PERFORMANCE OF NONLINEAR GRADING COATING ON POLYMERIC OUTDOOR INSULATORS UNDER LIGHTNING IMPULSE VOLTAGES

Rahisham ABD RAHMAN
Cardiff University – United Kingdom
AbdrahmanR@cardiff.ac.uk

A. HADDAD
Cardiff University – United Kingdom
Haddad@cardiff.ac.uk

Noureddine HARID
Cardiff University – United Kingdom
HaridN@cardiff.ac.uk

ABSTRACT

This paper investigates the performance of an 11kV polymeric outdoor insulator equipped with a nonlinear grading material when subjected to a lightning impulse voltage. The grading layer is introduced as a field dependent material at the interface between the core and the silicone housing. The equipotential contours and electric field distribution over the insulator surface were computed and analysed using the Finite Element Method (FEM). Comparative studies show that the nonlinear grading layer, with an appropriate electrical property, can be an effective approach to reduce the electrical stress along the insulator by redistributing the surface field into a more uniform distribution.

INTRODUCTION

Rapid developments in high voltage and power systems insulations have encouraged power utilities around the world to switch to polymeric outdoor insulators as a replacement for conventional glass and porcelain insulators. Polymeric insulators offer the advantage of light weight, cost effectiveness, breakage resistance and more importantly excellent electrical performance in a range of pollution environments due to their hydrophobic surface property. In the presence of moisture, hydrophobicity prevents the formation of continuous conductive film, hence minimising leakage current and the probability of dry band arcing.

However, polymeric materials may temporarily or permanently lose their hydrophobicity when subjected to intense surface discharges [1]. This condition is likely to occur in the event of lightning strikes in which the surge voltage varies widely in magnitude and rise time. The surge voltage results in a significant rise of electric field at the surface of the insulator, particularly near metal terminal areas. Under unfavourable conditions, high field on the insulator surface facilitates the propagation of discharges and the subsequent growth of arcing may eventually cause a complete flashover or insulation failure. Therefore, the control of electric field along the insulator surface is very important and highly desirable.

In recent years, researchers started to employ Zinc Oxide (ZnO) based coating that exhibit highly nonlinear properties to alleviate the stress on polymeric outdoor insulators. Preliminary results from previous research investigations were encouraging. For example, it was demonstrated in [2] that the incorporation of ZnO grading layer helps in reducing the field by approximately 55%, giving an improved field distribution around the insulator. Other authors [3] studied the effect of a thin nonlinear grading layer on composite insulator under rain condition. It was found that the tangential field along the leakage path on the grading-coated insulator was improved, with peak field intensities at high-stress locations reduced to a level below the breakdown threshold.

In this paper, an 11kV polymeric outdoor insulator with nonlinear grading material is modelled using the COMSOL® Multiphysics platform. The main objective is to evaluate the stress performance of the grading layer under transient impulse voltage imposed by a lightning strike. Equipotential contours and field distribution along the leakage path for an insulator with and without grading layer are compared. The effect of grading material electrical properties on its effectiveness to control electrical stress is examined.

PROPOSED FIELD CONTROL USING MICROVARISTOR

In this work, a new proposal is suggested to control the electric field along the insulator profile using tapered ZnO microvaristor compound. The grading layer is introduced at the interface between the core and the silicone housing. It is coated onto the FRP core with a smooth graded thickness toward the middle as illustrated in Figure 1. The extra thickness at the terminals is intended to accommodate high fields in these regions. The cone-shaped coating allows concentrated field to be gradually redistributed away from the metal terminals.

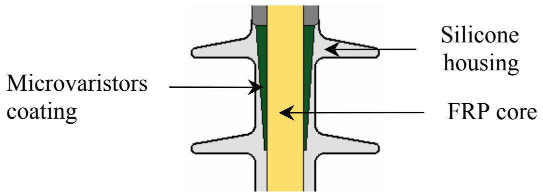


Figure 1. Arrangement of microvaristors coating.

MODELLING PROCEDURE

Insulator Profile

The polymeric insulator in this study is a 4-shed overhead line insulator used on 11 kV systems. Its profile and geometric dimensions are shown in Figure 2. The basic construction comprises three key components; metal flanges, fibre core and insulation housing. The flanges, made of forged steel are used for the voltage energisation and ground terminations. They are crimped to a fibre reinforced rod with a relative permittivity, ε_r=7.1 at a separation of 160mm. The rod, as a core of the insulator, is to provide essential mechanical support from the tower and support the overhead conductor. Silicone rubber (SiR), a synthetic polymer compound having a relative permittivity ε_r=4.3 is used as the insulation housing. The measured crepage distance along the silicone surface is approximately 360 mm. Both core and silicone rubber in this simulation were assumed to be perfect insulators with a conductivity of $1\text{x}10^{-13}$S/m.

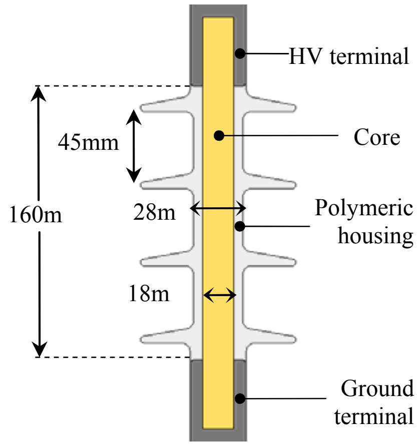


Figure 2. Insulator profile and dimensions

Stress Grading Coating

The grading material employed in this study features highly nonlinear field dependency properties. It is a micro-scaled electroceramic particle, called microvaristors that exhibit electrical behaviour similar to the ZnO varistor in arrester applications [4]. Interestingly, the switching threshold can always be tailored to desired value during the manufacturing process, giving flexibility for the material to be used in a wide range of applications.

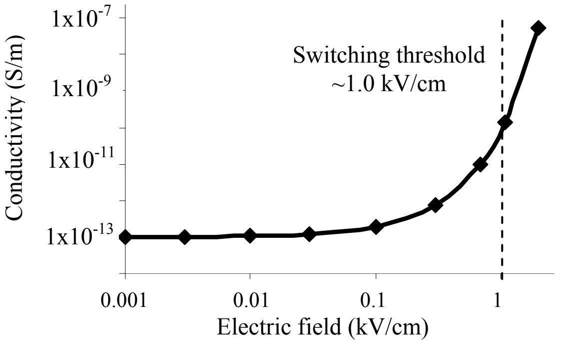


Figure 3. Characteristic of the grading compound

Figure 3 shows the nonlinear characteristic of the microvaristors used in this simulation. The field threshold for conduction as can be seen occurs approximately at 1.0kV/cm. The material operates as insulator in the linear region where the field strength is relatively low. As the applied field exceed the threshold level, the grading material starts to conduct. The nonlinear field dependent conductivity, as depicted in Figure 3 can be represented by a general exponential expression given by equation (1).

$$\sigma(E) = \sigma_0 \exp (\sigma |E|) \tag{1}$$

σ_0 is the initial conductivity while α is a positive constant which determine the rate of change in conductivity. Relative permittivity of the microvaristors composite as quoted by the manufacturer is 12. The electrical properties of the material used in this computation are summarised in Table1.

Table 1 Material properties used for modelling

Material	Relative Permittivity, ε_r	Conductivity, σ (S/m)
Forged steel	1	$5.9\text{x}10^{7}$
Air	1	$1.0\text{x}10^{-13}$
Silicone Rubber	4.3	$1.0\text{x}10^{-13}$
FRP Core	7.1	$1.0\text{x}10^{-13}$
Grading material	12	$\sigma = f(E)$

Impulse Energisation

To study the performance of the nonlinear grading layer under transient condition, the HV terminal is energised with a lightning impulse voltage. The impulse waveform considered for this simulation is shown in Figure 4, with the magnitude of 50kV and a rise time of 1.2µs.

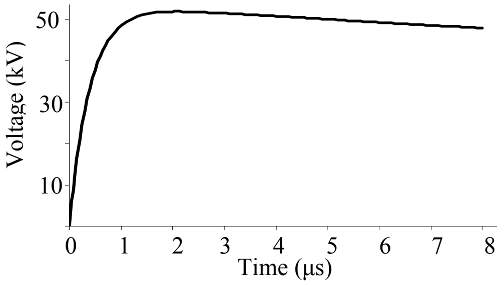


Figure 4. Lightning impulse waveform for energisation

Finite Element Method (FEM)

The transient FEM analysis is performed using Quasi-Statics Electric Current in time-steps domain setting. The module assumes currents that varies slowly with the electromagnetic fields [5]. Induced current from magnetic and electric fields coupling is neglected for simplicity. In the computation, the potential and electric field are calculated by solving the following differential equation given in expression (2).

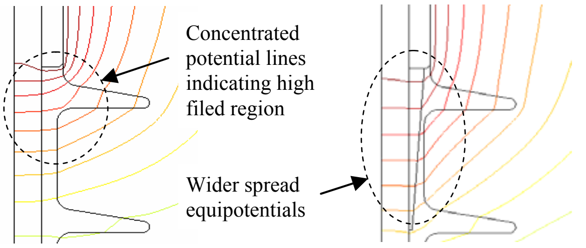
$$\frac{-\nabla \cdot \partial\left(\varepsilon_0 \varepsilon_r \nabla V\right)}{\partial t} - \nabla \cdot \left(\sigma \nabla V - J^e\right) = Q_j \tag{2}$$

where J^e: External current density (A/m^2)
Q_j: Current source (A/m^3)
σ: Electric conductivity (S/m)
ε : Permittivity

RESULTS AND DISCUSSION

Equipotential Profiles

The equipotentials around polymeric insulator with and without nonlinear grading coating are compared in Figure 5. For clarity purpose, only half of the insulator structure was presented. Both insulators are subjected to the lightning impulse voltage, shown in Figure 4.



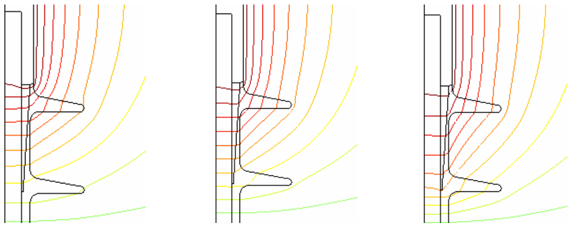
(a) Insulator without grading coating

(b) Insulator equipped with grading coating

Figure 5. Equipotential lines around polymeric insulator at impulse instant of 1.2µs.

From the above figure, it can be seen that insulator with the stress grading layer demonstrate a better and improved equipotentials profile. The presence of grading material result in wide and equally spread contours. It redistributed the concentrated lines over the insulator surface and away from the high field regions. The grading material in this state is in its conduction phase as the applied field exceeds the switching threshold.

To examine the effect of the nonlinear grading during the impulse voltage, equipotentials were computed at different instants of the impulse front; 100ns, 600ns and 1.2µs, shown in Figure 6.



100 ns 600 ns 1.2 µs

Figure 6. Equipotential around insulator at different instant rise times during transient voltage.

As can be observed, the contours are concentrated near the HV terminal at time instant of 100ns. With the magnitude around 10kV, the grading material remains as insulator due the field that may not reach the conduction threshold. As the voltage continues to rise, the electric field become higher, and hence, drives the microvaristors into its conduction state. As a result, the intense potential lines in the high field regions are relieved and become further apart, shown by the equipotentials profile at impulse instant of 600ns and 1.2µs in Figure 6.

Electric Field Distribution

Determination of field strength and its distribution on insulator surface is important to study electrical discharge activities. Leakage current along the wet pollution film is largely driven by the tangential electric field. The flow of current causes surface heating, leading to the formation of dry bands. The corresponding tangential field along the leakage path for the equipotentials in Figure 6 are computed and compared in Figure 7. Leakage distance is measured on the polymeric surface from the ground up to the HV terminal.

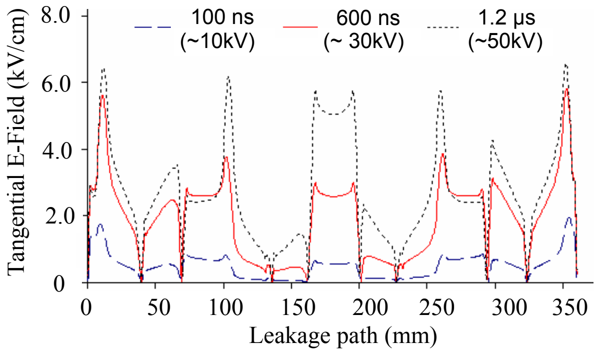


Figure 7. Tangential field distribution along insulator surface at different impulse instants.

Grading effect at time 100ns in the impulse is barely seen due to the passing field that may not reach the conduction threshold. At 600ns, the electric field increases and the peaks at both ends become more significant. The electric field appeared to be more uniform with the maximum impulse voltage at 50kV. Peaks as found on the field curve at 100ns and 600ns were successfully suppressed. In addition, the highest field as can be seen is almost at the same level to the peak value for the energisation of 30kV. The result clearly shows the relief effect on the high field regions which also confirmed the computed equipotentials in Figure 6.

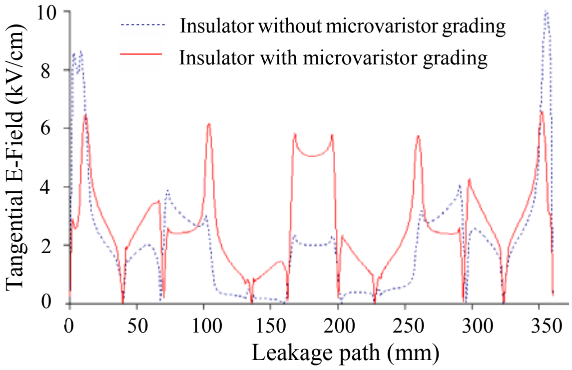


Figure 8. Tangential field distribution along the leakage path with the peak energisation of 50kV.

A comparison of electric field distribution for insulator with and without microvaristor grading is shown in Figure 8. The field were computed at the maximum impulse voltage of 50kV. As can be observed, the microvaristor-graded insulator provides a better and more uniform distribution compared to the one without grading material. High fields at both HV and ground ends are reduced and well distributed over the leakage path. These improvements are detailed in Table 2 and can be clearly seen in the time domain plot, shown in Figure 9.

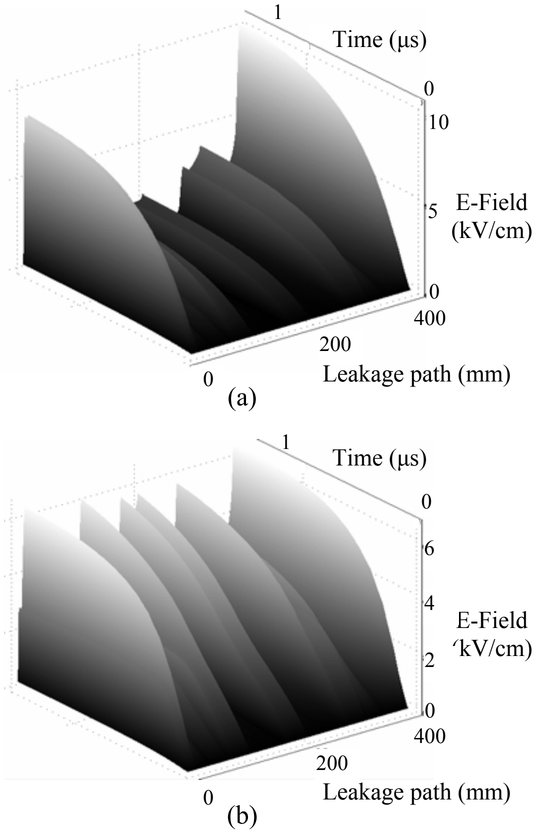


Figure 9. Field distribution in time domain plot for insulator (a) without and (b) with the grading coating.

Excellent field control with the self recovery approach realised by nonlinear grading material is expected to reduce surface discharges and hence improve the flashover performance during the transient over voltage i.e. lightning. Furthermore, dry band formation under polluted ac condition will be suppressed. This will be the subject of a future investigation.

Table 2. Summary of the electrical stress performance

Field on polymeric surface	Insulator without grading	Insulator with grading	Improvement
Maximum field near HV end (kV/cm)	10.26	6.55	36.2%
Maximum field near ground end (kV/cm)	8.58	6.41	23.8%
Peaks uniformity (Standard deviation)	3.41	0.36	89.4%

CONCLUSION

The effect of nonlinear grading material on polymeric outdoor insulator under lightning impulse voltage was presented in this paper. Development of the computational model has been described in details. The computation of equipotentials and field distributions along the leakage path were performed using FEM approach. The proposed microvaristors coated core on polymeric insulator results in a substantial enhancement in the electrical performance under fast transient conditions. High fields near terminals were successfully suppressed and field distributions over the insulator surface were improved and made more uniform. Nonlinear grading material could therefore be a useful approach to achieve stress relief on polymeric outdoor insulators during transient overvoltage.

ACKNOWLEDGEMENTS

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

REFERENCES

[1] J. Kim and M. K. Chaudhury, 1999, "Corona-discharge-induced hydrophobicity loss and recovery of silicones," in *Electrical Insulation and Dielectric Phenomena, 1999 Annual Report Conference on*, pp. 703-706 vol.2.

[2] B. Boettcher*, et al.*, 2001, "Stress control system for composite insulators based on ZnO-technology," in *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, pp. 776-780 vol.2.

[3] D. Weida*, et al.*, 2008, "Electro-Quasistatic High-Voltage Field Simulations of Insulator Structures Covered with Thin Resistive Pollution or Nonlinear Grading Material," in *IEEE International Power Modulators and High Voltage Conference, Proceedings of the 2008*, pp. 580-583.

[4] F. Greuter*, et al.*, 2004, "Microvaristors: Functional fillers for novel electroceramic composites," *Journal of Electroceramics,* vol. 13, pp. 739-744.

[5] "COMSOL Multiphysics User's Manual," ed: Version 3.5a.