ELECTRIC FIELD AND VOLTAGE DISTRIBUTION AROUND COMPOSITE INSULATORS

E. P. Nicolopoulou*, E. N. Gralista, V. T. Kontargyri, I. F. Gonos, I. A. Stathopulos
National Technical University of Athens, School of Electrical and Computer Engineering,
High Voltage Laboratory, 9 Iroon Politechniou St., Zografou Campus, GR 15780,
Athens, Greece
*Email: hveleni@mail.ntua.gr

Abstract: This paper deals with the distribution of the potential and of the electric field inside and around composite insulators which are used for the suspension of high voltage overhead power transmission lines. The calculations were carried out with the 2-dimensional version of the electromagnetic analysis program OPERA which is based on the Finite Elements Method. An insulator model is simulated first by the static solver and then by the steady state ac solver and the results are compared in order to assess the accuracy of each analysis program. The main conclusion is a trade-off between simulation accuracy and computational time. Furthermore, the adequacy of the Finite Elements Method is examined by comparing the results to those derived from the analysis carried out by other researchers with the Boundary Elements Method. Some general conclusions regarding the advantages and disadvantages of these numerical methods are displayed. Finally, the influence of the surface pollution on the dielectric behaviour of the insulator is investigated.

1 INTRODUCTION

The choice of the proper type of insulator is a very important part of the designing procedure of a transmission line as flashover effects and failure of the insulation may lead part of the transmission network out of service. Thus, the performance of the insulators is of great interest, because it affects the fault costs and maintenance routines of power systems. In this direction of improving the reliability of the system, composite insulators have been introduced over the past decades and are increasingly used to replace ceramic insulators [7].

Despite their lower weight, the easier handling, the reduced installation and maintenance costs and their better performance under high pollution conditions, composite insulators are more sensitive to the magnitude of the electric field strength. High values of the electric field intensify the corona effect around conductors and cause in general audio noise, radio noise, partial discharges and premature deterioration of the insulation quality [1, 2].

Moreover, environmental factors such as heat, ozone, UV radiation, salt and dust deposition, acid rain and wind are responsible for the gradual loss of the hydrophobicity of the polymer material [5]. This aging of the insulation material combined with sustained partial discharges may result to erosion of the sheath and consequently possible fracture of the rod due to its exposure to the air.

The evaluation of the electric field distribution in the vicinity of insulators is therefore necessary and can be carried out practically only via laboratory experiment on full-size equipment. A very convenient method to avoid such time consuming tests is the numerical simulation of the setup.

In this paper, the field analysis of an insulator modeled by other researchers [1, 2] with the Boundary Elements Method (BEM) is carried out with software based on the Finite Elements Method (FEM) and the results are compared. Furthermore, the differences between a static solution of the problem and a simulation with the steady state ac solver are investigated. Finally, simulations of the insulator under pollution conditions are carried out.

2 SIMULATION PROCEDURE

2.1 About Opera-2d

The suite of programs for the two dimensional electromagnetic field analysis, OPERA-2d, which is used for the simulations, applies the Finite Elements Method (FEM) to solve the partial differential equations (Poisson's, Helmholtz, and Diffusion equations) that describe the field [10].

The program provides a lossy dielectric option which enables modelling the behaviour of devices consisting of materials with both conductive and dielectric properties, such as electric insulating components. Special routines within OPERA-2d lossy dielectric solver support complex permittivity and thus a complex electric scalar potential.

A static solution involves at first a calculation of the current flow problem, the results of which are used as input to the electrostatic analysis. The fundamental equations that relate the electric field intensity **E** to the scalar potential *V* and the divergence of the electric flux density **D** to the charge density *ρ* are [10]:

$$\mathbf{E} = -\nabla V \quad (1)$$

and

$$\nabla \mathbf{D} = \rho \quad (2)$$

respectively. The usual Poisson's equation for the description of the electrostatic potential arises by combining equations (1) and (2) and introducing the dielectric permittivity tensor *ε*:

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (3)$$

$$\nabla \cdot \varepsilon \nabla V = -\rho \quad (4)$$

The software determines whether the model contains any materials with non-zero conductivity in order to solve the following conduction (current flow) equation in addition to the electrostatic Poisson's equation:

$$\nabla \cdot \sigma \nabla V = 0 \quad (5)$$

where σ is the conductivity
and J the current density:

$$\mathbf{J} = \sigma \mathbf{E} \quad (6)$$

In time-varying problems (harmonic ac analysis), the electric and magnetic fields are normally solved in a coupled manner. Assuming that inductive effects are negligible in semi conducting dielectric problems, the software solves for

$$\nabla \cdot \varepsilon_c \nabla V = 0 \quad (7)$$

and

$$\varepsilon_c = \varepsilon_0 \varepsilon_r - j\frac{\sigma}{\omega} \quad (8)$$

where ε_c is the complex permittivity
ε_r is the relative permittivity
ε_0 is the vacuum permittivity
$\omega = 2\pi f$ is the angular frequency and
f is the regular frequency

2.2 Verification of the FEM

The field analysis of a suspension insulator is an open boundary problem, which means that theoretically the most appropriate approach is that of the BEM. However, the large computational time required by the BEM is a disadvantage which leads us to the FEM as a possible alternative. The FEM has the disadvantage of adding complexity in the modelling phase of the problem, because the external boundaries of the problem must be set by designing a large background region. Thus the total number of elements required for the meshing of the whole model is increased.

In order to investigate the adequacy of the FEM an insulator model described in [1] is analyzed with the FEM Opera-2d software. The insulator to be modeled is used for the suspension of the transmission lines from a 345kV transmission tower. It consists of a fiberglass rod with relative permittivity 7.2 and a polymeric material housing (including the sheath and 72 weathersheds) with relative permittivity 4.5. It is also equipped with two metal fittings at the line and ground end and with a grading ring at the line end.

An axi-symmetric problem was set up based on the symmetry of the insulator and the grading ring. However, this arrangement does not take into account the three-dimensional topology of the conductor at the line end [8]. The space around the suspended insulator is simulated as a background region with relative permittivity 1. The borders of the background are chosen by increasing the dimensions of the region until the size of the background has no longer effect on the voltage distribution.

An important part of the structural design of the problem is the generation of a mesh by separating the region of the model into triangular elements, where the finite elements method will be applied. The mesh density is higher inside the insulator - especially in critical regions such as corners or the edges of the weathersheds and gradually decreases as we approach the borders of the background region [8]. The meshed insulator model together with the background region consists of 201766 elements and 405857 nodes.

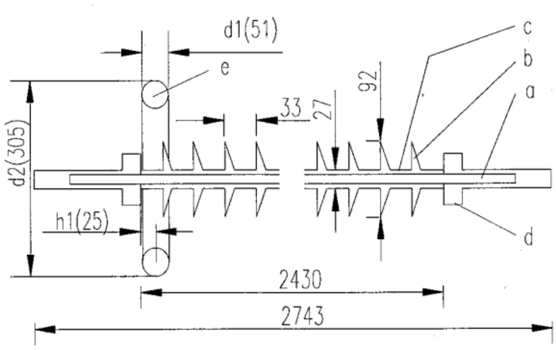

Figure 1: Simplified geometry and dimensions of the nonceramic insulators to be modeled: (a) fiberglass rod (b) polymeric material weathersheds (c) polymeric material sheath (d) metal end fitting and (e) grading ring [1].

The OPERA-2d static solver has been used in order to calculate the voltage distribution along the centre line of the insulator rod which is illustrated in Figure 2 in percentage values of the applied voltage and the insulation distance. The results are compared to those of the BEM analysis in [1], where the model of the insulator with the weathersheds and the grading ring had 1249 elements applied to the surface of boundaries and the interfaces of different media.

A satisfying level of agreement between the FEM and the BEM results [1] (black line in Fig. 2) is observed. It must be pointed out that the BEM distribution in the centre line of the rod in Figure 2 refers to a simplified insulator model without weathersheds, whereas the FEM distribution in Figure 2 has been calculated taking into account the weathersheds. The great proximity of the results, despite this difference, confirms the negligible effect of the weathersheds and indicates that the FEM, which generally requires less computational time, can replace with sufficient solution accuracy the BEM in this kind of open boundary problems.

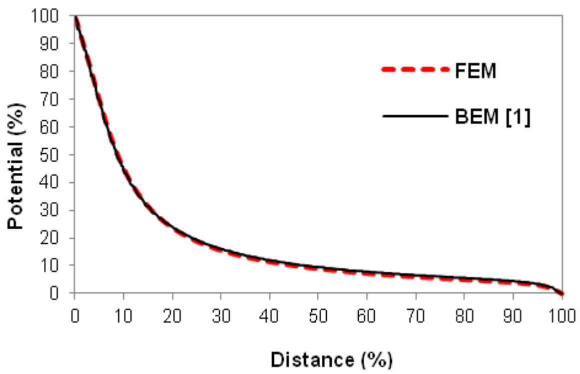

Figure 2: The potential distribution along the insulation distance at the centre line of the rod (R=0mm).

3 RESULTS

3.1 Comparison of the solvers

The second stage of the analysis aims at a comparison between the various solvers provided by the Opera software.

In order to acquire an initial overview of the field distributions, the problem is at first analyzed from a quasi-static perspective and a static simulation of the model is executed. The insulator is then simulated by the steady state ac solver in order to approach its true functional conditions (f=50Hz). In both cases a 1kV voltage has been applied as a reference scenario from which the corresponding field values for every voltage level derive. The voltage (in V, under the abbreviation POT) and electric field (in V/m, under the abbreviation EMOD) distributions across the centre line of the rod and across the edges of the weathersheds calculated with both solvers are presented in Figures 3-6. It must be noted that the presented electric field strength has been calculated as the resultant value from the radial (E_r) and the vertical (E_z) component of the vector:

$$\mathrm{EMOD} = \sqrt{E_z^{\,2} + E_r^{\,2}} \tag{9}$$

Although the results of the two solvers are in good agreement regarding the voltage distribution (Figures 3 and 4) both across the centre of the rod and the edges of the weathersheds, significant deviation is observed in the field distributions. As shown in Figures 5 and 6, the static solver overestimates the values of the electric field strength in the axis of the rod and underestimates them at the weathersheds. The biggest disagreement is observed close to the energized and the grounded end of the insulator.

The computational time on an Intel® Core (TM) 2 Quad CPU Q9400@ 2,66GHz processor with 4 GB installed memory (RAM) was approximately 1min for the static analysis and 5min and 35 sec for the ac analysis. The static solution introduces an RMS error over the whole model 0,59% and a weighted RMS error 0,09%, whereas the corresponding values for the steady state ac solver are only 0,30% and 0,04%.

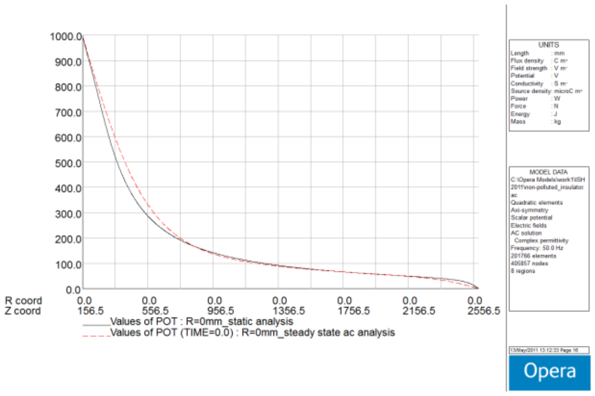

Figure 3: The potential distribution along the centre line of the rod (R=0mm) calculated with the static and the steady state ac solver.

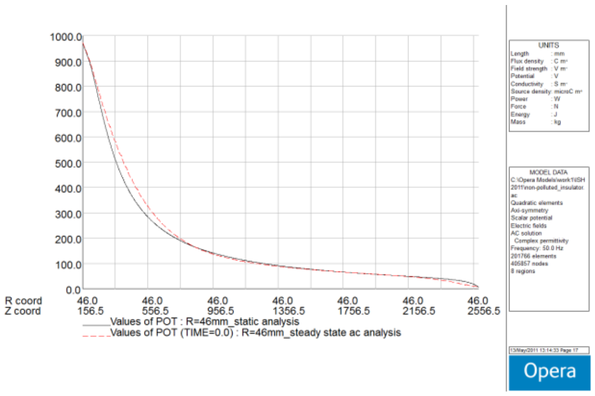

Figure 4: The potential distribution on a vertical line across the edges of the weathersheds

(R=46mm) calculated with the static and the steady state ac solver.

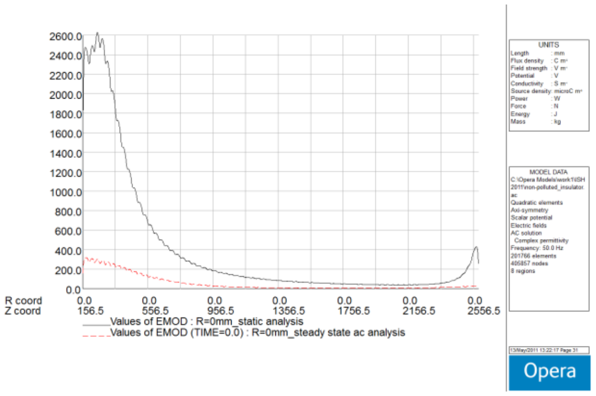

Figure 5: The electric field distribution along the centre line of the rod (R=0mm) calculated with the static and the steady state ac solver.

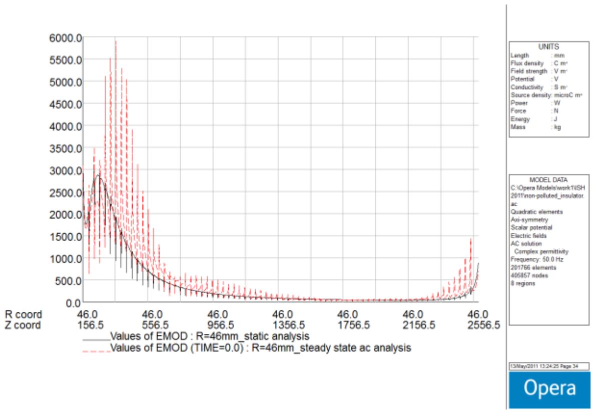

Figure 6: The electric field distribution on a vertical line across the edges of the weathersheds (R=46mm) calculated with the static and the steady state ac solver.

The comparison of the results indicates a major trade-off between simulation accuracy and analysis time. The ac solver requires 5 times the computational time of the static solver, which is a considerable aspect of the problem, especially for complex models. However, based on the distribution graphs and the above error values, it provides more accurate results that differ from those of the static analysis.

3.2 Influence of the surface pollution

The calculation of the electric field distribution is of great importance, when it refers to polluted insulators, because flashover accidents, which may cause breakdown of the transmission network, occur more frequently in polluted insulators [7]. After long time exposure in the air, high voltage insulators - especially in industrial and coastal regions - are often covered with a conductive pollutant layer such as salt or dust deposition. Under high humidity conditions, the electrolytes of the contamination layer are dissolved and the surface conductivity rises. The flow of the surface leakage current leads to the formation of dry bands in the regions with higher current density and lower wetting level. As a result the voltage is redistributed and due to the higher electrical stress of the dry regions, partial arcs evolve, which may eventually cause the full insulator flashover depending on the wet layer resistance [3-4, 6].

The environmental pollution is simulated by adding a thin pollutant layer on the surface of the insulator model. The pollution scenario studied in the present analysis includes heavily polluted core and upper shed surfaces and bottom shed surfaces with medium pollution [3]. The difference in the severity of the pollution is simulated by varying the thickness of the contamination layer, which is $\delta=10^{-3}$m for the heavily polluted regions and $\delta=0.5\cdot10^{-3}$m for the medium polluted regions. The electric conductivity σ (S/m) of the pollutant remains the same across the entire insulator surface and is chosen to be higher than that of the polymer housing, in order to simulate the higher current flow on the insulator surface under contamination conditions.

The simulation of the polluted model is carried out with the steady state ac solver which takes into account more accurately the presence of the high surface conductivity. The voltage and electric field distributions across the edges of the weathersheds for (a) the non-polluted insulator model and the polluted insulator model with contamination conductivity (b) $\sigma=10^{-5}$S/m and (c) $\sigma=10^{-4}$S/m are shown in Figures 7 and 8 respectively. It is obvious that the polluted insulator is more highly stressed.

The voltage distribution of the non-polluted insulator is capacitive, which means that it is mainly defined by the own capacitance of the insulator as well as by its stray capacitances. After adding the pollution layer the insulator surface becomes more conductive and the voltage distribution turns into resistive-capacitive. As the pollution conductivity rises the voltage distribution gradually approaches the linear resistive distribution.

For the better interpretation of the results we can treat the product of the layer thickness (δ) and the pollution conductivity (σ) as a single parameter called surface conductivity (σδ in S). For the chosen values of δ, a pollutant with conductivity $\sigma=10^{-5}$S/m leads to a surface conductivity ranging from 10^{-10}S to 10^{-8}S, for which a resistive-capacitive behaviour is expected according to [9]. An increase of the pollutant conductivity up to $\sigma=10^{-4}$S/m causes transition to a resistive behaviour, as it creates a surface conductivity within the range 10^{-8}S-10^{-7}S [9].

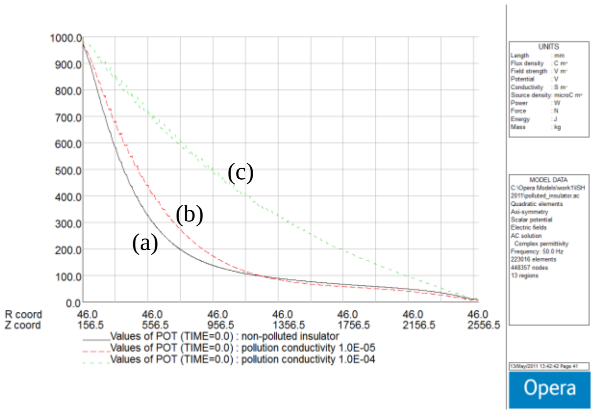

Figure 7: The potential distribution on a vertical line across the edges of the weathersheds (R=46mm) calculated with the steady state ac solver for
(a) the non-polluted insulator
(b) pollution conductivity σ=10^{-5}S/m
(c) pollution conductivity σ=10^{-4}S/m

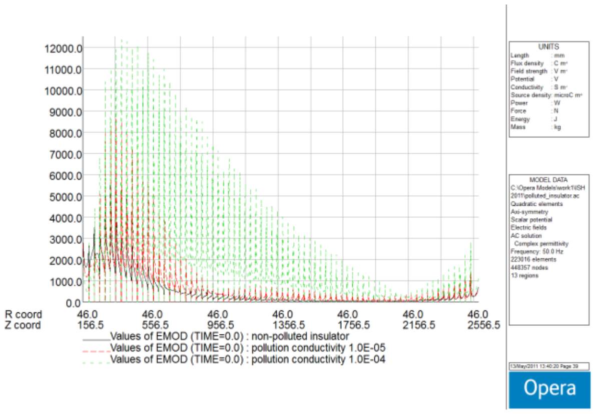

Figure 8: The electric field distribution on a vertical line across the edges of the weathersheds (R=46mm) calculated with the steady state ac solver for
(a) the non-polluted insulator
(b) pollution conductivity σ=10^{-5}S/m
(c) pollution conductivity σ=10^{-4}S/m

In both cases of pollution conductivity, the values of the electric field strength exceed those of the non-polluted insulator. A further conclusion is that a deposition of a pollutant with higher conductivity creates higher field values and may thus cause easier flashover.

4 DISCUSSION

In the present work the adequacy of the FEM for the field analysis of a suspension insulator, despite the theoretical limitations, is demonstrated by the proximity of the simulation results to those obtained by a BEM algorithm. In this kind of open boundary problems the FEM which requires less computational time can replace with sufficient accuracy the BEM. Additionally, important conclusions for the trade-off between static and ac analysis have been drawn. A steady state ac simulation requires multiple computational time in comparison to the static solver, but it provides smaller model errors and results that are closer to the true functional conditions. Finally, a conductive layer on the insulator surface has been used in order to simulate the environmental pollution. The main observations are the increased voltage and field values and the transition to a resistive potential distribution when the values of the pollution conductivity are high.

5 ACKNOWLEDGEMENTS

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