described in Section 3. A relative permittivity of 80 is assumed considering water as a dominant substance when the pollution is in its conductive state. The material properties used for the insulator modelling are summarised in Table 1.

Table 1: Material properties used for computer modelling

Material	Relative Permittivity, ε_r	Conductivity, σ (S/m)
Air background	1	$1.0\text{x}10^{-13}$
Forged steel	1	$5.9\text{x}10^{7}$
Fibre core	7.1	$1.0\text{x}10^{-13}$
Silicone Rubber	4.3	$1.0\text{x}10^{-13}$
Pollution layer	80	$\sigma_p=f(E_s)$

2.2 Finite element modelling

Field computations are performed using the COMSOL Multiphysics FEM package. A 2-dimensional (2D) insulator model built for this simulation is shown in Figure 2(a), where half of the insulator is shown due to symmetry. The mesh elements of the problem domain are shown in Figure 2(b), with further refinement in the region of interest along the leakage path.



(a) (b)

Figure 2: (a) A 2D symmetrical insulator model and (b) Mesh discretization of the domain problem

The insulator model is simulated using Quasi-Static Electric Current module in time-steps domain setting. The module assumes slowly varying currents and electromagnetic fields, which is valid for insulator problems and many other HV applications that operate at power frequency [13]. This execution mode allows the pollution model to be specified by a nonlinear expression for the computations and field analysis.

3 POLLUTED INSULATOR UNDER WET WEATHER CONDITIONS

In practice, the distribution and amount of contaminants deposited on the insulator surface is non-uniform and largely depends on the nature of the environment. To reduce modelling complexity, the pollution layer is assumed to be uniform over the insulator surface. In wet atmosphere, the pollution layer becomes conductive, hence, allowing flow of leakage current along the creepage path from the HV terminal to the ground terminal. The current density J combined with the tangential surface electric field E cause surface heating. For a pollution conductivity, σ, the power dissipation, P, that leads to surface evaporation is given by

$$P = EJ = J^2/\sigma \qquad (1)$$

The surface conductivity is highest when the pollution is saturated with water. However, the conductivity decreases with time as the moisture from the wet pollution layer starts to dry out due to the joule heating. Considering the above power term given in Equation (1), the evaporation rate, and, hence, the surface conductivity is expected to fall rapidly at higher fields. The pollution layer is considered dry, imposing highly resistive region when the surface electric field exceeds the air breakdown threshold at about 10kV/cm. This surface field-conductivity relationship can be translated into a general graphical representation as shown in Figure 3.

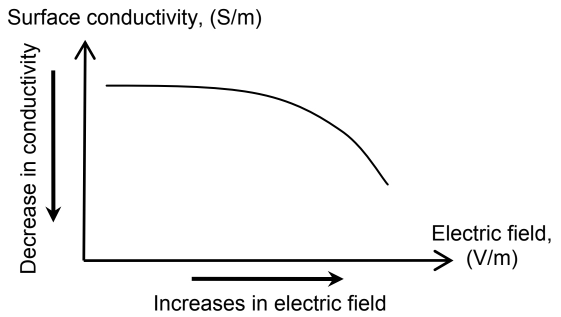


Figure 3: General plot of pollution conductivity as a function of surface electric field.

3.1 Fog condition: Uniform wetting action

In a foggy atmosphere, tiny water particles move in a very slow and random motion. They could reach all insulator surfaces almost in any direction. For this reason, the wetting action under fog condition is assumed to be constant and uniform on the insulator surface. Figure 4 shows a plot of pollution conductivity as a function of electric field developed for simulation under fog condition. It is based on the basic principle and assumptions explained above.

As can be seen, the conductivity is maximum and nearly constant in the low electric field region. The pollution in this state is saturated with water and the dissipated power is negligible due to low electric field. The initial conductivity, 0.6μS/m is obtained from laboratory measurements using a low voltage set-up. Referring to Equation (1), an increase in electric field results in an increase in surface heating. The pollution conductivity gradually decreases as the electric field increases. After exceeding a certain field threshold, the drying process due to joule heating causes a rapid reduction in surface conductivity. This can be observed for the field region above 1kv/cm in Figure 4. The surface conductivity is considered negligible at field magnitudes higher than 10kV/cm, reflecting the drying effect which turns the wet conductive region into a dry and highly resistive area on the polymeric surface.

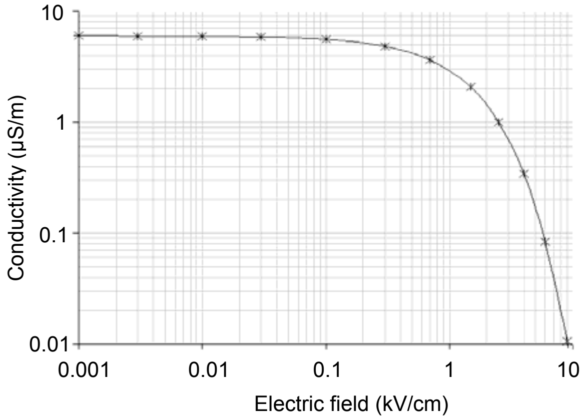


Figure 4: Field-conductivity relationship for the pollution model under fog weather condition (i.e. uniform wetting action).

3.2 Light rain condition: Non-uniform wetting action

The dry band formation is governed by the power dissipated and the rate of moisture deposited on the polluted surface (wetting rate). Dry bands often occur when the drying rate is equivalent to, or greater than the wetting rate. In many cases, dry bands and surface discharges are less significant when subjected to heavy rain conditions. The rain could wash out the pollutants and re-wet the dry regions on the insulator surface, hence, reducing the probability of electrical discharges. The problem arise when polluted insulators exposed to drizzle or light rain weather conditions. Unlike fog particles, water from the rain may not reach the entire polymeric surface uniformly. Surfaces that are facing the rain for example are subjected to a higher wetting rate compared with those in the sheltered regions of the under-sheds surface. For modelling purposes, the uniform pollution layer is subdivided into three main regions namely H (high), M (medium) and L (low) regions as shown in Figure 5. Each region is categorised based on the wetting actions in practice. Region H, assigned to the upper surface represents a highly wetted area. Water from the rain can easily reach these surfaces without any obstacles. Half of the under sheds close to the tip, indicated by region M are classified as a region with medium wetting rate while the remaining regions down to the shank, marked by region L is considered to be the least wetted surface due to its sheltered location protected by the sheds.

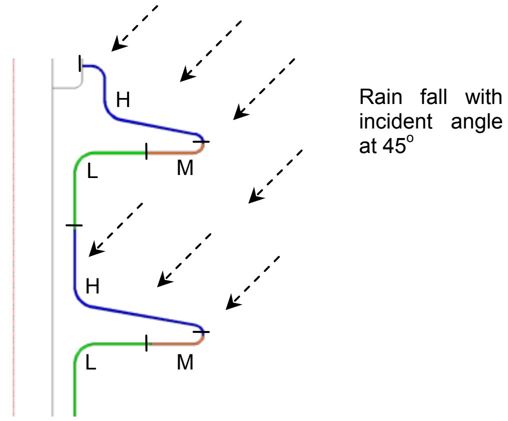


Figure 5: Subdivision of pollution layer under light rain condition

Figure 6 shows three independent surface conductivity curves proposed to characterise the pollution layer under light rain conditions. Each curve, marked by H, M and L is assigned to the pollution model in regions H, M and L respectively. As can be observed, the curves have a similar general trend with a little difference in the initial conductivity and field threshold. These differences are accounted for by the wetting action on the polymeric surface under light rain conditions. Curve H is assigned with the highest surface conductivity, 0.6μS/m considering region H as the most water-saturated area. The medium and least saturated areas M and L are respectively characterised by slightly lower conductivities of 0.4μS/m and 0.2μS/m respectively. The field threshold determines the field level at which the pollution conductivity starts to decrease rapidly.

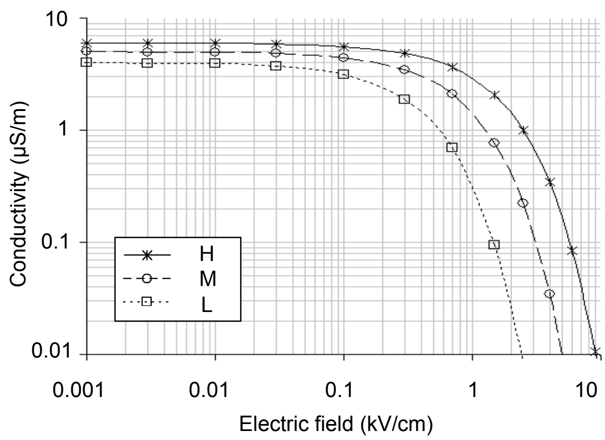


Figure 6: Field-conductivity relationship for the pollution model under light rain weather condition (non-uniform wetting action).

The region with a low field threshold represents a less wetted area and, therefore, is subject to a higher probability of dry band formation. For this reason, the pollution model in region L is proposed with the lowest field threshold, followed by region M and H with moderate and highest field thresholds, indicating surfaces that are exposed to a greater wetting rate.

4 SIMULATION RESULTS AND DISCUSSION

In this study, the electric field and potential distributions are computed along the polymeric surface. The insulator is first simulated under dry-clean and polluted surface conditions with a single conductivity at 0.6μS/m. These are the common modelling conditions that have been presented in most of the published literature. The effects of wetting and drying processes for the polluted case are not taken into consideration. The simulation results will be adopted as a control and for comparison purposes. Figure 7 shows the computed equipotential profiles around the insulator under dry-clean and uniformly polluted surface conditions. The distributions in both cases are similar; except for a small deviation found on the polluted insulator which is due to the presence of a thin conductive film on the insulator surface.

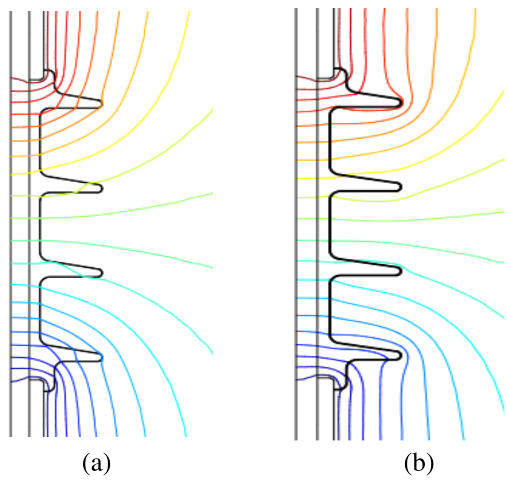


Figure 7: Equipotentials around insulator under (a) dry-clean surface (b) uniformly polluted condition with a single conductivity value

The tangential electric field distributions along the leakage path are compared in Figure 8. This field component is responsible for driving the leakage current on the polymeric surface. The leakage path distance is measured along the creepage of the insulator housing from ground up to the HV voltage terminal as shown in Figure 9. The Field distribution on the polluted surface appears to be smoother compared with the dry-clean insulator. The conductive pollution film in this case helps to re-distribute concentrated field lines over the insulator surface and, hence, suppressing the peaks as found on the field profile under dry-clean conditions.

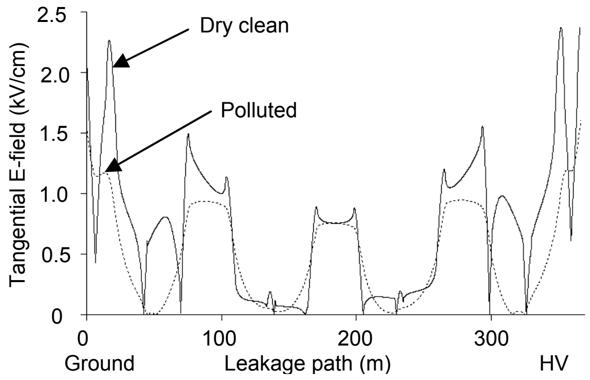


Figure 8: Comparison of tangential electric field distribution for insulator under dry-clean and polluted surface condition (single conductivity of 0.6μS/m).

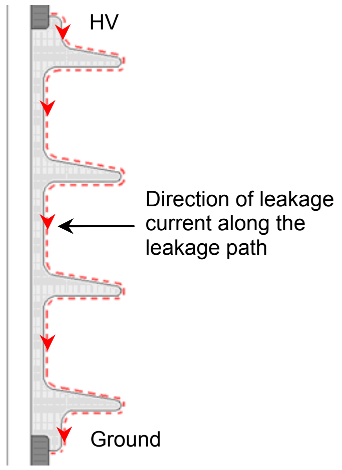


Figure 9: Leakage path and direction of current flow on 2D symmetrical model

The computed field distribution from the proposed nonlinear dynamic model under fog condition with uniform wetting is shown in Figure 10. The pollution model in this case is characterised by a nonlinear field-dependent conductivity. As can be observed, there is a slight difference between the two field profiles. The dynamic model indicates a redistribution of the field.

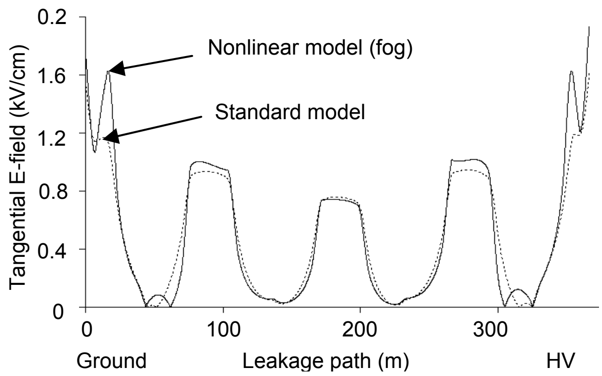


Figure 10: Field distributions from the proposed nonlinear model (fog condition) and standard model (single conductivity of 0.6μS/m).

The peaks at both ends are due to the reduction in surface conductivity when reaching the drying threshold at higher field regions. Such results could be interpreted as an acceleration process for dry banding as higher fields appear due to redistribution which follows heating effects.

The field distribution under light rain conditions, assumed with non-uniform wetting is shown in Figure 11. The pollution is characterised by the properties described in Section 3.2. The nonlinear pollution model provides a field distribution with a series of peaks at different locations on the polymeric surface. Similar to the result under fog conditions, these peaks can be accounted for by a reduction in pollution conductivity due to the drying effect that is considered in this investigation. It is identified that the field increase occurs on the sheltered and least wetted surface indicated by region L (see Figure 5). In most experimental work, dry bands and electrical discharges are commonly observed on the shank regions, which confirms the simulation results obtained using the proposed model.

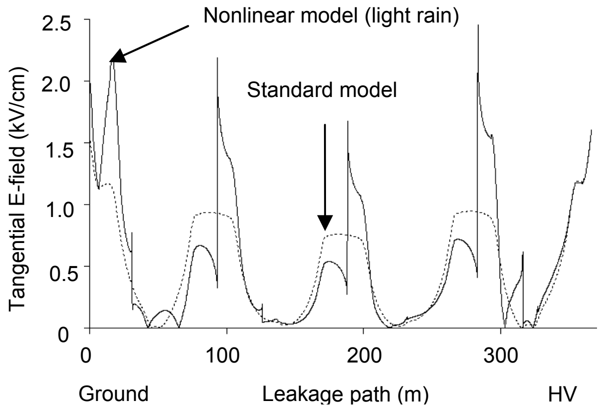


Figure 11: Field distributions from the proposed nonlinear model (rain condition) and standard model (single conductivity of 0.6μS/m).

5 CONCLUSION

A pollution model having nonlinear field dependent conductivity is proposed for use in the computation of the electric field distribution along the leakage path of outdoor polymeric insulators. The dynamic aspects of wetting and drying actions are described with assumptions to characterise the pollution layer under wet weather conditions of fog and light rain. The field distribution obtained from the nonlinear dynamic model offers a detailed and more realistic profile with the presence of peaks which may be useful to predict formation of dry bands and discharges on the insulator surface. The field-dependent surface conductivity model has demonstrated the unfavourable field redistribution which may result in accelerated dry-banding and hence and, hence, discharging.

6 ACKNOWLEDEMENTS

Rahisham Abd-Rahman would like to thank University Tun Hussein Onn Malaysia (UTHM) for the study leave and financial support for his postgraduate studies.

7 REFERENCES

[1] D. L. Williams, A. Haddad, A. R. Rowlands, *et al.*, "Formation and characterization of dry bands in clean fog on polluted insulators," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 6, pp. 724-731, 1999.

[2] A. J. Phillips, J. Kuffel, A. Baker, *et al.*, "Electric Fields on AC Composite Transmission Line Insulators," *IEEE Transactions on Power Delivery,* vol. 23, pp. 823-830, 2008.

[3] P. K. Mukherjee, A. Ahmed, and H. Singer, "Electric field distortion caused by asymmetric pollution on insulator surfaces," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 6, pp. 175-180, 1999.

[4] R. A. Rahman, N. Harid, and A. Haddad, "Stress control on polymeric outdoor insulators," in *Universities Power Engineering Conference (UPEC), 2010 45th International*, 2010, pp. 1-4.

[5] Q. Weiguo, S. A. Sebo, and R. J. Hill, "Practical Cases of Electric Field Distribution Along Dry and Clean Nonceramic Insulators of High-Voltage Power Lines," *IEEE Transactions on Power Delivery,* vol. 22, pp. 1070-1078, 2007.

[6] H. J. Wei, S. Jayaram, and E. Cherney, "A study of electrical stress grading of composite bushings by means of a resistive silicone rubber coating," *Journal of Electrostatics,* vol. 63, pp. 273-283, 2005.

[7] Z. Rong, Z. Yun, C. Weiyuan, *et al.*, "Measurement of electric field distribution along composite insulators by integrated optical electric field sensor," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 15, pp. 302-310, 2008.

[8] T. Zhao and M. G. Comber, "Calculation of electric field and potential distribution along nonceramic insulators considering the effects of conductors and transmission towers," *IEEE Transactions on Power Delivery,* vol. 15, pp. 313-318, 2000.

[9] E. Asenjo S, N. Morales O, and A. Valdenegro E, "Solution of low frequency complex fields in polluted insulators by means of the finite element method," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 4, pp. 10-16, 1997.

[10] A. Yializis, E. Kuffel, and P. H. Alexander, "An Optimized Charge Simulation Method for the Calculation of High Voltage Fields," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-97, pp. 2434-2440, 1978.

[11] J. L. Rasolonjanahary, L. Krahenbuhl, and A. Nicolas, "Computation of electric fields and potential on polluted insulators using a boundary element method," *Magnetics, IEEE Transactions on,* vol. 28, pp. 1473-1476, 1992.

[12] BS EN 60507: 1993, "Artificial pollution tests on high voltage insulators to be used on a.c. systems", Bristish Standard.

[13] "COMSOL Multiphysics User's Manual", Version 3.5a.